UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

DIGITAL DESIGN AND SIMULATION IN INTELLIGENT MANUFACTURING

INCLUSIVE AND SUSTAINABLE INDUSTRIAL DEVELOPMENT

Digital Design and Simulation in Intelligent Manufacturing

UNITED NATIONS
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United Nations Industrial Development Organization (UNIDO) "Intelligent Manufacturing Technology and its Application in Small and Medium-sized Enterprises(SMEs)" (No.140037) project is committed to introduce SMEs in Chinese manufacturing to the concept of Intelligent Manufacturing(IM) and its attendant ICT needs, increase awareness towards IM and carry out trainings on IM technology and its theory. Digital Design and Simulation in Intelligent Manufacturing is a textbook compiled for the mentioned IMT trainings, an achievement of the UNIDO Intelligent Manufacturing project;

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CHAPTER 1

Overview of Intelligent Manufacturing

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1.1 Development of Intelligent Manufacturing

Manufacturing is an important factor of a country's international competitiveness and comprehensive strength and plays a significant role in the country's economic construction. Driven by the technological revolution, industrial revolution, digitalization and information eras, manufacturing has gone through the development from single piece production to flow line production, to flexible production and finally to intelligent manufacturing.

Intelligent manufacturing grows gradually with the continuous development of information and communication technologies. In 1988, Professor P. K. Wright of New York University and Professor D. A. Bourne of Carnegie Mellon University first proposed the concept of Intelligent Manufacturing in their book Manufacturing Intelligence.

Intelligent manufacturing(IM) is an intelligent human machine integration system composed of intelligent machines and human experts, and capable of performing intelligent activities such as analysis, inference, judgment, conception and decision-making in the manufacturing process. By means of the cooperation between human beings and intelligent machines, the system will broaden, extend and partially replace the mental work of human experts in the manufacturing process. Intelligent manufacturing extends the concept of manufacturing automation to flexibility, intelligence and high integration.

Intelligent manufacturing is a derivative of artificial intelligence. Artificial intelligence(AI) is the intelligence implemented on a computer through artificial means. With the improvement of product performance, the complexity and refinement of product structures and the diversification of product features, the amount of design and process information contained in products soars. Accordingly, the information flow in production lines and equipment increases, and the amount of information on manufacturing processes and management rockets inevitably. As a result, the hotspot and frontier in the development of manufacturing technologies will turn to improving the ability, efficiency and scale of manufacturing systems to handle the explosively growing manufacturing information. Advanced manufacturing equipment cannot run without information input, and flexible manufacturing systems(FMSs) will shut down immediately once the information source is cut off. Manufacturing systems are changing from conventional energy-driven to information-driven, which requires manufacturing systems to be flexible and intelligent; otherwise, they cannot handle such a large amount of complex information. Moreover, the ever-changing market demand and fiercely competitive environment also requires manufacturing systems to be highly flexible, agile and intelligent. As a result, intelligent manufacturing is attracting more and more attention.

In the 1990s, developed countries began to focus on and study intelligent manufacturing technologies as the informationtechnology and artificial intelligence advanced. The USA, Japan and other countries have set up funds and experimental bases for intelligent manufacturing research projects, and great achievements have been made in the studies and practices of intelligent manufacturing.

In April 1990, Japan launched an international cooperative research program called the"Intelligent Manufacturing System(IMS) Initiative", in which developed countries such as the USA, the European Communities, Canada and Australia participated. The program had an investment budget of US $1 billion in total and was intended to carry out a preliminary research plan for 100 projects.

In the same period, Canada developed the Strategic Development Plan 1994-1998. In the Plan, knowledge-intensive industries were considered as the foundation of driving the global economy and Canadian economy, the importance of the development and application of intelligent systems were identified, and specific research projects including intelligent computer, human machine interface, mechanical sensors, robot control, new devices and system integration in dynamic environments were selected.

Due to the financial crisis in 2008, developed countries have gained an understanding of the importance of manufacturing. They proposed a development strategy called"Returning to Manufacturing", regarded intelligent manufacturing as the future trend of development and introduced a series of supporting policies in order to seize the high ground in the technological competition of international manufacturing.

In 2008, the UK government proposed a strategy titled"High Value Manufacturing"to encourage local enterprises to produce more world-class high value-added products, make high value manufacturing (HVM) the main driving force of UK economic development and promote entrepreneurial innovation in the whole process from conceptualization to commercialization. The government also encouraged the application of intelligent technology and expertise and the provision of innovative products, production processes and associated services with the potential for sustained growth and high economic values. In this way, the goal of reinvigorating the British manufacturing industry could be achieved.

In 2009, the USA launched a"Reindustrialization"program which specified the development of high value-added manufacturing such as advanced manufacturing technologies, new energy sources, environmental protection, information and other emerging industries based on high and new technologies to rebuild a new industrial system with strong competitiveness.

In the same year, South Korea put forward the"New Growth Driver Planning and Development Strategy"which identified 17 industries in 3 major areas as the development priorities to promote cooperative construction of the digital industrial design and manufacturing digitalization and strengthen policy support for the basic development of intelligent manufacturing.

In 2013, Germany launched the"Industry 4.0",in which the modality adopted was to build an integrated and intelligent industrial manufacturing system on distributed and modular industrial manufacturing units by virtue of industrial network broadband and multifunctional sensing devices. Consequently, the entire industrial process including manufacturing, engineering, material use, supply chain and lifecycle management was fundamentally reconstructed.

In 2013, France put forward a program called"The New Industrial France", which allowed France to regain industrial strength through innovation and rank one of the most competitive nations in the world. The purpose was to revitalize the industrial power of France in 10 years. The program also identified 34 projects as the supporting points of France's industrial recovery, ranging from big data to cloud computing, from a new generation of high-speed trains to electric planes, and from intelligent textile to factories of the future.

In 2014, India launched the "Made in India" campaign in which the country would be transformed into a "global manufacturing hub" by improving the capacities for infrastructure construction, manufacturing and smart cities as three pillars of this new economic reform strategy which is expected to attract the investment from international manufacturing giants by improving the investment environment.

In 2015, China unveiled the "Made in China 2025" plan which specified the basic guidelines of "innovation-driven, quality priority, green development, structure optimization and talent-oriented" and the basic principles of "market-led, government-guided, thinking long-term based on the current situation, advancing on the whole, making breakthroughs in key areas, independent development, opening up and cooperation". The plan was intended to achieve the strategic goal of a manufacturing power through "Three Steps": the first step is to become a manufacturing power by 2025, the second step is to become a medium-level manufacturer among the world's top producers by 2035, and the third step is to rank China in the top league in terms of comprehensive strength by 2049.

Currently, a number of front-end information technologies such as big data and cloud computing have accelerated the transformation of the manufacturing to intelligence. As the global manufacturing is speeding up towards the digital and intelligent era, intelligent manufacturing has a growing influence on manufacturing competitiveness.

1.2 Intelligent Manufacturing Technologies

Intelligent manufacturing technologies (IMTs) are the integration of intelligent technologies and manufacturing technologies. IMTs can be described variously in terms of scopes and categories.

1.2.1 Core Intelligent Technologies in Intelligent Manufacturing

a) Image recognition

Image recognition is a computer technology that can process, analyze and understand images to identify targets and objects in various modes. In general industrial use, an industrial camera is used to take pictures and then software is applied for further recognition and processing of the pictures according to grayscale difference of these pictures.
Image recognition is an integral component of intelligent manufacturing, and 3D object recognition is a critical technology to recognize object geometry in intelligent manufacturing service systems.

b) Real-Time location system

A Real-Time Location System (RTLS) is a signal-based radio positioning means which can be either active or passively inductive. The RTLS can track and manage various materials, parts, tools, devices and other assets in real time. Due to the requirements to track the whereabouts of in-process products in the production process and the storage positionsof materials, parts and tools, the intelligent manufacturing service system shall be provided with a real-time location network system as well as a production process real-time monitoring system (transparent factories, real-time production progress tracking, and production management systems).

c) Cloud Computing

Cloud Computing is a branch of distributed computing and is designed to use the network "Cloud" to break down a huge data computing and processing program into countless small programs to be processed and analyzed by a system composed of multiple servers, and send the obtained results to users. Cloud Computing is capable of processing tens of thousands of data in a concise time (seconds) to deliver powerful network services. Cloud Computing is the central nervous system of the virtual Internet brain.

d) Cybersecurity

Cybersecurity refers to the protection of hardware, software and data of a network system against destruction, modification or disclosure due to occasional or malicious causes, and the guarantee that the system runs continuously, reliably and normally without any interruption of network services. Digitalization fosters the development of manufacturing, while it poses threats to the cybersecurity of factories as well. Nowadays, people are increasingly relying on computer networks, automated machines and ubiquitous sensors during the manufacturing process. The digital technical data of the manufacturing process support the entire process of product design, manufacturing and services and thereby must be protected.

e) Artificial Intelligence

Artificial Intelligence(AI) is a new technical science involving the research and development of theories, methods, technologies and application systems to simulate, expand and extend the intelligence of human beings. As a branch of computer science, AI attempts to understand the nature of intelligence and produce new intelligent machines which are able to respond in a manner similar to human intelligence. Studies in this field include robotics, language recognition, image recognition, natural language processing and expert systems. As the theories and technologies have become increasingly mature and the application fields have continuously expanded since the birth of Artificial Intelligence, AI is capable of simulating the information process of human consciousness and thinking.

1.2.2 Core Manufacturing Technologies in Intelligent Manufacturing

a) Industrial Robot

An industrial robot is a good assistant in intelligent manufacturing. It is a multi-joint manipulator or a multi-degree-of-freedom robotic installation for industrial applications. Industrial robots can execute missions automatically and implement a variety of features through their own power and control capabilities. Industrial robots can be operated by humans or run in accordance with pre-programmed procedures. Modern industrial robots can also act based on the principles and guidelines of AI technologies.

b) Industrial Internet

Industrial Internet is a global network that connects people, data and machines. It represents a high integration between the global industrial systems and advanced computing, analysis, sensing technologies and the Internet. The nature and core of Industrial Internet is the connection and integration of equipment, production lines, factories, suppliers, products and customers through an Industrial Internet platform. This can help expand the industry chain of manufacturing sectors and form cross-device, cross-system, cross-plant, and cross-regional interconnections, thus improving the efficiency and promoting the intelligence of the entire manufacturing service system. It is also conducive to driving integrated development of manufacturing and achieving leaping development between manufacturing and service industries for the efficient sharing of various elements and resources of the industrial economy.

c) Industrial Big Data

Industrial Big Data technologies refer to a number of techniques and methods that exploit and demonstrate the valuecontained in Industrial Big Data, including data planning, acquisition, pre-processing, storage, analytical mining, virtualization and intelligent control. The application of Industrial Big Data is a process of integrating and applying several technologies and methods of Industrial Big Data to obtain valuable information for specific industrial big data sets. The ongoing research and breakthroughs of Industrial Big Data technologies are fundamentally intended to discover new patterns and knowledge and extract unknown and valuable information from complex data sets to promote product innovation, improve operational level, enhance production & operation efficiency, and expand new business models of manufacturing enterprises.

d) 3D printing

3D printing is a technology that allows the layer-by-layer build-up of an object by using powder metal, plastics or other adhesive materials based on a digital model file. The mainstream processes of 3D printing include extrusion molding, photopolymerization molding and granular material molding. 3D printing is normally implemented by a materials printer using digital technologies. 3D printing is often used in the fields of mould manufacturing, industrial design, and has been gradually applied for the direct manufacturing of certain products. There are parts and components printed by using this technology. This technology is also applied in jewelry, footwear, architecture, engineering & construction (AEC), automobiles, aerospace, dental and medical industries, education, geographic information system, civil engineering, firearms and other fields.

e) Computer simulation

Computer simulation is a comprehensive technology using system models to conduct experimental research on actual or hypothetical systems in accordance with similar principles, information technologies, system technologies and expertise in relevant fields and in conjunction with tools such as computers and various physical effect instruments. In terms of the application features, computer simulation industries can be categorized into computer simulation tests, simulation training, virtual manufacturing and other fields. Computer simulation technologies are now widely applied in national defense, industries and other human production and life aspects.

1.3 Intelligent Manufacturing and Design Simulation

Simulation is a comprehensive technology using system models to conduct dynamic tests on actual or hypothetical systems by taking advantage of computers and special physical effect instruments. The influence of simulation technologies has already expanded from the initial aviation, aerospace and nuclear industries to all fields of the national economy such as machine manufacturing, electric power, transportation, medical care and education.

Prior to the materialization of an industrial product, simulation technologies can be used to research and evaluate the design concepts, potential product performance, value, operation efficiency and adaptability, thus greatly decreasing development risks and cycles and reducing development costs.

At the very beginning of the design of a product scheme, a "Digital Twin" is created for the product, and then different simulation analysis software is applied on a computer to simulate the performance attributes of the product. In this way, the product development cycle is shortened to the furthest extent, the product performance is optimized, the problems with the physical mock-up are reduced, and the design efficiency is improved.

For example, as collision tests were conducted repeatedly in the design of a car in the past, several real cars would be destroyed in the collision and the development period would last for years. With simulation technologies, however, all collision results can be computed quickly as long as appropriate data are input in the software. The most significant benefit of simulation technologies is to "reproduce" people's thoughts in a virtual world.

As an important link to industrial production, the innovative capability of product design determines the market response of the product to some extent. The novelty of a product design mainly depends on the competence of product designers who need a certain space to unfold their talent. The rapid development of simulation technologies provides these product designers with great display spaces and infinite possibilities.

Intelligent manufacturing cannot do without the support of simulation technologies. At present, simulation technologies have already become an irreplaceable means of analysis, research, design, evaluation, decision-making, and training for any complex systems, especially high-tech industries. These technologies are also an important technical means to bring China from a manufacturing country to a manufacturing power. According to statistics, the annual investment of software and hardware input for simulation technologies is between 3-5 billion yuan in China.

Some large companies in the world have also widely applied simulation technologies to all aspects of industrial intelligent manufacturing to improve their development efficiency, strengthen data acquisition, analysis and processing capabilities, decrease decision-making errors and reduce business risks.

Boeing utilized simulation technologies in the design and manufacturing of Boeing 777, and designers wore a head-mounted display (HMD) to enter a virtual aircraft and examine the performance of the aircraft. From conceptual design to simulation and finalization to the direct manufacturing of a product passing test flights successfully, the development cycle was halved and the cost was cut down by hundreds of millions of US dollars. Virtalis, headquartered in the UK, uses virtual reality technologies to allow manufacturers to truly perceive a project under construction such as submarines or apartment buildings. Companies such as British BAE, Leyland and Rolls-Royce also applied virtual reality systems using simulation technologies to improve product manufacturing quality, reduce errors and avoid rework. Dean Brown of British BAE said, "Without any exaggeration, people can 'walk' in a building being created to examine every problem accurately."

Simulation technologies also play a significant role in military manufacturing. The latest flight simulator is featured in a brand new electronic instrument, high-speed big data computing computer, precise tracking device and high-quality graphic simulator to provide immersive flight teaching and training for novice pilots with low flight experiences. The flight simulator plays a major role in improving the pilots' operational level as the pilots may develop strong skills and master fine techniques in a controlled environment in this case. For the reasons given above, the USA has listed simulation as a critical technology among national defense technologies and even ranked the simulation environment as one of the seven essential demands of modern local wars. Many countries have now considered simulation technologies as the priority of the national defense industry and incorporated them into the national strategy.

Frontier technologies that should be encouraged include intelligent perception, self-organized network and virtual reality in accordance with Outline of Long and Medium-term National Science and Technology Development Plan (2006-2020).

According to the Plan, the simulation industry shall adapt to the new trend of national scientific and technological development, focus on independent innovation, vigorously carry out key technology research and simulation platform development, and cultivate and improve the endogenous power of the simulation industry. The industry should be developed to hold the world's advanced industrial and technological advantages quickly, foster the social and economic transformation and upgrading, and drive the scientific development of national strategic emerging industries and national economy. This is the national strategic mission endowed to the capability building of the simulation industry.

CHAPTER 2

Product Digital Design and Simulation

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Product Digital Design and Simulation

This chapter mainly introduces the change of product design engineers in the manufacturing industry from traditional hand-drawn 2D drawings to the use of computerized 3D design software for product designs due to the emergence of computers, and then states the importance and necessity of 3D simulation technologies for product performance inspection.

2.1 Development History and Current Situation of Digital Design

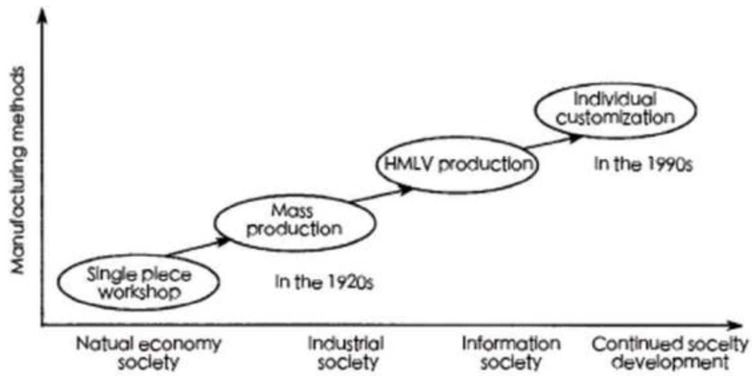
2.1.1 Emergence of Digital Design

The digitalization of product design has emerged as a result of human beings entering the information age and is rooted in the huge demands of modern manufacturing enterprises for technologies. With the rapid development of information technologies and the acceleration of economic globalization, modern manufacturing has changed dramatically such as shortened product lifecycle, the date of delivery serving as a major competitive factor, personalized user needs, and increased high-mix low-volume production. Modern manufacturing has stepped into a new era of digital design, digital manufacturing, digital testing and digital product management with core features as follows: 1) the introduction of digital technologies in the whole production process, 2) the popularization and deepening of the applications of computer-aided technologies and system integration technologies in all links of the product lifecycle, 3) the comprehensive upgrading of enterprises in terms of design, manufacturing, management and other aspects, and 4) the technological advancement in traditional industries. In fact, digital technologies have already been the main technical support for the survival and development of manufacturing enterprises, especially small and medium-sized enterprises, and an effective approach for enterprises to continuously expand their competitive advantages.

Looking back into the history, product design technologies have undergone a long process of technological progress. In the First Industrial Revolution featured infeatured in large-scale production by machines, humans used steam engines to drive the machines and processed raw materials and fabricated various necessary tools on the machines, thus forming mature technologies for mass production of products. During this period, revolutionary production system innovations such as "specialized production of parts and components", "interchangeable and standard parts", "instrumentation of measurement and tests" and "mass production" were born. Then, in the 1920s, Ford pioneered automatic assembly production lines, put forward the standardization concept and introduced scientific management ideas, thus resulting in a new production mode of "low-mix high-volume (LMHV)". With the high-volume production mode, lower costs and stable quality was possible. This production mode was also featured in highly interchangeable parts and components, small product selection ranges, fixed functions, large production volumes, and lower costs and prices. The economy under this production model was called the economy of scale. In a rather long period afterwards, this model has achievedunprecedented success and been typically applied in automobile manufacturing, serialized machine tool manufacturing, household appliance assembly lines, etc.

Since the 1990s, customers have significantly increased their consumption levels, which has results in increased competition among enterprises all the while as economic growth and technological advances continue. The world has entered an era of economic globalization and global industrial division. In the 21st century, with the rapid development of computers and information technologies, human beings have entered the so-called information society in which modern manufacturing based on global information flow, logistics and talent flow has changed dramatically. As the society moves forward, the manufacturing methods or production modes of products have evolved and advanced continuously from "mass production" to "high-mix low volume (HMLV)" production and "individual customization" as shown in Figure 2-1.

Figure 2-1 Production mode changes with society development



The process of conveying an idea through rational planning and deliberate programs in various forms of feelings is generally called "design". Human beings work hard to remake the world, create civilization and produce material and spiritual wealth, but the most fundamental and important creative activity is product manufacturing. The preplanning of manufacturing activities is characterized as design that may include planning techniques and processes of any manufacturing activities. The development of design techniques depends on the change in production modes. According to Figure 2-1, production relies on manual copying and imitation at the single piece workshop stage, and product design is not independent from the product production process due to small volume and undefined structures. However, "product design" is separated as a specialized division of labor in the product production process at the mass production stage. In this paper, the product design of the manufacturing industry not only refers to the concept of industrial designs, but also covers all researches related to products in general including product profiles, product designs, product models, production molds,product tests and product quality,and related studies on the production process such as time study, motion study and method study, and correlates these researches and studies with the economic indexes of products to bring about a number of management sciences adapted to mass industrial production.

For design technologies, the design tools used by human beings have evolved and developed continuously, especially with the advent of computers, causing revolutionary changes to product design technologies.In the Stone Age, humans could only carve their ideas about a new product into stones. However, they could already draw product designs on paper and started to unify symbols after entering the age of steam engines. During the Second World War, a great number of industrial products were processed and manufactured in accordance with unified standard drawings, and people began to use drawing tools such as gauges of uniform weights and measures (imperial system) to achieve a high degree of consistency of the design of drawings with the mass production of products. The International Organization for Standardization (ISO, 1947) had been founded at the end of the Second World War, which also marked the global society entrance into the era of electrification. In 1946, the world's first computer ENIAC was launched and completely changed the way that human beings engaged in product designs. Computers were applied to product design technologies with giant development potentials soon upon its invention. In the 1950s, the first computer-aided plotting system was built and computer-aided design (CAD) technologies with simple drawing features emerged accordingly. The CAD technology of curved surface patches was launched in the early 1960s, and commercial computer drawing equipment was introduced in the middle 1960s.In the 1970s,a complete CAD system was developed.Later, a raster scan display that was capable of producing realistic graphics emerged,and various types of graphic input devices such as manual cursors and graphic input boards were introduced, which promoted the development of CAD technologies. In the 1980s, a specialized design workstation with powerful graphic features was announced, so that CAD technologies began to be popularized in small and middle-sized enterprises (SMEs) and directed towards standardization, integration and intelligence. In recent years, intelligent CAD technologies have been developed with the introduction of AI and expert system technologies into CAD, which has greatly enhanced the capabilities of CAD systems and implemented a more automated design process. CAD technologies are widely applied in architectural design, electronics and electrical engineering, scientific research, mechanical design, software development, robotics, clothing industry, publishing, factory automation, civil construction, geology, computer art and other fields.

China self-developed CAD technologies have helped manufacturing industry make great progress since the reform and opening up. As an integral component of advanced manufacturing technologies, the research and application of CAD technologies will become an indispensable approach to advance the technological innovation and renovation of China's manufacturing enterprises. Since the 1990s, CAD/CAM industries with Chinese characteristics have been gradually formed in China, with the key emphasis on CIMS application engineering. CIMS is the integration of computer aided design(CAD),computer aided manufacturing (CAM), computer aided process planning (CAPP), computer aided engineering (CAE), management and decision-making, network and database, quality assurance systems and other unit techniques.In the application of CIMS,hundreds of large and medium-sized enterprises and scientific research institutions are selected as the application factories of CIMS to promote the implementation and application of CIMS technologies and drive the development of CAD technologies at a higher technical level.A clear goal of driving the productivity using CAD technologies has been proposed at the beginning of the reform. Upon continuous exploration, China finally decided to implement the automation of drawing design through a project titled "Throwing off Drawing Board", which is considered as a breakthrough to promote and apply CAD technologies as well as a strategic decision in line with China's national conditions with small investment and quick effects. The "Throwing off Drawing Board" project is intended to encourage the design departments of enterprises to widely adopt advanced CAD technologies, instead of manual drawing. In this project, enterprises do not have to invest too much to form the scale of microcomputer drawing quickly and enable CAD to come straight to designers from "computer rooms", greatly improving the design quality and efficiency. After more than 30 years of efforts, the CAD penetration rate in domestic engineering institutes has already risen from 60% to 100%. The application of CAD technologies has achieved remarkable results. Common feedback from enterprises includes shortened design cycle by 1/2 and above, remarkably improved product quality, reduced labor input by 1/2 and above, and significantly lower costs.

In addition to the "Throwing off Drawing Board" project, digital design technologies have also changed the traditional product development process. Normally, product design follows the sequential engineering of "design-drawing-manufacturing-assembly-prototype testing". However, prototypes generally cannot meet all design standards at the first place due to structural design, dimensional parameters, materials, manufacturing processes and other reasons. In this case, it is inevitable to revise the design repeatedly and remanufacture and retest the prototypes in the development of a new product, thus resulting in a long development cycle, high costs, poor performance and low efficiency. The application of digital design and 3D digital models allows designers to have a more realistic view of the product being designed and the development process, as well as to recognize the underlying characteristics such as the shape, size and color of the product to verify the validity and feasibility of the design.Through digital analysis, designers can compute and simulate the performance, dynamic characteristics and process parameters of the product, including quality characteristics, deformation process, mechanical characteristics and motion features, simulate the assembly process of parts and components, and check the parts and components used for suitability and correctness. By means of digital processing software, designers can define the machining process and carry out NC machining simulation, predict the machining performance and effect of parts and products, and modify the designs promptly according to the simulation results. Designers can also use a virtual model of the product for direct interaction with the designed product to provide a unified visualized information platform for communication among related personnel.This parallel design idea, also known as concurrent engineering, stresses the integration of information,process and feature,and can effectively shorten the development cycle of products and improve product quality.

With the development of economy in the new century, there are higher requirements for design technologies of products including comprehensive application of digital engineering in the design and manufacturing processes and transformation of traditional technical contents and systems. Digitalization can be applied to address all kinds of computing problems involved in engineering computation such as differential equations, partial differential equations and matrix eigenvalue. At the same time, digitalization is expanding to other branches of disciplines including statistics, data mining, computer algorithms, graphics, image processing and biocomputing. Digital design is based on the application of numerical computation methods computer software and hardware technologies, network transmission technologies and information processing technologies to establish a set of design methods and related technologies that support the entire product development and production process. Digital design also supports design evolution based on design rules and domain knowledge. Specifically, it supports convenient and rapid innovative design, variant design, optimized design and redesign. In addition, digital design supports data management, process control and optimization throughout the product development process. Digital technologies applied in the design process include computer-aided conceptual design (CACD), computer-aided geometric modeling (CAGM), computer-aided engineering (CAE) and product data management (PDM). Digital manufacturing (DM) defines and describes the manufacturing process and equipment digitally, and implements the product processing and manufacturing through the control of a computer in network environment, including computer-aided manufacturing (CAM), computer-aided process planning (CAPP), computer-aided tooling design (CATD) and computer-aided planning (CAP).

2.1.2 Connotation and Extension of Digital Design

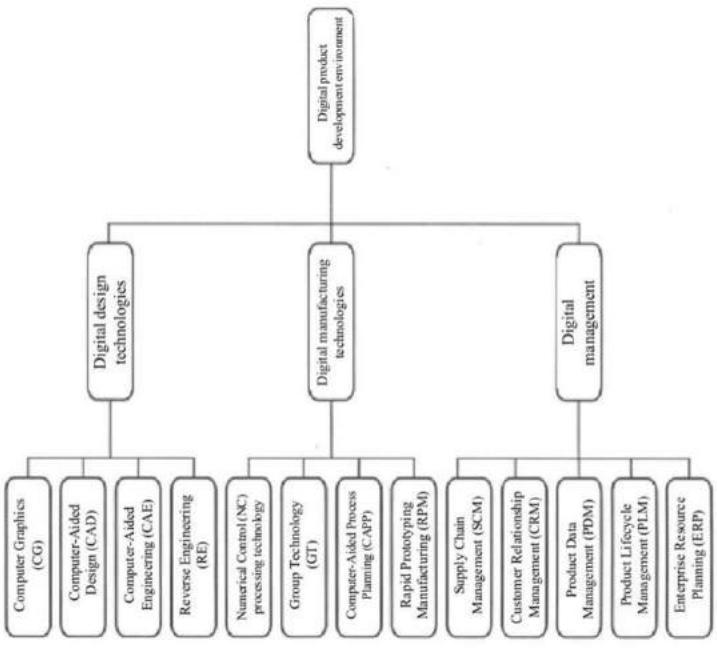
In digital design, computer software and hardware technologies are applied to improve product development quality and efficiency. Digital design focuses more on the role of computers, digital information, network technologies and intelligent algorithms in product development compared with traditional product development methods.

Digital design and manufacturing mainly consists of computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided process planning (CAPP), and computer-aided engineering (CAE) and product data management (PDM) and supports the whole product development process, innovative product design, product-related data management, and product development process control and optimization of enterprises. In summary, product modeling is the foundation, design optimization is the main body, numerical control technologies are the tool, and data management is the core, as shown in Figure 2-2.

Figure 2-2 Digital product design and manufacturing concept

As computer, network and database technologies are maturing and the Standard for the Exchange of Product Model Data (STEP) is improving continuously, a variety of digital development technologies present a trend of crossover, fusion and integration, resulting in more complete features, quicker access to information, higher efficiency and easier to use. Figure 2-3 shows the digital product development environment and its discipline system.

Figure 2-3 Digital design knowledge system



a) Computer-aided design (CAD)

Computer-aided design (CAD) is considered as the origin of information and digitalization and primarily used to design products, components and parts including 3D modeling and 2D product drawing. CAD is supported by curved surface modeling, solid modeling, parametric design, feature technologies and variable parameter technologies.

b) Computer-aided engineering (CAE)

Computer-aided engineering (CAE) mainly refers to the use of computers to analyze performance and safety of projects and products and simulate the expected working conditions and operations for early detection of design defects and verification of the availability and reliability of expected projects, product features and performance.

c) Computer graphics (CG)

Computer graphics (CG) is a discipline that uses mathematical algorithms to transform a 2D or 3D graphic into a grid on the computer display. In other words, CG studies the representation of graphics and the implementation of related principles and algorithms of graphics computation, processing and display in computers. Specifically, CG studies graphics hardware, graphics standards, graphics interaction technologies, raster graphics generation algorithms, curve and surface modeling, solid modeling, realistic graphics computation and algorithms, non-realistic plotting, scientific computing visualization, computer animation, natural scenery simulation and virtual reality.

d) Reverse engineering (RE)

Reverse engineering (RE), also known as inverse engineering, uses 3D digital measuring equipment to measure the geometric data of the contour of an existing 3D object (a sample or model) accurately and quickly (without the original product drawings and documents) constructs, edits and modifies the measurement data to generate a digital curved surface model in a general output format. In this way, it is possible to produce a physical 3D model or a NC machining program, or provide section contour data necessary for rapid prototyping and manufacturing.

e) Computer-aided process planning (CAPP)

In computer-aided process planning (CAPP), a computer will output process files such as process routes and procedures automatically after the geometric information (graphics) and process information (materials, heat treatment, batches, etc.) of a machined part are entered. CAPP has fundamentally changed the traditional practices of relying on personal experience and drafting process specifications manually, promoted the standardization and optimization of processes and improved the quality of process design. CAPP is supported by information modeling technologies, process design automation and the Standard for the Exchange of Product Model Data.

f) Group technology (GT)

Group technology (GT) takes advantage of the similarity between things and classifies them into groups according to certain criteria. Things in the same group can be processed by the same method for higher efficiency. Full application of GT will fundamentally affect the management system and working mode of enterprises and improve their standardization, specialization and automation levels. In mechanical manufacturing projects, GT is the foundation of computer-aided manufacturing.

g) Rapid prototyping (RP)

Rapid Prototyping (RP) was developed in the 1990s and is considered as a major breakthrough in the field of manufacturing technologies in recent years. RP integrates mechanical engineering, CAD, numerical control technology, laser technology and materials science and technology, and allows automatic, direct, quick and accurate materialization of design ideas into a prototype with certain features or direct manufacturing of a part. In this way, the product design can be evaluated, modified and tested rapidly, and the product development cycle can be effectively shortened.

h) Product data management (PDM)

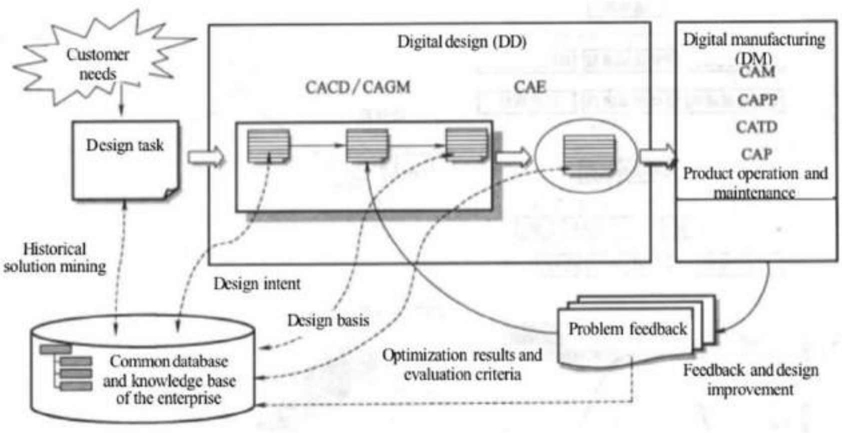
Product data management (PDM) is designed to manage all product-related information (including part information, configuration, documents, CAD files, structures and authorities) and all product-related processes (including process definition and management). PDM can improve production efficiency, facilitate product lifecycle management, enhance efficient utilization of documents, drawings and data and standardize the workflow.

i) Enterprise resource planning (ERP)

Enterprise resource planning (ERP) includes the integrated management of all resources (logistics, capital chain, information flow and human resources) of an enterprise, the use of information technologies to implement supply and marketing chain management and the scientific management of every link in the supply chain. In enterprises, ERP management mainly consists of three aspects, namely production control (planning and manufacturing), logistics management (distribution, procurement and inventory management) and financial management (accounting and financial management).

A complete digital design platform or system is available by integrating all or part of the systems above, as shown in Figure 2-4.

Figure 2-4 Composition of product digital technologies



In the 21st century, the rapid development of computer, IT, network and management technologies have brought great challenges as well as new opportunities to manufacturing enterprises and new product development. The digital product design and manufacturing technologies have shown the following development trends in the era of networking and information.

(a) Network-based all-digital design and manufacturing technologies are used to implement completely no-drawing design and all-digital manufacturing. PDM technologies are applied to perform concurrent engineering and improve product development efficiency and quality.Series, standard, borrowed and purchased parts are used to reduce repetitive design. Efficient data links in the network environment are utilized for cooperative product design and manufacturing. A large platform for all-digital design and manufacturing is established through the system integration of CAD/CAPP/CAE/CAM/PDM/PLM and other modules.

(b) Digital design and manufacturing technologies are combined with enterprise resource planning, supply chain management and customer relationship management to form the overall information framework of an enterprise. Digital design can be applied to product design, process and manufacturing procedure management; digital design data can be incorporated into ERP to achieve the production, supply, sales, staff, assets and property management of the enterprise; digital design data can also be used to carry out SCM and implement automatic logistics management between the enterprise and its upstream enterprises; and a digital design system can be connected with the CRM system to help the enterprise build, explore and improve the relationship with customers. The integration of the technologies above can significantly improve the management level of the enterprise, realize unblocked transmission of information flow, logistics and capital flow within the enterprise or between the enterprise and the outside world, increase the enterprise's response to market, shorten the product development cycle, and ensure that the enterprise has competitive advantages.

(c) The Internet, Intranet, Cloud and big data platforms are used to associate business processes of the enterprise closely and manage all links of the product development process efficiently and orderly. This will lay the foundation for entering the era of Internet of Things (IoT) in the future.

(d) Virtual factories, virtual manufacturing, dynamic enterprise alliance, agile manufacturing, network manufacturing and manufacturing globalization are becoming the key trend in the development of digital design and manufacturing technologies.

In virtual manufacturing, electronic documents and related information for product development can be transferred between alliance enterprises through the Internet. By virtue of the Just in Time (JIT) production, zero inventory of logistics is possible between partner manufacturers to reduce inventory costs. Settlements between partner manufacturers can be done through E-commerce. Enterprises can use E-commerce methods such as Business to Business (B2B) or Business to Customer (B2C) to sell products. In addition, after-sales services and technical support for users or products can also be provided through electronic services.

2.1.3 Application of Digital Design Technologies in Small and Medium-Sized Enterprises (SMEs)

Compared with large enterprises, especially large multinational enterprises, small and medium-sized enterprises (SMEs) have many obvious weaknesses such as low risk resistance, low R&D investment, weak technical strength and few product varieties. For continuous production and development in fierce international competition, it is undoubtedly a smart strategy for SMEs in the manufacturing industry to enhance the application of digital design and manufacturing technologies. Currently, SMEs still have many shortcomings in the application of digital design and manufacturing, primarily including the following three aspects.

a) SMEs only apply single digital design and manufacturing technology and fail to have effective technology portfolios and system integration in place. This situation is very common among SMEs. For example, many automobile parts and accessory manufacturers have adopted a completely no-drawing design mode. In this mode, the application of CAD technologies is highly mature, but the processes from machining drawings (CAD) to CNC machine tools are almost completely linked up manually, that is, there is no seamless linking between CAD and CAM. Taking a medium-sized automobile part manufacturer that has solved the linking problem between CAD and CAM for another example, the manufacturer may be unable to analyze and test an automobile part when the strength, temperature field, stress field and fatigue of the part need to be analyzed due to product quality issues. In other words, the manufacturer cannot climb over the "technical mountain" between CAD/CAM and CAE. In fact, SMEs are unable to build a complete integrated system of CAD/CAPP/CAE/CAM/PDM/PLM due to size and capital limitations. This is also a major cause that hinders enterprises from gaining greater economic benefits and competitive advantages from digital design and manufacturing technologies.

b) SMEs also have certain problems such as division between different departments, lack of unified specifications and plans and separation from the core production department in the application of digital design and manufacturing technologies. These problems are mainly resulted from the situation that the SME managers lack comprehensive and long-term consideration on the use of new digital technologies. For example, some enterprises possess more R&D departments than they actually need and employ a group of high-level analysis engineers or design engineers. As a result, these departments may be seriously underutilized, many R&D activities fail to deliver the expected results due to constraints from other departments, and lower efficiency is caused because of deviation from the production process. As the digital design and manufacturing technologies discussed above are integrated organically, SMEs often lose more than they gain when they simply pursue the leading position of a single technology in digital design and manufacturing technologies.

c) SMEs are normally sluggish or lag behind in the upgrade of digital design and manufacturing technologies. For example, some SMEs still use the CAD technologies developed 10 years ago or even 20 years ago. Except for graphic design drawings, they hardly produce any new digital design works, such as the 3D modeling and 3D simulation of a mechanical part. For another example, although the R&D departments of some enterprises can carry out basic finite element analysis, they are unable to solve complex engineering problems requiring numerical computation. This is not surprising in SMEs due to the rapid development of digital design and manufacturing technologies. Taking finite element analysis for an example, the latest finite element computing capabilities have already covered a wide range of fields including multi-disciplines, multi-physical coupling fields, nonlinearity, complex materials, multi-scale and complex processes. It is very difficult and unnecessary for SMEs to keep in step with the advancement of these computing technologies. Nevertheless, SMEs must find out a way to win in the digital economy for survival and development.

2.2 Digital Design Technologies

This section introduces digital design from the perspective of CAD. As the development of digital design will inevitably lead to the rise of digital simulation technologies, the next chapter will introduce the development and current status of simulation technologies.

2.2.1 Overview of Computer-Aided Design

Computer-Aided Design (CAD) is a method and technique of using computer software and hardware systems to assist people in product design, mainly including design, drawing, engineering analysis and documentation activities. From the perspective of design methods, designers use CAD software and computer hardware to complete the design process. With respect to design technologies, CAD technologies transform the physical model of a product into a digital model stored in the computer to provide shared information sources for subsequent manufacturing, management and other processes. CAD initially referred to computer-aided drafting. Upon decades of research and application, the concept of CAD has changed in nature. It now covers the entire lifecycle of products and has become an integral fundamental part of digital design and manufacturing systems. A general CAD system mainly has the features as follows:

◆Modeling, including solid modeling and curved surface modeling;

◆Transformation between 2D and 3D graphics;

◆Parametric design;

◆Graphics processing, including dynamic display, edition, blanking, rendering and output of graphics;

◆Analysis and simulation of 3D motion mechanisms;

◆Preliminary finite element analysis and optimization;

◆Data processing and exchange;

◆Secondary development.

CAD is the earliest and most widely applied technology in the machinery industry and has created considerable economic benefits. A typical example is Boeing 747 in the US which was manufactured later than the British Trident aircraft, but was completed earlier due to the application of CAD technologies.

Existing popular CAD software systems mainly include:

a) Autodesk Computer-aided Design (AUTOCAD) developed by US Autodesk. This software has been updated continuously since it was launched in 1982, and the latest version is AUTOCAD2019. The software is featured in comprehensive functions, the longest development history and the widest application scope, and it is also the most popular CAD software in China.

b) Unigraphics NX (UG) launched by Siemens PLM Software. This software, also known as an interactive CAD/CAM system, is used to provide digital modeling and verification methods for the product design and processing of users. Although this software is designed to run on workstations at the beginning, it is increasingly applied on PCs with the development of PC hardware and the rapid growth of personal users. Currently, the software has become a major 3D design application in the modeling industry.

c) SolidWorks software owned by Dassault Systems, France. This software is considered as a "rising star" after AUTOCAD and is the first Windows-based 3D CAD system in the world. In recent years, SolidWorks Corporation has become the most profitable company in the CAD/CAM industry because its technological innovation is in line with the development trend of CAD technologies. Its fundamental advantage lies in the continuous update of software technologies to adapt to the new advancement of technologies. For example, SolidWorks is the best choice for concurrent design by product stages (drafting-part drawing-shop drawing-assembly drawing-construction drawing) in WINDOWS and adapts to the current trend of digital design technologies. In addition, SolidWorks is also the most convenient CAD software for cooperative design through the Web and in line with the current in-depth development trend of Internet technologies.

d) Pro/Engineer (integrated and upgraded to CREO since 2010) developed by US Parametric Technology Corporation. As CAD/CAM/CAE-integrated 3D design software, Pro/Engineer is famous for its parametric modeling feature and is also the first software that applies parametric modeling technologies. In the Chinese market, Pro-E is mainly applied in customer electronics, high technologies, toy product design and mold design, which means that users are more concerned about part modeling, surface modeling, engineering drawings, optimization design methods, parting and mold design as well as reverse modeling.

e) CATIA, a flagship product of Dassault Systems, France. As an integral component of the PLM cooperative solution, CATIA can help manufacturers design their future products through modeling and support all industrial design processes including product design, analysis, simulation, assembly and maintenance.

In addition to the 5 major CAD software products mentioned above, there is also customized CAD software for special industries, such as the Advanced Aircraft Analysis (AAA) software, Shark FX-AP modeling software and Shark CAD-AP series software developed specifically by US DAR (Design, Analysis and Research) Corporation for aircraft design and analysis.

China also has some representative CAD software systems with independent intellectual property rights. Examples include:

◆InteCAD, developed by National CAD Support Software Engineering Research Center of Huazhong University of Science and Technology and Wuhan Tianyu Software Co., Ltd. and popular in domestic machinery industry;

◆TArch, AUTOCAD-based CAD series software for construction engineering developed by Beijing Tangent Engineering Software Co., Ltd., which has occupied the key market of the domestic construction industry;

◆Zhongwang CAD software, a 3D CAD/CAM software system with complete independent intellectual property rights that integrates the features of "surface modeling, solid modeling, mold design, assembly, sheet metal, engineering drawings and 2-5 axis machining" and covers the entire product design and development process.

There are also CAXA software produced by Beijing CAXA Technology Co., Ltd., GstarCAD software of Gstarsoft Co., Ltd, and Sinovation 3D developed by Hotem software. It should be noted that the secondary development of a customized CAD software system suitable for China's national conditions and industry specific requirements based on existing CAD systems has been proven to be a shortcut to the success of independent development of CAD software.

2.2.2 Common Computer-Aided Design Software Systems

The 5 common CAD software systems are compared by virtue of the Table below.As shown in the Table, these popular CAD software systems have their own advantages and characteristics. Enterprises or engineers may refer to the evaluation and indexes given in Table 2.1 to select a CAD software system. For example, CATIA is preferred for automotive enterprises, e.g. Dongfeng Motor Corporation. For another example, small and medium-scale machine manufacturing enterprises need to make appropriate choices according to the features of their products. Enterprises engaged in mold processing and manufacturing or operating numerical control machining may select UG or SolidWorks, and enterprises specialized in assembly lines of machinery products may choose Pro/E. Generally, the most popular AutoCAD software can meet the demands of many small and micro manufacturing enterprises or civil construction enterprises.

The selection of a suitable CAD software product is very important as CAD plays a central and leading role in digital design simulation and manufacturing.

Table 2-1 Technical characteristics and indexes of common CAD software

CAD software / Characteristics	Autocad	SolidWorks/SolidEdges	Unigraphics NX	Pro/Engineer	CATIA
Supported OS and hardware	WinPC	WinPC and workstation/workstation	First workstation and then WinPC	First workstation and then WinPC	IBM workstation
Basic features (5 points)	2D drawing and editing (5/5) 3D solid modeling (1/5) 2D-3D conversion (2/5) Parametric modeling (2/5) Rendering (2/5) Curve and surface modeling (2/5) Graphic processing function (2/5)	2D drawing (3/5) 3D solid modeling (3/5) 2D-3D conversion (4/5) Parametric modeling (4/5) Rendering (5/5) Curve and surface modeling (4/5) Graphic processing function (4/5)	2D drawing (3/5) 3D solid modeling (2/5) 2D-3D conversion (3/5) Parametric modeling (2/5) Rendering (4/5) Curve and surface modeling (3/5) Graphic processing function (4/5)	2D drawing (2/5) 3D solid modeling (3/5) 2D-3D conversion (3/5) Parametric modeling (5/5) Rendering (3/5) Curve and surface modeling (4/5) Graphic processing function (2/5)	2D drawing (1/5) 3D solid modeling (5/5) 2D-3D conversion (4/5) Parametric modeling (4/5) Rendering (4/5) Curve and surface modeling (5/5) Graphic processing function (4/5)
Design flow	Sample library and standard part library	Engineering drawing, assembly design, collaboration, CNC	NX industry/product, CNC, Mold and customized processes	Customized CABLING/CAT/CDT	Full process, full coverage and full collaboration
Special features	Compatible with Windows OA	Compatible with all Windows styles and cooperative	Three-tier software architecture and product association and collaboration	Single database and feature parameterization	Interactive and fully correlated parallel hybrid modeling
Secondary development	Auto lisp, Visual lisp, VB, C++	VB,VC++, support OLE	Open Grip, C, mem script, UI style	Pro/Program, Pro/Develop	Self-contained CAD/E/M systems
Module function	Machinery/electricity/civil engineering/clothing and other industries	Parts/surfaces/sheet metal/rendering/characteristics	Injection molding/PostBuilder/collaboration/CAE	Assembly management/customization/CAE/CAM	Surface/PDG/ASD/IDR/STD/SHP
Master file/conversion/template	DWG/DXF/DWT	PRT/ASM/DRW/DXF…IGES/STEP	PRT/FEM/SIM…/IGES/STEP	PRT/ASM/DRW/MFG/FRM/STEP	A series of CATDrawing files
Market competition	Traditional 2D drafting, middle and low-end market	A new star in WinPC, middle-end market	Large-scale interactive CAD/CAM	Mainstream CAD/CAM/CAE	Very large-scale integration, high-end market
Major applications	SMEs in machinery/electricity/civil engineering/clothing and other industries	Aviation, automobile and machinery	Mass industrial products of molded plastic automobiles	Machinery/cables/molds	Multinational enterprises in aviation and automobile industries
User experience	Most popular, easy to learn and use	Familiar to Win users, easy to learn and use	Well integrated with CNC, hard to learn	Customized and targeted learning	Need specialized and systematic training for higher efficiency

2.3 Development and Current Status of Simulation Technologies

2.3.1 Overview of Simulation Technologies

System simulation is a new subject formed gradually with the development of computer technologies. Simulation is the process of conducting experimental research on an physical system by establishing a system model. There has been analog machine simulation, hybrid machine simulation (integration of simulation and digital technologies), digital machine simulation and mathematical-physical simulation (integration of mathematical models and physical effect models) since the combination of simulation technologies and computer technologies in the 1940s. At the very beginning, simulation technologies were primarily applied in a few fields including aviation, aerospace and atomic reactors which were featured in high costs, long cycles, high risks, and difficulty in actual system tests. Subsequently, these technologies have developed to some major industrial sectors such as electricity, petroleum, chemistry, metallurgy and machinery, and further expanded to certain non-engineering systems such as social systems, economic systems, transportation systems and ecosystems. In fact, modern system simulation technologies and comprehensive simulation systems have become an indispensable approach for analysis, research, design, evaluation, decision-making, and training of any complex systems, especially in the high-tech industry. As the application scope is expanding, the benefits are remarkable.

The basic principle of simulation is to find out the pattern of a physical process by analogizing or simulating the process with a physical or mathematical model. Actually, simulation is based on similarity phenomena, namely geometric similarity and physical similarity. In engineering application, system simulation can be categorized into the following three types in terms of implementation modes and methods.

a) Physical simulation

Physical simulation is intended to construct a physical model of an actual system according to the physical properties of the system and carry out simulation experiments on the physical model. Physical simulation is intuitive and realistic, but it is not as convenient as mathematical simulation. For complex systems, the creation of a physical model usually requires huge investment of money and time. Once the model is created, the structure and parameters can hardly be modified. Moreover, physical simulation runs in real time.

b) Mathematical simulation

Mathematical simulation does not require an expensive physical system or physical effect equipment that simulates the realistic environment of the objective work. It is designed to establish an equivalent mathematical model and write, compile, and run simulation programs on a computer. During the mathematical simulation experiment, users can change the system parameters or structure by using the keyboard or other input devices, display the simulation results through Cathode Ray Tube (CRT), printers, plotters or other output devices, or save the results to storage devices such as a magnetic tape, disc or optical disc. Mathematical simulation can run in real time or variations of real time (super real time or slower than real time). Mathematical simulation has the features of economy, flexibility and model generality. With the development of parallel processing, graphics, AI and simulation software and hardware technologies, mathematical simulation is widely gaining traction across sectors.

c) Hybrid simulation

Hybrid simulation, also known as semi-physical simulation, covers three types:

◆hardware-in-the-loop simulation. In hardware-in-the-loop simulation, one part of an actual system is described using a mathematical model and converted into a simulation model running on the computer, and the other part of the system is introduced into a simulation loop as a real object (or a physical model). Normally, pure mathematical simulation can hardly be carried out due to the difficulty (or impossibility) in building an accurate mathematical model for some parts of a real system as well as the impact of non-linear and random factors that are difficult to implement. In this case, hardware-in-the-loop simulation is available to replace the parts that are not easy to model with real objects. Hardware-in-the-loop must run in real time as there are real objects and hardware in the loop. Hardware-in-the-loop simulation can be applied to verify the performance indexes and reliability of certain parts of the real system or even the entire system, adjust system parameters and control rules precisely, and check the correctness of the mathematical model and the accuracy of mathematical simulation results. Hardware-in-the-loop simulation has been developed into an indispensable technical means in the research fields of aerospace, aviation and weapon systems.

◆Software-in-the-loop simulation. Software-in-the-loop simulation interfaces the system computer with the simulation computer to carry out system simulation experiments. The interface is used to convert digital information in different formats. Special system software is widely applied for control, navigation and guidance computations in precise and complex systems such as the navigation and guidance systems of satellites and aircrafts. As software is getting larger sizes and stronger features, software is particularly important in the tests of the systems. In this context, software-in-the-loop simulation is developed. Normally, software-in-the-loop simulation needs run in real time.

◆Man-in-the-loop simulation. Man-in-the-loop simulation refers to simulation experiments where operators perform operations in the system loop. In this simulation mode, mathematical models are used to run the dynamic properties of an object on a computer, and a variety of physical effect instruments that imitate human senses including the senses of sight, hearing, touch and movement are applied to simulate the physical environment that people perceives. As operators are in the loop, man-in-the-loop simulation must be performed simultaneously.

There are three ways to build a model according to the mastery of the simulation object model and the properties of the object. (A) For systems with clear internal structures (white box), the known basic rules can be applied to derive the mathematical models of the systems. (B) For systems with unclear or not very clear internal structures (black box), the models of the systems can be assumed and then modified through experimental verification if experimental observation is allowed. (C) For systems with unclear or not very clear internal structures, the models can be assumed though data collection and inductive statistics if direct experimental observation is not allowed. Electromechanical systems normally fall into the first two cases. Most links in the electromechanical systems can be described by physical or mathematical models. Certain parameters (e.g. frictional characteristics) can be obtained through experimental observation.

2.3.2 Simulation Graphics Interaction and Animation Technologies

The core objective of computer graphics (CG) is to create effective visual communication. In science, graphics can be used to visualize scientific results to the public. In epistemology, CG plays an important role in helping human brains understand the nature of things from the perspective of graphic images because graphic images are more insightful than pure numbers. In software systems, the graphical user interface (GUI) is normally the most direct human-computer interaction (HCI) form. In digital design and computation, graphics are used as "the most intuitive design language".

The core objective of CG (visual communication) can be divided into three underlying tasks, namely representation, interaction and drawing. Briefly, CG focuses on how to "represent" and "draw" a colorful subjective and objective world interactively in a computer. The "representation" here involves how to display the subjective and objective world in the computer (representation and modeling of 2D and 3D objects); "drawing" relates to how to represent the objects in the computer in an intuitive graphic manner (drawing of 2D and 3D objects); and "interaction" refers to the technology of implementing "representation" and "drawing" effectively by using computer input and output devices. In this process, "representation" is the "data layer" of CG and includes various geometric representations of an article or object in the computer, and "drawing" is the "view layer" of CG and refers to the process of displaying and representing graphics data. "Representation" is modeling and input, while "drawing" is display and output. "Interaction" is the "control layer" of CG and performs valid object input and output tasks and solving problems in the interaction with users.

The research of CG mainly focuses on the mathematical construction methods and graphic displays of points, lines, areas, volumes and fields, and appropriate changes over time. The research shall include the following aspects:

a) Methods and mathematical algorithms for the description of graphics of complex objects. The representation of 2D or 3D scenes is the premise and basis for the display of computer graphics, including curve and curved surface modeling technologies, solid modeling technologies, and modeling and simulation of natural scenes such as texture, cloud and wave. The display of 3D scenes includes raster graphics generation algorithms, wire-frame graphics and realistic graphics theories and algorithms.

b) Input of the graphic description data of objects.

c) Storage of geometric and graphic data, including data compression and decompression.

d) Graphic data operation and processing of objects, including image and graphic-based hybrid rendering technologies, natural scenery simulation, graphical user interface, virtual reality, animation technology and visualization technology.

e) Graphic data output display of objects, including graphic hardware and graphical interaction technologies.

f) Real-time animation and multimedia technologies, exploring various hardware/software methods, development tools, animation languages and multimedia technologies for high-speed animation

g) Development of technical standards related to graphics applications.

Important applications of CG include (1) computer-aided design and manufacturing (CAD/CAM); (2) computer animation; (3) scientific computing visualization; and (4) virtual reality. CAD/CAM has been discussed in the previous section.

In computer animation, common graphic processing and 3D animation software include Photoshop,Illustrator,CorelDraw ,Rhinoceros,Maya, 3DMAX, XSI and LightWave. General Windows's graphic display driver packages include OpenGL and DirectX, and common representation technologies and tools include key frame animation, layer animation, path animation, interactive animation, expressions, rigid body dynamics, flexible body dynamics and certain deformation tools. These technologies and tools can be combined to access better production features.

2.3.3 Finite Element Method

Finite element method (FEM) is a commonly used high-performance numerical computation method. The basic principle of this method is to discretize and convert the continuum problem into a matrix solution for numerical computation.FEM can be traced back to 1940s. Courant first applied piecewise continuous functions and minimum potential energy principle defined on a triangular region to deal with the St. Venant's torsion problem. It is known that the first successful attempt of modern FEM is the application of a rigid frame displacement method to the planar elastic mechanics problem by Turner and Clough et al. in the aircraft structure analysis in 1956. Therefore, the prototype of FEM is also known as "the matrix displacement method in structural analysis". In 1960, Clough further addressed the planar elastic problem and formally used the term "Finite Element Method" for the first time. Many methods are derived from the basic finite element method to solve special issues such as various plate and shell elements, 3D elements of complex materials, finite strip method, boundary element method, hybrid element method, non-conforming element method and quasi-conforming element method.

With the advance of computer hardware and software technologies, the development of finite element software has roughly undergone the following stages:

a) Finite element computing software;

b) Finite element analysis and design software, i.e. the integration of FEM and CAD software;

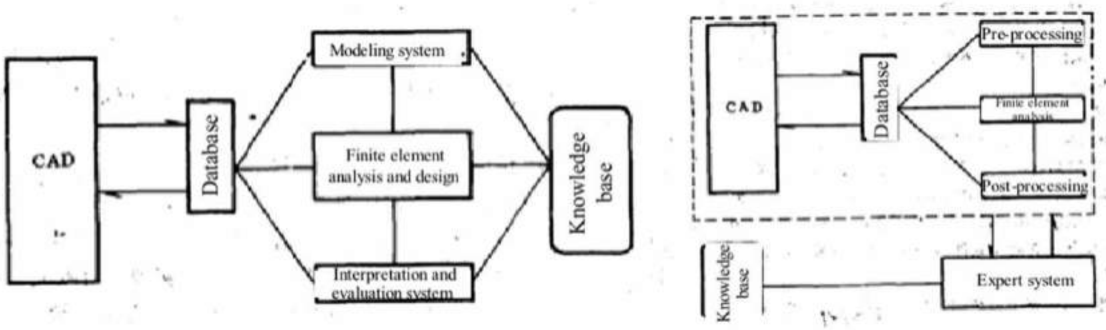
c) Expert systems for finite element analysis and design, i.e. the integration of FEM and CAD and expert system software;

d) Intelligent finite element structure analysis system, i.e. incorporation of AI in FEM software; and

e) Integrated finite element software development environment, that is, FEM began to form a large digital design and analysis system.

Generally, a FEM procedure contains three parts, namely pre-processing, finite element computing and post-processing. The computing power of the system will be greatly extended when FEM is integrated with other computer software technologies. Taking a typical intelligent finite element structure analysis system for example, the block diagram of the relationship between CAD and FEM is given in Figure 2-5.

Figure 2-5 Relationship between CAD and FEM



The basic idea of FEM is very creative. In general, the finite element analysis (FEA) or finite element method (FEM) is a method for numerical solutions of continuous physical field problems. The spatial distribution of one or more related variables shall be determined for the continuous physical field problems. For example, the temperature distribution in an engine piston or the displacement and stress distribution of concrete pavement are urgent problems to be solved in engineering. Mathematically, a physical field problem is described by a differential equation or integral expression, both of which are applicable to finite element formulation. A universal finite element program covers ready-to-use finite element formulation. When people know very little about finite element knowledge or scarcely use the knowledge to solve problems, the application of finite element programs may lead to disturbing or even disastrous consequences. A single finite element can be considered visually as a small piece of structure, and the term "finite" distinguishes these small pieces from the infinitesimal elements in calculus. In each finite element, one physical variable is allowed to only have simple spatial changes, such as described by the sum of items of a polynomial. Actual changes in the area spanned by the element are almost certainly complicated, so that FEM only provides approximate solutions. The connection points of the elements are called "nodes", and the set of elements is called a finite element structure. The commonly used term "structure" refers to a defined object or area. The specific arrangement of the elements is called a mesh. In numerical analysis, a finite element mesh is expressed by an algebraic equation with unknown values of nodes to be solved. The unknown value at a node is the value of a variable in the physical field, depending on the shape of the element or its first derivative. The solution of the node value completely determines the spatial variable of the field on the element in conjunction, when together with the node variable on a given element. In this way, the physical variables that change continuously over the entire structure are approximated by each element in the form of segments. Therefore, although FEM cannot provide the exact solution, the accuracy of the solution can be improved by dividing the structure into more elements. This is adequate to meet the computational accuracy requirements in engineering. In summary, FEM has many advantages including strong generality and clear physical concepts compared with other numerical methods.

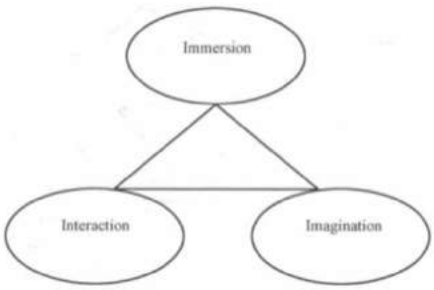
Finally, it is important to mention the Meshless Method or Meshfree Method that has developed rapidly in recent years. Without the generation of meshes in numerical computation, the methods can simulate the flow fields of various complex shapes conveniently by constructing a discrete control equation of interpolation functions according to some randomly distributed coordinate points. The methods can be roughly divided into two categories: one is Lagrange-based particle methods such as the smoothed particle hydrodynamics (SPH) method and the moving particle semi-implicit (MPS) method based on SPH; and the other is Euler-based gridless methods such as the Gridless Euler/Navier-Stokes solution algorithm and the Element Free Galerkin (EFG) method. Meshfree methods can be used conveniently to compute the simulated flow fields of complex shapes through coordinate points, but it is difficult to improve the accuracy of numerical computation in case of high Reynolds number flows. The Element Free Galerkin method has become the most prevalent and widely used meshfree computation method at present, with existing commercial software such as LS-dyna, Abaqus and Radioss being incorporated into the computation module of this method. CAE programs and CAD interfaces based on meshfree methods have advantages because the solid area does not need to be meshed. For example, the SolidWorks XFlow module applies meshfree methods for CFD computation and has great technical advantages. Although meshfree methods tend to be used as an alternative of the FEM numerical method, FEM still holds the absolute dominant position in the engineering numerical analysis field.

2.3.4 Virtual Reality Technologies

Virtual reality (VR) can be considered as the 3D visualization of virtual things or the reproduction of the real 3D world. VR is not only a human-computer interface, but also the use of modern technologies such as computer technologies, sensing and measuring technologies, simulation technologies and microelectronic technologies to construct a simulated virtual world where users may interact with people or things in the virtual world by receiving and responding to various sensory stimuli of the simulated environment to produce an immersive feeling upon the real reproduction of certain environment. Therefore, the term "virtual reality" contains three aspects of meaning: (1) VR is a multi-viewpoint and real-time dynamic 3D environment based on computer graphics that can be either the realistic reproduction of real world or the virtual world beyond reality; (2) users may interact directly with the environment where they are immersed through the senses of sight, hearing and touch and using their natural skills and the ways of thinking; and (3) during the operation process, human acts as an subject immersed in the virtual environment in the form of real-time data source, but not just an outsider viewing from the window.

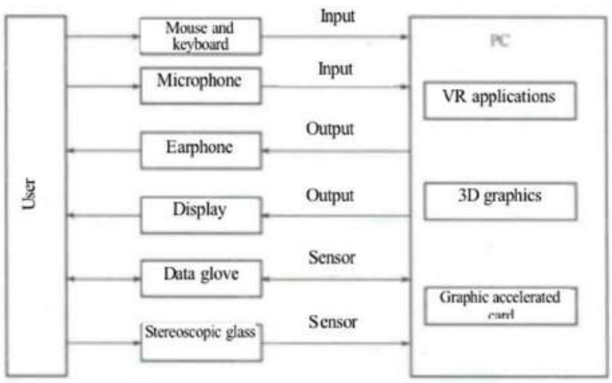
US scientists Burdea G and Philippe Coiffet proposed the triangle theory of VR technologies, i.e. VR has the features of immersion, interaction and imagination, as shown in Figure 2-6.

Figure 2-6 Features of VR technologies



In practices, VR systems are generally classified into four modes according to the level of "immersion" and the degree of interaction, namely desktop-VR systems, immersion-VR systems, augmented-VR systems and distributed-VR systems. The composition of a typical system is shown in Figure 2-7.

Figure 2-7 Embodiment structure of desktop-VR system



In addition to the typical applications in the fields of electronic games, film and television production, tourism, mobile wearing and social networking, VR technologies are promising in industrial, medical and educational sectors. VR may also be widely applied in digital design and production field.

With VR technologies, virtual product design, virtual product manufacturing, virtual production process and virtual product display and maintenance can be performed in the manufacturing industry. VR technologies can be used to assist manufacturing engineers in improving product design, optimizing product performance, improving product quality and design efficiency and reducing development costs. Nowadays, VR technologies have been widely used in the industrial field.

a) Application of VR in automobile manufacturing

VR technologies are applicable to the virtual design of automobiles. Traditional new model design is costly and time-consuming. When VR technologies are used, the physical drawings and models of the whole automobile can be omitted, and the development process of a new automobile can be completed in the computer, so that the development cycle is significantly shortened. The development period of a new automobile was 48 to 60 months in the 1990s, and has been reduced to 18 to 24 months since the application of VR technologies. Additionally, VR design can also be used to modify design schemes conveniently, and identify and correct design defects in the early stage to avoid huge economic losses.

b) Application of VR in shipbuilding

The application of VR technologies to the development of a virtual ship design system throughout the lifecycle can improve the quality of ship design, reduce shipbuilding costs and shorten the shipbuilding cycle. A VR simulation system can also be applied in the shipbuilding stage for realistic 3D visualized virtual display of the shipyards, facilities, ship internal structures and layouts, hull making and predetermined process flows. Engineers may interact with a hull model in the virtual environment to complete steel pretreatment, cutting and bending. Meanwhile, the VR system can also provide a hull assembly feature to help users understand the hull assembly process and hull structure by simulating real assembly methods.

c) Application of VR in aircraft manufacturing

As the development cycle of modern aircrafts is getting shorter and shorter, the requirements for aircraft performance are continuously growing and aircraft technologies are increasingly complex. Therefore, the application of VR technologies has been one of the critical approaches to ensure the success of aircraft development during the aircraft development process. In the process of aircraft design, VR technologies can be applied to carry out aircraft flight simulation demonstration, ergonomics analysis and overall layout, assembly and maintenance evaluation in advance, identify and correct design defects in the early stage, and implement the closed loop iteration of "design-analysis-improvement". In this way, VR technologies can significantly foster the improvement of aircraft design capabilities.

In addition, VR is also widely used in industrial sectors such as energy exploitation simulation, hydraulic engineering simulation and power system simulation.

2.4 Digital Design and Simulation Intelligence

The research of CAD technologies focuses on computer-aided conceptual design, computer-supported cooperative design, massive information storage, management and retrieval, design methods and related issues, and support innovative design. CAD technologies have undergone the development process of 2D planar graphic design, interactive graphic design, 3D wire-frame model design, 3D solid modeling design, free form surface modeling design, parametric design and feature modeling design.In recent years, there have been many advanced technologies such as variable technologies and virtual product modeling technologies. With the popularity of the Internet, integration, collaboration and intelligence have become the new development features of CAD technologies. CAD software has developed into networked platforms that support cooperative design, remote design and information sharing. Specifically, the development trend of intelligent CAD technologies covers the following aspects:

a) Variable design environment

The advanced Variational Geometry eXtended (VGX) technology is a core CAD technology launched by SDRC. VGX provides a 3D variable control technique that runs throughout the process of 2D sketch design, 3D part modeling and assembly design. It is capable of completing variable sketching, establishing variable equations and designing variable characteristics. It supports users in modifying the design directly as well as modifying the design based on their experiences, thus users are allowed to change the original constraints, establish new constraints and delete old constraints flexibly at any time, or mark dimensions that are independent of the modeling order, without the need to concern about the design order. VGX can be used to perform free and creative design of any geometric and engineering constraints under under-constrained conditions, and it can generate flanges automatically on the edges of complex surfaces. The completely integrated variable design environment of VGX supports unified wireframes, trimmed surfaces and solid modeling. The VGX technology extends variable product structures, and allows users to directly operate the geometric modeling, design process, features and design constraints of a complete 3D digital product in real time. At the same time, VGX can retain the product information for each intermediate design process as the design deepens.

VGX provides a 3D environment for users to interact with models. Designers no longer concern about how to convert 2D design information into the 3D format when defining the relationships on parts and components, so that the design modeling process is simplified. Designers may edit and modify any features on a part directly and graphically. This allows them to design their 3D products more intuitively and in real time. In a master model, users may implement the intent of capturing the design, analysis and manufacturing dynamically. The VGX technology greatly improves the intuitiveness and reliability of interactive operations, thus making CAD software easier to use and more efficient.

As for the deepening of CAD technologies from the perspective of design, the research on optimum and intelligent design technologies is undoubtedly the fundamental direction because the ultimate goal of design is to provide a number of design schemes that meet all requirements and constraints, and select and determine the optimal scheme. The CAD technologies that have been introduced and applied have played a critical role in performing design automation and improving design efficiency, but these technologies mainly focus on the implementation of design schemes in the middle and downstream stages. In the upstream design stage such as conceptual and schematic design where a design concept or a design scheme is produced, the creative activities of designers are crucial to design quality and product innovation. Intelligent design technologies or intelligent CAD technologies that will provide effective support for designers at a higher level of creative thinking activities are truly computer-aided design. Intelligent CAD technologies are the combination of CAD technologies and AI technologies. The AI technologies of expert systems, case-based reasoning, constraint satisfaction and neural networks have been extensively studied in CAD technologies and have been implemented in certain professional applications of CAD systems. As the field of AI technologies is still developing, the combination of the technologies emerged after the 1980s such as qualitative reasoning, fuzzy reasoning and non-monotonic reasoning with CAD technologies need to be further explored.

Traditional optimization techniques are not completely suitable to solve problems as the technical systems are increasingly complex and the number of technical problems is ever growing. In this case, the research and application of generalized engineering optimization design methods and techniques should be valued. The generalized engineering optimization design methods and techniques are related to the product optimization across systems, properties and processes as well as the integration of modeling, identification, analysis and redesign. Designers may adopt full-system and full-performance modeling based on a large amount of basic knowledge and expertise, use a variety of traditional and advanced optimization methods for parallel optimization, analyze the optimization process and results by using visualization and other technologies, and provide redesign suggestions.

b) Introduction of databases and expert systems into CAD

When CAD develops to a certain stage, there are going to be more and more digital design products, so that engineers naturally consider the establishment of a database, that is, they save good designs for future reference and to build databases related to CAD technologies. At the same time, upon years of design and mass production of similar products, engineers need to propose innovative ideas on the design of new products. In this context, expertise and skills are required for creative design of new products, which produces the requirements for product-related knowledge bases as well as creates great demands for talents who master and apply the knowledge. As these professional talents are very limited, computer software systems that replace "expert ideas" with computer programs have emerged accordingly, that is, introducing databases and expert systems into CAD. This development trend has always been the underlying work of intelligent digital design from the 1980s to present. For example, CAD digital model and simulation computing technologies have been applied in the research on "mechanical fault diagnosis expert system" of typical electromechanical products since the 1990s, which has made significant scientific and technological achievements in "non-destructive testing of crane steel cables" and "mechanical fault diagnosis expert system for rotor supported by vibration signals".

c) Introduction of AI technologies

Design is a highly intelligent human creative activity. An intelligent CAD system is developed when knowledge engineering is introduced into the CAD system. Intelligent CAD is inevitably the development trend of digital design and manufacturing technologies. The combination of smart CAD or intelligent CAD with knowledge base-based expert systems has become a new trend in solving engineering problems. A knowledge-based design repository is established based on the application of knowledge and information. With a digital design database, designers can promptly and accurately obtain the information and assistance necessary for product development. Using the Internet, designers can share and exchange information and address the requirements for knowledge during the product design process. Processing of design data through big data and artificial intelligence covers from database to data warehouse to knowledge base, from simple dataset to data knowledge mining by following certain rules, as well as making the data self-learned and self-accumulated. If this intelligent process is implemented simultaneously with practical engineering applications, it is possible to achieve a crucial leap-forward advance of manufacturing technologies. Specifically, intelligent CAD software applies the dynamic navigation technology, thus users may even think that a coworker is giving directions during the design process and the design work is completed in the communication with the coworker. AI technologies have made astounding progress in recent years, and artificial intelligence is expected to bring revolutionary changes to digital design and virtual manufacturing.

CHAPTER 3
Product Strength Design

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Product Strength Design

3.1 Overview of Strength Design

The failure of different materials due to insufficient strength varies. Brittle fracture and plastic yield are two types of material failure. Components made of brittle materials (e.g. cast iron) will break suddenly under tension when the deformation is very small. Plastic components will be subject to plastic deformation before breaking, and they cannot work properly due to failure to maintain the original shape and dimensions. However, the failure of components is not always caused by strength. For example, failure may result from insufficient rigidity where the machine tool spindle is subject to excessive deformation and the machining accuracy cannot be guaranteed even when no plastic deformation occurs. The bending of a compressed slender rod is failure caused by insufficient stability. In addition, different loading methods such as impact and alternating stress and different environmental conditions such high temperature and corrosive media may also lead to failure.

The stress when a brittle material breaks is ultimate strength S_b, and the stress when a plastic material reaches the yield point is yield limit S_s. The two stresses are the ultimate stress when a component fails. In order to ensure sufficient strength of the component, the actual stress **S** of the component under load is obviously lower than the ultimate stress. In the strength calculation, the ultimate stress divided by a factor larger than 1 is considered as the allowable stress expressed by [**S**] .For plastic materials,

$$[s] = \frac{s_s}{n_s}$$

For brittle materials,

$$[s] = \frac{s_b}{n_b}$$

Where, the factor n_s or n_b greater than 1 is called safety factor. The allowable stress [**S**] is taken as the maximum working stress of the component. The working stress **S** shall not exceed the allowable stress [**S**] .Therefore, the strength condition of the component under axial tension or compression is obtained as follows.

$$s = \frac{F_N}{A} \pounds [s]$$

According to the above strength condition, strength check, section design and strength calculation including the determination of allowable load can be performed. In engineering practice, it is generally allowable that the working stress **S** is slightly higher than [**S**] but does not exceed 5% of [**S**].

The stress at a dangerous point of the actual component is not always uniaxial. Experiments in complex stress states are much more difficult than those under uniaxial tension or compression. A common practice is to machine the material into a thin cylinder. Under the action of internal pressure P, the cylinder wall is in the state of biaxial stress. The ratio of the two principal stresses can be set to predetermined values if axial tension is provided. In addition to the internal pressure and axial forces of the thin cylinder test, torque is also applied from time to time. In this case, a more common situation is available. There are also other test methods for complex stress states. Nevertheless, it is not easy to fully reproduce various complex stress states encountered in practices. Besides, there are infinite possibilities in terms of methods and ratios of stress combination in complex stress states. If, like uniaxial tension, experiments are carried out to determine the failure state and define the strength condition, then a variety of stress states must be tested separately to determine the failure stress and create the strength condition. This is often impracticable due to technical difficulties and heavy workload. These problems are often solved in a process of reasoning based on existing test results, putting forward hypotheses, speculating the cause of material failure and creating the strength condition.

3.2 Mechanical Properties of Metal Materials Under Tension

In addition to stress calculation, mechanical properties of materials shall also be learned in the analysis of strength of a component. The mechanical properties of materials refer to the deformation and failure characteristics of materials under the action of external forces. Mechanical properties shall be measured by experiments. Tests carried out in a slow and steady loading manner at room temperature, called static load tests at ambient temperature, are the basic tests to determine the mechanical properties of materials. For the comparison of test results of different materials, provisions on the shape, machining accuracy, loading rate and test environment of test samples are given in the national standard Metallic Materials-Tensile Testing. A section with length being L is taken from the test sample as the test section, and L is called gauge length. For a circular cross-section test sample, there are two ratios of the gauge length L to the diameter d, namely

$$L=5d \text{ and } L=10d.$$

There are a variety of materials commonly used in engineering. The mechanical properties of materials under tension will be introduced by taking low-carbon steel as the main representative in the following sections. Low-carbon steel is the carbon steel with carbon content lower than 0.3%. This type of steel is widely applied in engineering and its mechanical properties are most typical in tensile tests.

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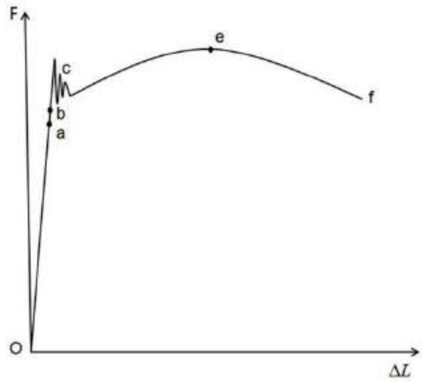
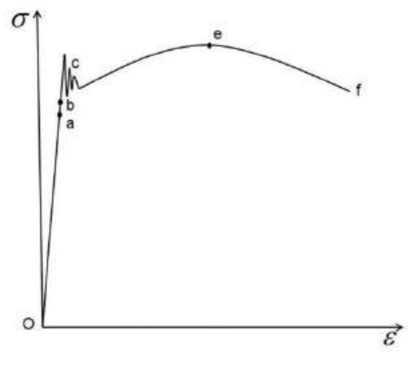
The test sample is mounted on a test machine and subjected to slowly increasing tension. For each tensile force F, there is an elongation DL at the gauge length L of the test sample. The curve showing the relationship between F and DL is called tension diagram or F-DL curve, as shown in the figure below.

Figure 3-1 Schematic diagram of F-DL curve



The F-DL curve is related to the size of the test sample. In order to eliminate the effect of the test sample size, the tensile force F divided by the original area A of the cross section of the test sample is the positive stress $s = \frac{F}{A}$; and the elongation DL divided by the original length L of the gauge length is the strain (engineering strain) $e = \frac{DL}{L}$. Incidentally, $\frac{DL}{L}$ is the average strain in the gauge length L. Strain is even as the strains at various points in the gauge length L are equal. At this time, the stain at any point is equal to the average stain. The relationship between s and e (as shown in the figure below) is plotted by taking s as the ordinate and e as the abscissa, and it is called stress-strain diagram or s-e curve.

Figure 3-2 Schematic diagram of s-e curve



According to the test results, the mechanical properties of low-carbon steel are generally as follows:

a). Elastic stage: The relationship between ***s*** and ***e*** is a straight line Oa at the initial stage of the tensile test sample, which means that the stress ***s*** is proportional to the stain ***e***, i.e.

$$s \mu e$$

Or an equation

$$s=Ee$$

This is the Hooke's law of tension and compression. In the equation, E is the material-dependent proportional constant and is called modulus of elasticity. Since the dimension of the stain e is 1, the dimension of E is the same as that of ***s*** and is generally expressed by GPa. $E = \frac{s}{e}$ where $\frac{s}{e}$ is the slope of the straight line Oa.The stress s_p corresponding to the top point a of the straight line is called proportional limit. Obviously, the stress is only proportional to the stain when the stress is below the proportional limit, and the material only conforms to the Hooke's law in this case. At this time, the material is linearly elastic.

After the proportional limit is exceeded, the relationship between s and e is no longer a straight line from the point a to b, but the deformation can also completely disappear if the tension is released. This kind of deformation is called elastic deformation. The stress s_e at the point b is the limit value when the material is only subjected to elastic deformation, and it is called elastic limit. The point a is very close to the point b on the s-e curve, so that there is no strict distinction between the elastic limit and the proportional limit in engineering.

If the tension is released when the stress is greater than the elastic limit, then part of the deformation of the test sample disappear accordingly, which is the elastic deformation discussed above. However, there is still part of deformation that cannot be eliminated, which is called plastic deformation or residual deformation.

b). Yield stage: The strain increases significantly when the stress raises beyond the point b to a certain value, and then the stress declines and fluctuates slightly. This is expressed in a small serrated line segment near the horizontal line on the curve s-e. The phenomenon that the stress fundamentally remains unchanged and the strain increases remarkably is called yield or flow. The maximum and minimum stresses at the yield stage are known as upper yield limit and lower yield limit, respectively. The value of upper yield limit pertains to factors such as the sample shape and loading rate and is generally unstable. The value of lower yield limit is more stable and can reflect the properties of the material. The lower yield limit is normally referred to as the yield limit or yield point and is expressed in s_s.

c). Strengthening stage: The material restores the resistance to deformation upon the yield stage. To make it continue to deform, a tensile force is required. This is called material strengthening. In Figure 3-2, the stress s_b at the top point e at the strengthening stage is the maximum stress that the material can withstand, and it is called ultimate strength or tensile strength. It is another important indicator to measure the material strength. At the strengthening stage, the lateral dimension of the test sample reduces significantly.

d). Local deformation stage: After the point e, the lateral dimension drops suddenly and sharply in a certain local range of the test sample to form a necking phenomenon. The tensile force necessary to continue the elongation of the sample declines accordingly due to the rapid reduction in the cross-sectional area of the necking portion. In the stress-strain diagram, the sample breaks when the stress $s = \frac{F}{A}$ calculated based on the original cross-sectional area A decreases accordingly and drops to the point f.

3.3 Four Common Strength Theories

As discussed above, there are two main types of strength failure, namely yield and fracture. Correspondingly, the strength theories are also classified into two categories: one is intended to explain fracture failure, and contains the maximum tensile stress theory and the maximum elongation linear strain theory; the other is aimed to explain the yield failure and includes the maximum shear stress theory and distortion energy density theory.These theories are introduced in turn as follows:

3.3.1 Maximum Tensile Stress Theory (First Strength Theory)

According to this theory, fracture is mainly caused by the maximum tensile stress. That is, no matter what the stress state is, the material will break once the maximum tensile stress reaches a certain limit pertinent to the properties of the material. Since the limit of the maximum tensile stress is independent of the stress state, it can be determined by the uniaxial stress state. The fracture takes place as long as the uniaxial tension meets s_1 (s_2=s_3=0) and s_1 reaches the ultimate strength s_b. In this case, the only prerequisite for fracture is that the maximum tensile stress hits s_b no matter what the stress state is according to this theory. Therefore, the fracture criterion is obtained.

$$s_1 = s_b$$

The ultimate stress s_b is divided by the safety factor to obtain an allowable stress [s], so that the following strength condition is created based on the first strength theory.

$$s_1 \pounds [s]$$

Brittle materials such as cast iron break on the cross section with the maximum tensile stress under uniaxial tension. The torsion of brittle materials also causes breaking along the slope with the maximum tensile stress. These are consistent with the maximum tensile stress theory. However, this theory neglects the effects of the other two stresses and cannot be applied to the states without tensile stress (e.g. uniaxial compression and triaxial compression).

3.3.2 Maximum Elongation Linear Strain Theory (Second Strength Theory)

According to this theory, fracture is mainly resulted from the maximum elongation linear stress. That is, no matter what the stress state is, the material will break once the maximum elongation linear stress e_1 reaches a certain limit pertinent to the properties of the material. Since the limit of e_1 is independent of the stress state, it can be determined by the uniaxial stress state. Assuming that the strain can still be calculated by the Hooke's law until the material breaks under uniaxial tension, the limit of the elongation linear strain shall be $e_u = \frac{s_b}{E}$ at the point of breaking. The material breaks as long as e_1 reaches the limit $\frac{s_b}{E}$ in any stress states according to this theory. Therefore, the fracture criterion is obtained.

$$e_1 = \frac{s_b}{E}$$

According to the Hooke's law:

$$e_1 = \frac{1}{E}[s_1 - m(s_2 + s_3)]$$

Substituting e_1 into the equation * to obtain the fracture criterion

$$s_1 - m(s_2 + e_1) = s_b$$

The value s_b is divided by the safety factor to obtain an allowable stress [S], so that the following strength condition is created based on the second strength theory.

$$s_1 - m(s_2 + s_3) \pounds [s]$$

When brittle materials such as aggregates and concrete are subjected to axial compression, the test block will crack in the direction perpendicular to the pressure if the contact surface between the test machine and the test block is lubricated to reduce the effect of friction. The direction of cracking is also the direction of e_1. When the cast iron is under the tensile-compressive stress and the compressive stress is large, the test results are also close to this theory. However, according to this theory, the strength shall be different from that of the uniaxial compression if additional pressure is applied in the direction perpendicular to the pressure of the compressed test block (so that the test block is subjected to biaxial compression). However, the test data of concrete, granite and sandstone reveal that there is no significant difference in the strength of the two cases. Similarly, according to this theory, the cast iron should be safer under biaxial tension compared with uniaxial tension, but the test results cannot demonstrate this point. In this case, the first strength theory is closer to the test results.

3.3.3 Maximum Shear Stress Theory (Third Strength Theory)

According to this theory, yield is mainly caused by the maximum shear stress. No matter what the stress state is, the material will yield once the maximum shear stress τ_{max} reaches a certain limit pertinent to the properties of the material. The yield takes place when $\tau_{max} = \frac{\sigma_s}{2}$ on the oblique section that is 45° to the axis under uniaxial tension (the normal stress on the oblique section is σ_s in this case). Thus it can be seen that $\frac{\sigma_s}{2}$ is the limit of the maximum shear stress resulting in yield. Since this limit is independent of the stress state, the material will yield as long as τ_{max} reaches $\frac{\sigma_s}{2}$ in any stress states. In any stress states,

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2}$$

Therefore, the yield criterion is obtained.

$$\frac{\sigma_1 - \sigma_3}{2} = \frac{\sigma_s}{2}$$

or

$$\sigma_1 - \sigma_3 = \sigma_s$$

The value σ_s is replaced with the allowable stress $[\sigma]$ to obtain the strength condition established according to the third strength theory.

$$\sigma_1 - \sigma_3 \leq [\sigma]$$

The maximum shear stress theory provides a satisfactory explanation for the yield of plastic materials. For example, when low-carbon steel is stretched, a slip line in the direction 45° from the axis is a trace that the material slips internally along the direction. The shear stress on the slope along the direction is exactly the maximum stress. It can be found that this theory is safer by comparing the maximum shear stress yield criterion with the test results.

3.3.4 Distortion Energy Density Theory (Fourth Strength Theory)

According to this theory, yield is mainly caused by the distortion energy density. That is, no matter what the stress state is, the material will yield once the distortion energy density u_d reaches a certain limit pertinent to the properties of the material. The yield stress is σ_s and the corresponding distortion energy density is $\frac{1+\mu}{6E}(2\sigma_s^2)$ under uniaxial tension. This is the limit of the distortion energy density resulting in yield. In any stress states, the material will yield as long as the distortion energy density u_d reaches the limit mentioned above. Therefore, the distortion energy density yield criterion is obtained.

$$u_d = \frac{1+\mu}{6E}(2\sigma_s^2)$$

In any stress states,

$$u_d = \frac{1+\mu}{6E}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right]$$

The yield criterion is thereby obtained upon rearrangement.

$$\sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right]} = \sigma_s$$

According to the equation, the yield criterion above is an elliptic curve. The value $\boldsymbol{s}_s$ is divided by the safety factor to obtain an allowable stress [$\boldsymbol{S}$], so that the following strength condition is created based on the fourth strength theory.

$$\sqrt{\frac{1}{2}\left[(s_1 - s_2)^2 + (s_2 - s_3)^2 + (s_3 - s_1)^2\right]} \, £ \left[s\right]$$

The test data of thin wall pipes made of several plastic materials such as steel, copper and aluminum suggest that the distortion energy density yield criterion is in line with the test data and is more consistent with the test results than the third strength theory. In case of pure shear, the result obtained from the distortion energy yield criterion is 15% larger than the result from the maximum shear stress yield criterion, indicating the greatest difference between the two criteria.

3.3.5 Summary

The strength conditions created on the basis of the four strength theories above can be written in a unified form as follows:

$$s_r \, £ \left[s\right]$$

Where, $\boldsymbol{s}_r$ is called equivalent stress and composed of three principal stresses in a certain form. In the order from the first strength theory to the fourth strength theory, the equivalent stresses are obtained as follows:

$$s_{r1} = s_1$$

$$s_{r2} = s_1 - m(s_2 + s_3)$$

$$s_{r3} = s_1 - s_2$$

$$s_{r4} = \sqrt{\frac{1}{2}\left[(s_1 - s_2)^2 + (s_2 - s_3)^2 + (s_3 - s_1)^2\right]}$$

The above are four common strength theories. For brittle materials such as cast iron, aggregates, concrete and glass that normally fail in the form of fracture, the first and second strength theories should be used. For plastic materials such as carbon steel, copper and aluminum that generally fail in the form of yield, the third and fourth strength theories should be applied. It should be noted that different materials may fail in different ways, but even the same material may also be subjected to different forms of failure in different stress states. For example, carbon steel fails in the form of yield under uniaxial tension, but when a screw made of carbon steel is stretched, the thread root may fracture due to the triaxial tension caused by stress concentration. This is because the material will hardly yield according to the equivalent stress formula of the third or fourth strength theory when the values of three principal stresses in the triaxial tension are close. For another example, cast iron fails in the form of fracture under uniaxial tension. However, the material adjacent to the contact point is in a triaxial compression state when a hardened steel ball is pressed on the cast iron plate. As the pressure increases, the plate will have prominent pits, indicating the occurrence of yield phenomenon. The above examples suggest the relevance of failure modes to stress states. Both plastic and brittle materials will fail in the form of fracture when the triaxial tensile stresses are close. Both plastic and brittle materials will be subjected to plastic deformation when the triaxial compressive stresses are close. In this case, the third or fourth strength theory should be applied.

3.4 Instances of Frame Strength Design for Commercial Vehicles

The chassis frame of a commercial vehicle is the backbone of a truck. The frame supports and connects various parts and components of the truck and bears the weight of the parts and components as well as the impact, twisting and inertial forces during motion. Sufficient strength and rigidity is the key for the truckto withstand internal and external loads, and the strength of the chassis frame is directly related to the safety performance and service life of the entire vehicle. In this section, the strength of the frame will be analyzed to verify that the frame meets the strength design requirements during service.

3.4.1 Basic Frame Parameters and Operating Mode Analysis

In order to evaluate the mechanical properties of the frame during service, primary considerations in this analysis include the operating modes such as full load bending, impact, braking, turning and torsion. For details of the operating modes, loads and constraints, see Table 3-1.

Table 3-1 Operating modes, loads and constraints

<table>
<tr><th>Operating modes</th><th>Constraints</th><th>Loads</th></tr>
<tr><td>Static load bending</td><td rowspan="4">Constraint on the degree of freedom in the xyz direction of the right front wheel;
Constraint on the degree of freedom in the xz direction of the front left wheel;
Constraint on the degree of freedom in the yz direction of the rear right wheel;
Constraint on the degree of freedom in the z direction of the left rear wheel.</td><td>1G in the Z direction</td></tr>
<tr><td>Vertical impact</td><td>2.5G in the Z direction</td></tr>
<tr><td>Turning</td><td>0.5G in the Y direction and 1G in the Z direction</td></tr>
<tr><td>Braking</td><td>0.8G in the X direction and 1G in the Z direction</td></tr>
<tr><td>Torsion 1 (FL_150mm)</td><td>Constrain on the other three wheels</td><td>Raise the front left wheel by 150mm</td></tr>
<tr><td>Torsion 2 (FL_150mm)</td><td>Constrain on the other three wheels</td><td>Raise the rear right wheel by 150mm</td></tr>
</table>

The frame analyzed this time is made of material B610L, and its basic mechanical parameters are given in Table 3-2 below.

Table 3-2 Basic mechanical parameters of the material

Material	Density (kg/m^3)	Modulus of elasticity (GPa)	Poisson's ratio	Yield limit (MPa)	Ultimate tensile strength (MPa)
B610L	7850	210	0.3	500	610

Parameters in the finite element analysis of the frame are given in Table 3-3.

Table 3-3 Basic parameters of the model

Parameter name	Value
Power assembly mass/kg	400
Cab assembly mass/kg	600
Cargo box assembly and cargo weight/kg	12000
Front spring/back main spring/back auxiliary spring rigidity (N/mm)	218/250/713
The distance that the frame sinks to ensure the action of the back auxiliary spring/mm	35

3.4.2 Creation of Analysis Models

a) Finite element modeling of the frame

The frame model is mainly comprised of structures such as side rails, cross members, side rail-cross member connectors and leaf spring supports. When a finite element model is built for the frame, the thin-walled parts (side rail, cross members and side rail-cross member connectors) are simplified to shell elements, and the solid components (leaf spring supports) are meshed with tetrahedron elements. The rivet connection between the components is simulated by using rigid elements. The size of the overall frame mesh is 6mm to ensure consistency of the size of the overall mesh. The geometric and mesh models of the frame are shown in Figure 3-3 and 3-4, respectively.

Figure 3-3 Schematic diagram of geometric model of the frame

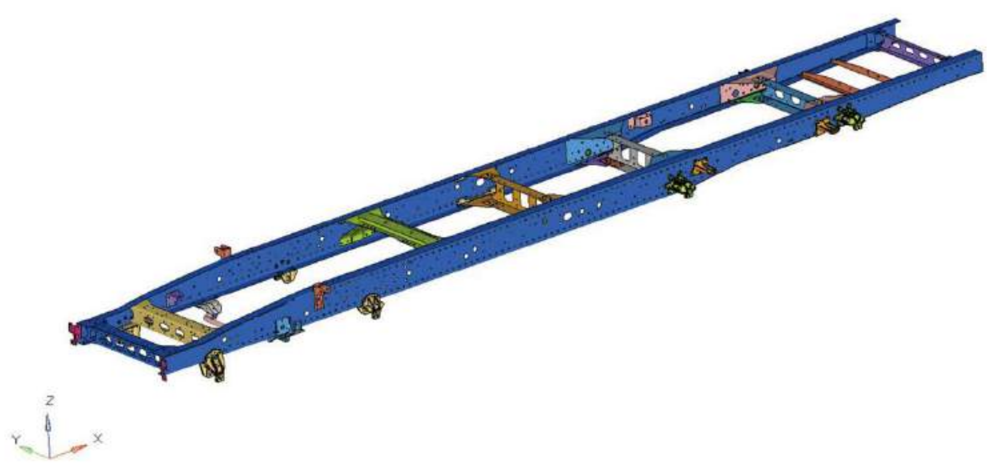
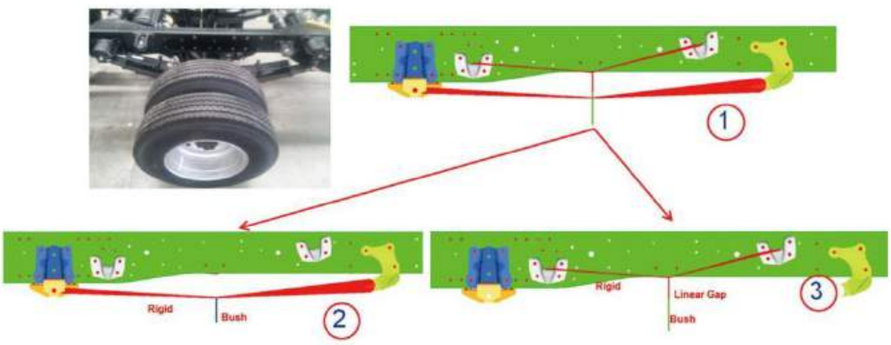


Figure 3-4 Schematic diagram of finite element model of the frame

b) Finite element modeling of rear leaf spring

The frame is connected with the wheels through the axle and the leaf spring. The load between the frame and the rear wheels is transmitted only by the main leaf spring when the truck is not loaded or only carries small loads. Only as the load rises, does the sinking of the frame increases. The rear auxiliary spring will contact the rear auxiliary spring support for load transmission only when the frame sinks to 35mm. Then, the main spring bears the load together with the auxiliary spring. To simulate the force on the frame truthfully and reasonably, a mechanical model of the rear leaf spring is created, as shown in Figure 3-5 below.

Figure 3-5 Mechanical model of rear leaf spring

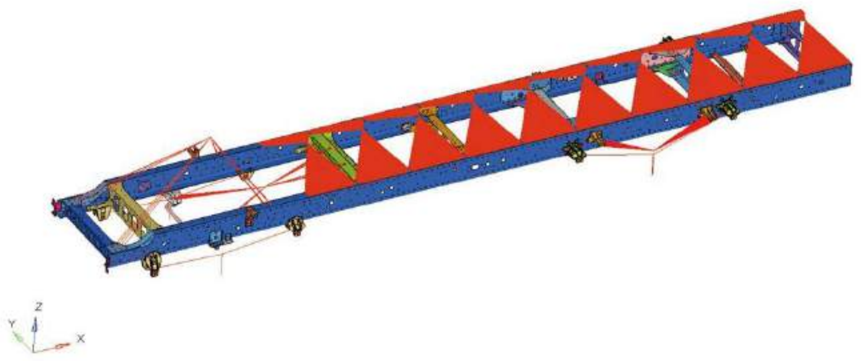


A complete mechanical model of the rear leaf spring is illustrated as 1 in the figure above, and 1 consists of 2 and 3. The main leaf spring is simplified to a spring element connected with the frame through a rigid element, and the auxiliary leaf spring is simplified to a bush element and a Linear Gap element (only pressure and no tension). The auxiliary leaf spring only works when the frame sinks to 35mm.

c) Finite element model of the frame assembly

The cab assembly, power assembly, cargo box assembly and cargo weight are simplified to centralized mass points, and connected with the frame through the rigid element RBE3. A finite element model of the frame assembly is shown in Figure 3-6 below.

Figure 3-6 Schematic diagram of finite element model of the frame assembly

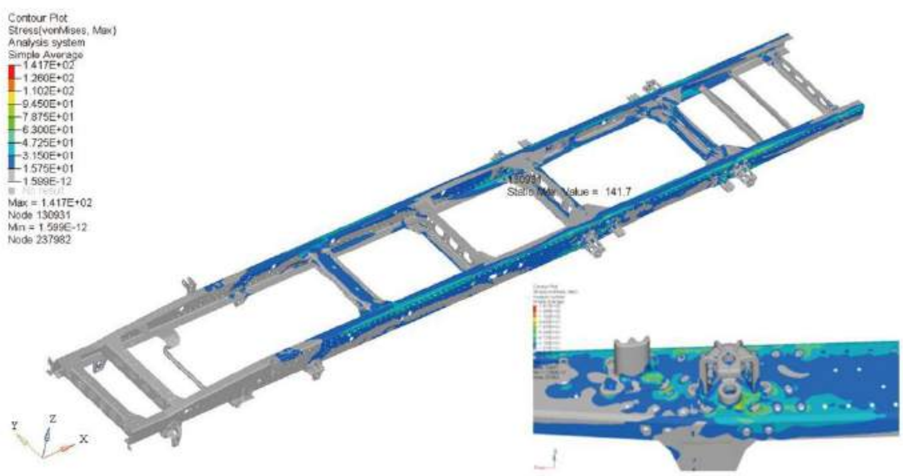


3.4.3 Frame strength analysis

a) Simulation analysis of static load bending mode

When the frame is fully loaded, the stress nephogram of the frame is illustrated in Figure 3-7 below.

Figure 3-7 Stress nephogram of static load bending mode

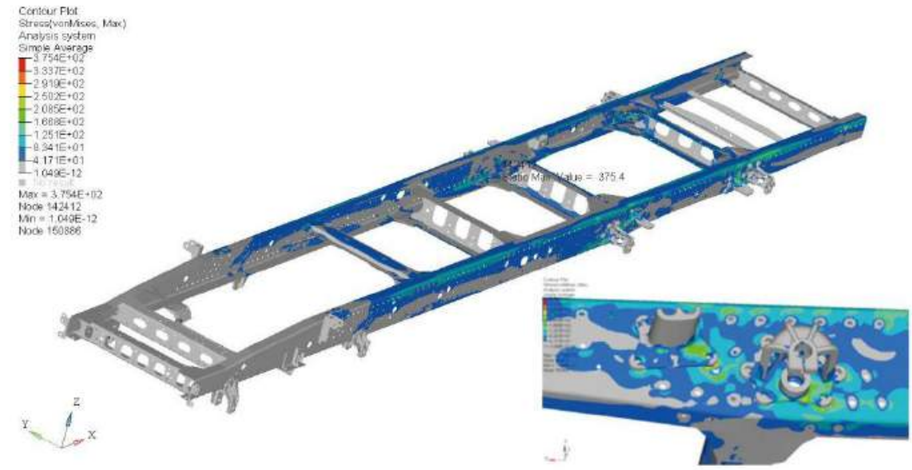


Where the frame is fully loaded, the maximum stress of the frame is 141.7MPa when the truck is running at a constant speed or at rest, which is lower than the yield strength 500MPa of the material, thus the frame meets the design requirements.

b) Simulation analysis of impact mode

When the frame carries 2.5G impact load, the stress nephogram of the frame is shown in Figure 3-8 below.

Figure 3-8 Stress nephogram of impact mode

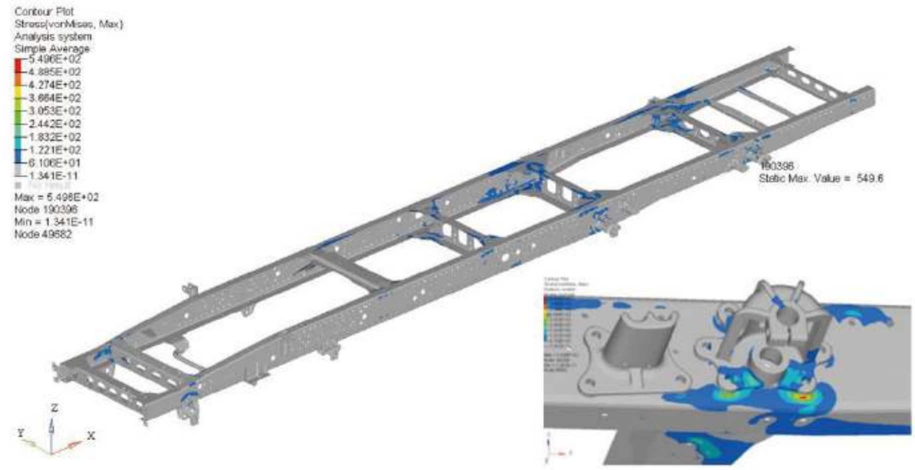


When the frame carries a 2.5G impact load, the maximum stress of the frame is 375.4MPa which is lower than the yield strength 500MPa of the material, thus it meets the design requirements.

c) Simulation analysis of turning mode

When the frame is subjected to a full load and a lateral 0.5G centrifugal force, the stress nephogram of the frame is illustrated in Figure 3-9 below.

Figure 3-9 Stress nephogram of turning mode

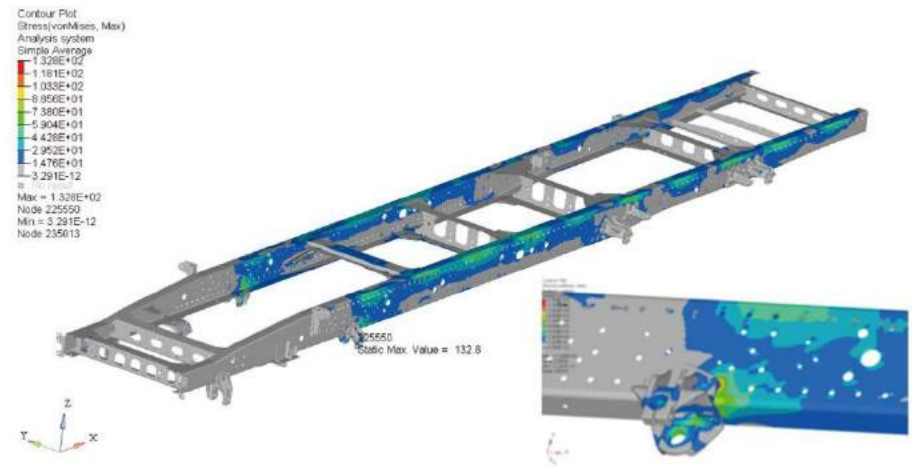


When the frame bears a full load and a lateral 0.5G centrifugal force, the maximum stress of the frame is 549.6MPa, which is higher than the yield strength 500MPa of the material, thus the frame does not meet the design requirements and needs local optimization of the structure.

d) Simulation analysis of braking mode

When the frame is subjected to a full load and a longitudinal inertial force (0.8G), the stress nephogram of the frame is shown in Figure 3-10 below.

Figure 3-10 Stress nephogram of braking mode

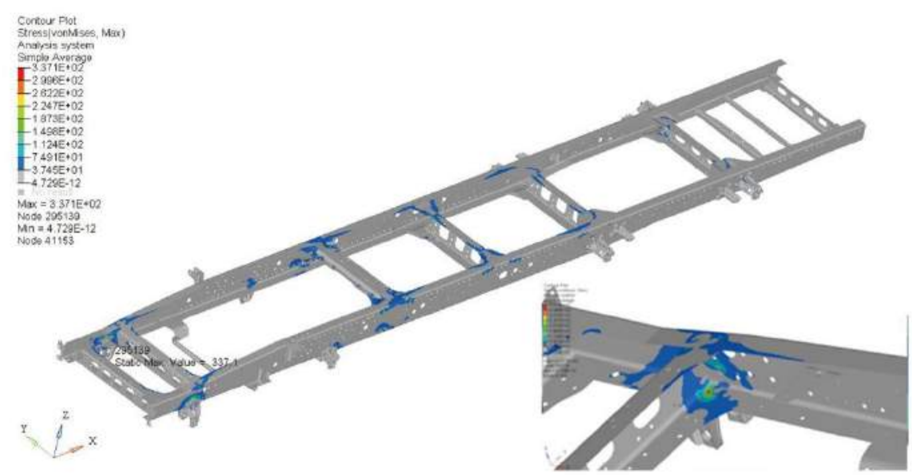


When the frame is subjected to a full load and a longitudinal inertial force (0.8G), the maximum stress of the frame is 132.8.7MPa, which is lower than the yield strength 500MPa of the material, thus the frame meets the design requirements.

e) Simulation analysis of torsion (FL_150mm) mode

When the left front wheel of the frame is raised by 150mm, the stress nephogram of the frame is shown in Figure 3-11 below.

Figure 3-11 Stress nephogram of the mode when the left front wheel is raised by 150mm

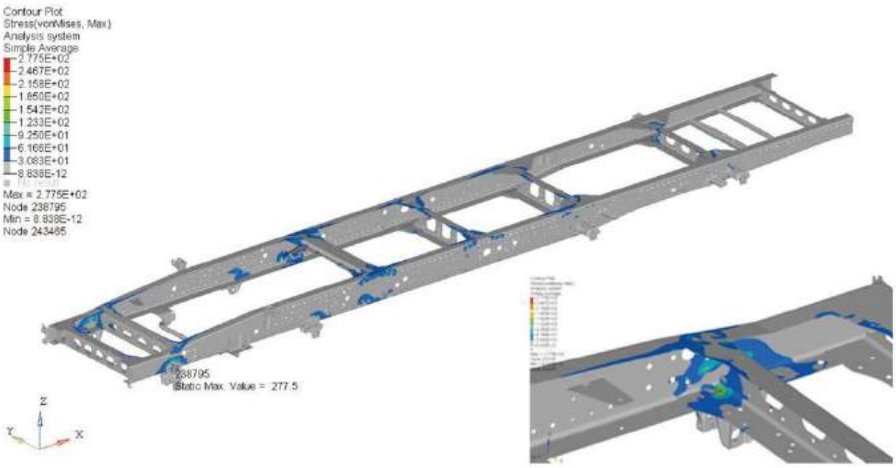


When the left front wheel of the frame is raised by 150mm, the maximum stress of the frame is 337.1MPa, which is lower than the yield strength 500MPa of the material, thus the wheel meets the design requirements.

f) Simulation analysis of torsion (RR_150mm) mode

When the right rear wheel of the frame is raised by 150mm, the stress nephogram of the frame is shown in Figure 3-12 below.

Figure 3-12 Stress nephogram of the mode when the right rear wheel is raised by 150mm

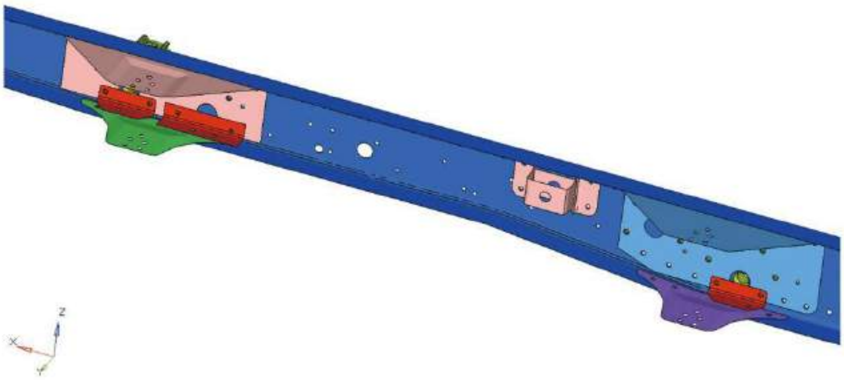


When the right rear wheel of the frame is raised by 150mm, the maximum stress of the frame is 277.5MPa, which is lower than the yield strength 500MPa of the material, thus wheel meets the design requirements.

g) Optimization of local frame structures

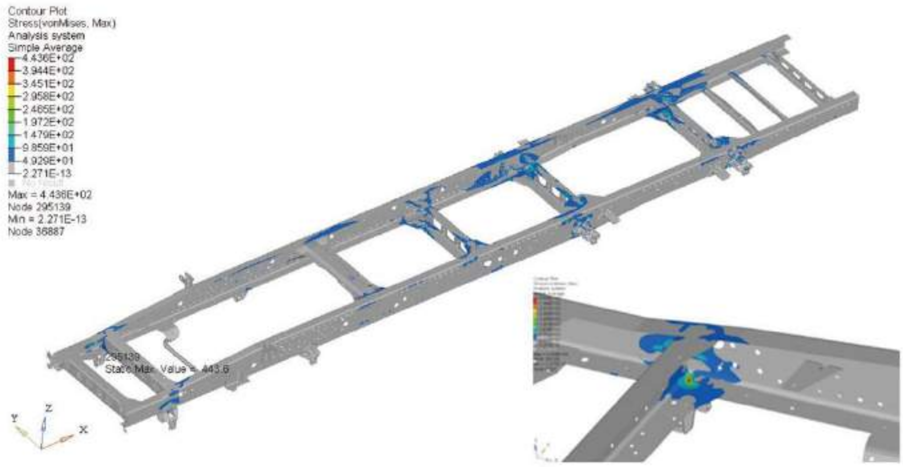
According to the analysis above, when the frame turns at a full load, the maximum stress of the frame is 549.6MPa, which is higher than the yield limit of the material, thus there is a certain risk of failure. Therefore, a L-shaped corner piece (red part) is arranged at the bolt holes where the rear leaf spring support is connected with the side rail as well as at the inner side of the side rail, as shown in Figure 3-13 below.

Figure 3-13 Schematic diagram of L-shaped corner piece



When the structurally optimized frame is subjected to a full load and a lateral 0.5G centrifugal force, the stress nephogram of the frame is illustrated in Figure 3-14 below.

Figure 3-14 Stress nephogram of the structurally optimized frame in the turning mode



When the structurally optimized frame bears a full load and a lateral 0.5G centrifugal force, the maximum stress of the frame is 443.6MPa, which is lower than the yield strength 500MPa of the material, thus the frame meets the design requirements.

3.4.4 Summary

According to the strength analysis of the frame, the peak stress of the frame in different operating modes is given in Table 3-4 below. When the frame is subjected to a full load and a lateral 0.5G centrifugal force, the peak stress of the frame is at the maximum, and the maximum stress is 443.6MPa, which is lower than the yield strength of the material, thus the frame meets the design requirements.

Table 3-4 Peak stresses and safety factors of the frame in different operating modes

Scheme	Full load	Impact	Turning	Braking	FL_150	RR_150
Stress/MPa	141.7	375.4	443.6	132.8	337.1	277.5
Safety factor	3.53	1.33	1.13	3.77	1.48	1.80

CHAPTER 4

Dynamic Design of Products

CHAPTER 4
Dynamic Design of Products

The product structure will vibrate and even produce noise under the action of dynamic loads during service. The generation of vibration and noise will seriously affect the use of the product and even reduce the service life of the product. Therefore, the dynamic design of the product should be conducted based on the load environment to control the dynamic response of the product structure, reduce vibration and noise, and improve the product quality.

Dynamic loads can be expressed in two ways, namely time domain and frequency domain. If a load is represented in the time domain, the structural dynamic response is transient. If a load is expressed in the frequency domain, the structural dynamic response is a frequency response. If the load in the frequency domain is power spectral density, the response is a random response.

Structure is excited by dynamic loads and produces dynamic responses. The structural response depends on external excitation and dynamic features of the structure. The structural dynamic features can be described by structural modes. Modal analysis is an important part of structural dynamic design.

4.1 Modal Analysis

4.1.1 Basic Concept

Modality is an inherent property of structures. Modal frequency is the resonance frequency of the structures, and modal shape is the structural vibration shape corresponding to the modal frequency.

Considering the equation

$$[M]\{\ddot{x}\} + [K]\{x\} = 0 \tag{4.1}$$

Assuming a solution of the simple harmonic motion

$$\{x\} = \{\varphi\}e^{i\omega t} \tag{4.2}$$

From the equation 4.2

$$\{\ddot{x}\} = -\omega^2\{\varphi\}e^{i\omega t} \tag{4.3}$$

Substituting the equations 4.2 and 4.3 into the equation 4.1

$$-\omega^2[M]\{\varphi\}e^{i\omega t} + [K]\{\varphi\}e^{i\omega t} = 0$$

Dividing both sides of the above equation by $e^{i\omega t}$ to simplify the equation

$$([K] - \omega^2[M])\{\varphi\} = 0 \tag{4.4}$$

This is a problem of a eigenvalue, so that there are two cases.

a) If det $([k]-\omega^2[m])\neq 0$, there is only the following according to the equation (4.4).

$$\{\varphi\} = 0$$

This is the so-called trivial solution without physical meaning.

b)To get the non-trivial solution of $\{\varphi\}$,det ([k]-ω²[m])=0 is required.

The eigenvalue problem is thereby transformed into the solution of the following equation.

$$\det([k]-\omega^2[m])=0 \text{ or } \det([k]-\lambda[m])=0 \qquad (4.5)$$

Where,$\lambda=\omega^2$

If the structure has N degrees of freedom, the eigenvalue problem will have N solutions , $\omega_s(\omega_1,\omega_2,\ldots,\omega_n)$ which are called the natural, characteristic or resonance frequency of the structure.

The characteristic vector $\{\boldsymbol{\varphi}\}_j$ corresponding to the natural frequency $\{\boldsymbol{\omega}\}_j$ is called normal mode or modal shape. A normal mode is the shape and mode in which the structure vibrates and deforms.

When the structure vibrates, its deformation at any time constitutes the linear superposition of the normal mode.

The stiffness matrix [K] and the mass matrix [M] of the structural finite element are real symmetric matrices and have the following orthogonal characteristics:

$$\{\varphi_i\}^T[M]\{\varphi_j\}=0 \qquad If\ i\neq j$$

$$\{\varphi_i\}^T[K]\{\varphi_j\}=0 \qquad If\ i\neq j$$

And

$$\omega_j^2=\frac{\{\varphi_j\}^T[K]\{\varphi_j\}}{\{\varphi_j\}^T[M]\{\varphi_j\}} \quad \text{Rayleigh quotient}$$

The natural frequency $\omega_s(\omega_1,\omega_2,\ldots,\omega_n)$ can be expressed by radians/second or hertz (hertz=cycles/seconds).

$$f_j(hertz)=\frac{\omega_j(radian/second)}{2\pi}$$

4.1.2 Modal Analysis Examples

For the modal analysis of the structure, the structural geometric model, Young's modulus of elasticity, Poisson's ratio and density as well as constraints are required. The structure can also be free in the modal analysis,so that the entire structure has six rigid-body degrees of freedom in the space. The modal analysis result will have six zero frequencies which correspond to the sixth-order rigid body mode.

Table 4.1 shows a structural finite element mesh with four fixed position constraints on the structural base. Modal calculation is performed upon the finite element modeling, and the calculation results of top ten-order modes are given in Table 4.1.

Figure 4.1 Structural finite element mesh

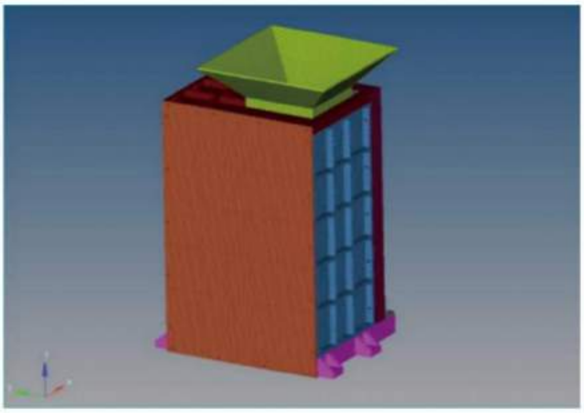


Table 4.1 Modal calculation results

Order	Frequency (Hz)	Vibration mode
1	185.6	Overall vibration in the X direction
2	240	Overall vibration in the Y direction
3	290.4	Local vibration of the top structure
4	313.3	Side plate vibration in the X direction
5	319.5	Internal component vibration in the Z direction
6	337.6	Local vibration of the top structure
7	358.7	Local vibration of the top structure
8	373.8	Local vibration of internal components
9	425.9	Local vibration of internal components
10	462	Local vibration of the top structure

Figure 4.2 Vibration mode diagram of the first-order mode at 185.6Hz

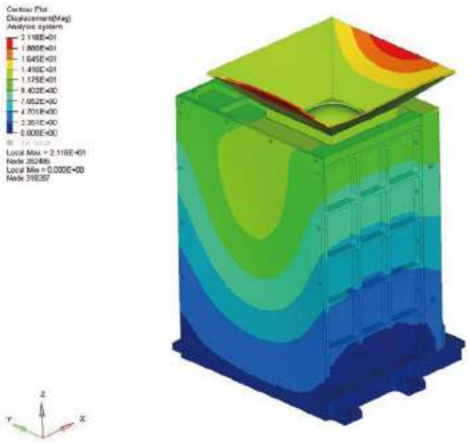


Figure 4.3 Vibration mode diagram of the second-order mode at 240Hz

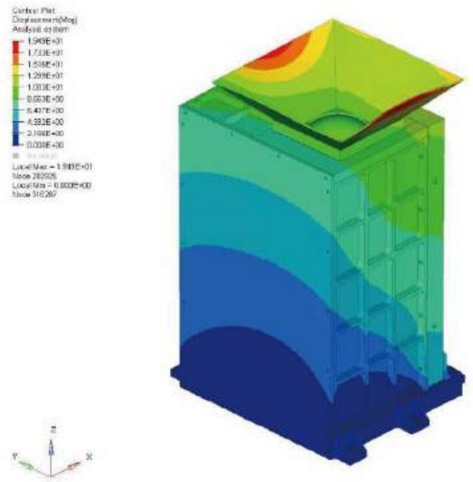


Figure 4.4 Vibration mode diagram of the third-order mode at 290.4Hz

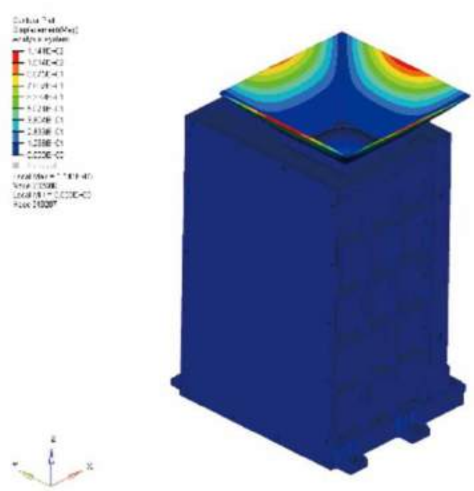
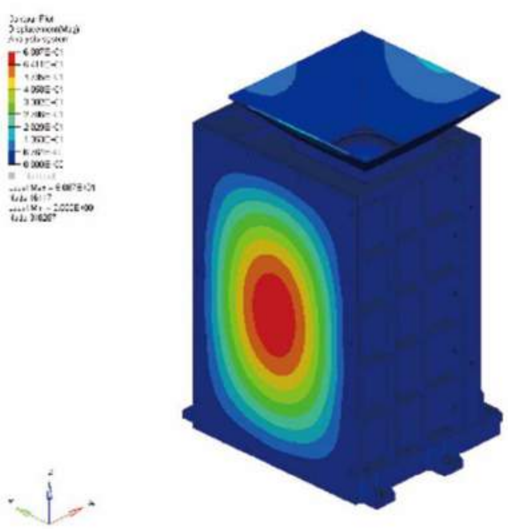


Figure 4.5 Vibration mode diagram of the fourth-order mode at 313.3Hz



4.2 Transient Response

4.2.1 Transient Response Analysis Method

If the structural excitation load changes over time, the displacement, stress and acceleration generated by structural responses vary with time accordingly.

A structural dynamic equation is created thereby.

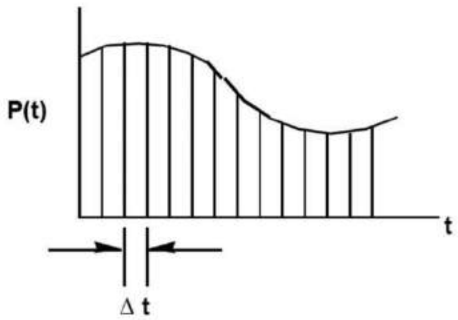
$$[M]\{\ddot{u}(t)\}+[B]\{\dot{u}(t)\}+[K]\{u(t)\}=\{P(t)\} \qquad (4.6)$$

For structural responses, the time step Δt is assumed as the discrete time points to solve the equation. Firstly, a central difference method is used to represent $\{\dot{u}(t)\}$ and $\{\ddot{u}(t)\}$.

$$\{\dot{u}_n\}=\frac{1}{2\Delta t}\{u_{n+1}-u_{n-1}\}$$

$$\{\ddot{u}_n\}=\frac{1}{\Delta t^2}\{u_{n+1}-2u_n+u_{n-1}\}$$

Figure 4.6 Discrete time



The equation (4.6) is numerically integrated by using the central difference method, so that

$$\left[\frac{m}{\Delta t^2}\right](u_{n+1}-2u_n+u_{n-1})+\left[\frac{b}{2\Delta t}\right](u_{n+1}-u_{n-1})+\left[\frac{k}{3}\right](u_{n+1}+u_n+u_{n-1})=\frac{1}{3}(P_{n+1}+P_n+P_{n-1})$$

Upon rearrangement,

$$[A_1]\{u_{n+1}\}=[A_2]+[A_3]\{u_n\}+[A_4]\{u_{n-1}\} \qquad (4.7)$$

Where

$$[A_1]=\left[M/\Delta t^2+B/2\Delta t+K/3\right] \qquad \text{Dynamic matrix}$$

$$[A_2]=1/3\{P_{n+1}+P_n+P_{n-1}\} \qquad \text{External force}$$

$$[A_3]=\left[2M/\Delta t^2-K/3\right]$$

$$[A_4]=\left[-M/\Delta t^2+B/2\Delta t-K/3\right]$$

Initial conditions from the previous step

The equation (4.7) can be solved by the similar classical Newmark-Beta method.

Transient responses can be computed in two ways. One is intended to solve the dynamic equation directly as discussed above, and is called immediate integration method. The other, as described below, is designed to use modes to transform the structural dynamic equation from physical coordinate space to modal coordinate space before solving the equation, and is called modal method for the transient response computation that is aimed to reduce the computation scale and improve the computational efficiency.

A modal method for transient response analysis

Transformation from physical coordinate space to modal coordinate space

$$\{u\} = [\varphi]\{\xi\} \tag{4.8}$$

Regardless of damping, the dynamic equation is

$$[M]\{\ddot{u}\} + [K]\{u\} = \{P(t)\} \tag{4.9}$$

Substituting the equation 4.8 into the equation 4.9 to obtain

$$[M][\varphi]\{\ddot{\xi}\} + [K][\varphi]\{\xi\} = \{P(t)\} \tag{4.10}$$

Left-handed multiplying the equation 4.10 by $[\varphi^T]$ to obtain

$$[\varphi^T][M][\varphi][\ddot{\xi}] + [\varphi^T][K][\varphi]\{\xi\} = [\varphi^T]\{P(t)\} \tag{4.11}$$

Where

$[\varphi^T][M][\varphi]$ = modal mass matrix (diagonal)

$[\varphi^T][K][\varphi]$ = modal rigidity matrix (diagonal)

$[\varphi^T]\{P(t)\}$ = modal force vector

The equation 4.11 can be written as a decoupled single-degree-of-freedom form:

$$m_i\ddot{\xi}^i + k_i\xi^i = p_i(t) \tag{4.12}$$

Where

$m_i = i_{th}$-order modal mass

$k_i = i_{th}$-order modal stiffness

$p_i = i_{th}$-order modal force

Damping in the modal method for transient response analysis

If the damping matrix B cannot be diagonalized by the modal vector matrix ϕ,

$$\phi^T B \phi \neq \text{diagonal}$$

Then, this is a coupling problem. In the modal coordinate space, Newmark-Beta class numerical integration of the direct integration method is used to solve the problem.

$$[A_a\{\xi_{n+1}\}] = [A_2] + [A_3]\{\xi_n\} + [A_4]\{\xi_{n-1}\} \tag{4.13}$$

Where

$[A_1] = [\phi^T]\left[\frac{M}{\Delta t^2} + \frac{B}{2\Delta t} + \frac{K}{3}\right][\phi]$ Dynamic matrix

$[A_2] = \frac{1}{3}[\phi^T]\{P_{n+1} + P_n + P_{n-1}\}$ External force

$[A_3] = [\phi^T]\left[\frac{2M}{\Delta t^2} - \frac{K}{3}\right][\phi]$

$[A_4] = [\phi^T]\left[-\frac{M}{\Delta t^2} + \frac{B}{2\Delta t} - \frac{K}{3}\right][\phi]$ Initial conditions from the previous step

If modal damping is applied, then each mode has a damping b_i and the dynamic equation can thereby be decoupled.

$$m_i\ddot{\xi}_i + b_i\dot{\xi}_i + k_i\xi_i = p_i(t) \tag{4.14}$$

or

$$\ddot{\xi}_i + 2\zeta_i\omega_i\dot{\xi} + \omega_i^2\xi_i = p_i(t)/m_i \tag{4.15}$$

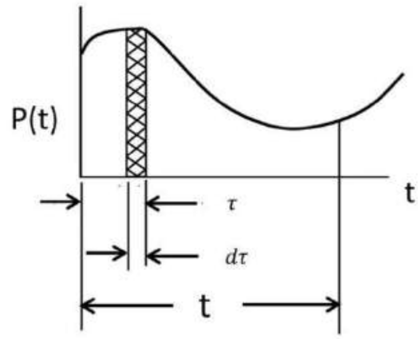
Where

$$z_i = b_i / (2 m_i w_i) \qquad \text{Modal damping ratio}$$
$$w_i^2 = k_i / m_i \qquad \text{Eigenvalue}$$

The Duhamel integration is used to solve the above decoupled single-degree-of-freedom equation:

$$\xi(t) = e^{-bt/2m}\left(\xi_o \cos\omega_d t + \frac{\dot{\xi}_o + (b/2m)\xi_o}{\omega_d}\right) + e^{-bt/2m}\frac{1}{m\omega_d}\int_0^t e^{bt/2m}\, p(\tau)\, \sin\omega_d (t-\tau)\, d\tau$$

Figure 4.7 Duhamel integration



4.2.2 Transient Response Examples

Modal analysis examples are utilized to compute transient responses, and the impact load given in Table 4.2 is applied on this basis. The response curves of displacement, stress and acceleration at a point on the structure as a function of time are illustrated in Figure 4.8, 4.9 and 4.10, respectively. The distribution nephograms of structural deformation displacement and stress at a time point are shown in Figure 4.11 and 4.12, respectively.

Table 4.2 Impact acceleration of half-sine wave

Impact acceleration	50g
Impact waveform	Half-sine pulse
Duration	10ms±1ms
Impact direction	X direction

Figure 4.8 Node455150 displacement response curve

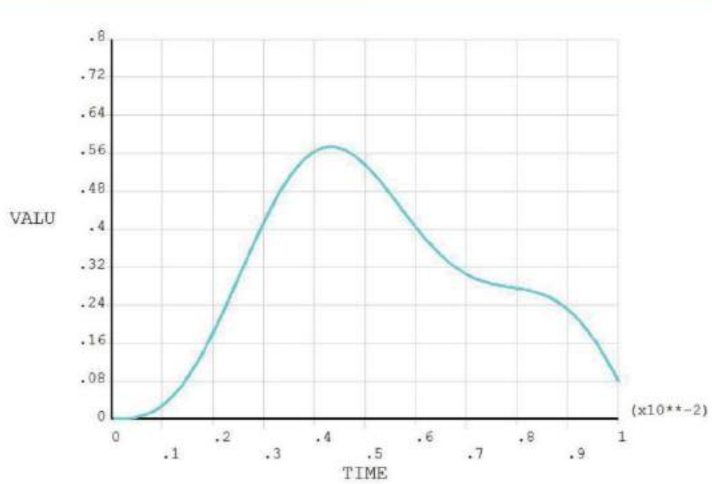


Figure 4.9 Node455150 stress response curv

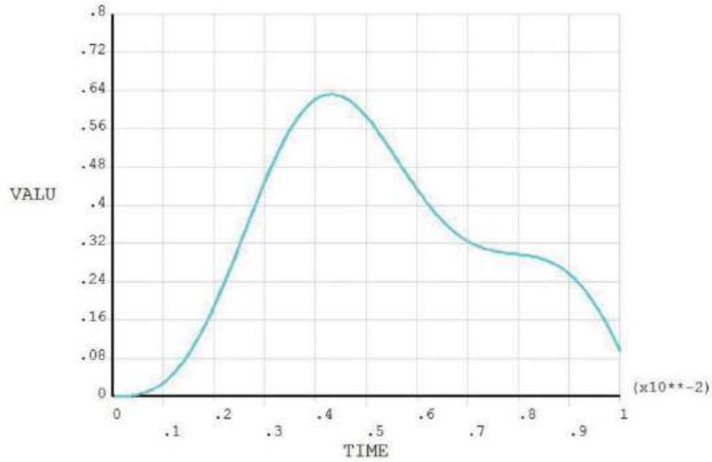


Figure 4.10 Node455150 acceleration response curve

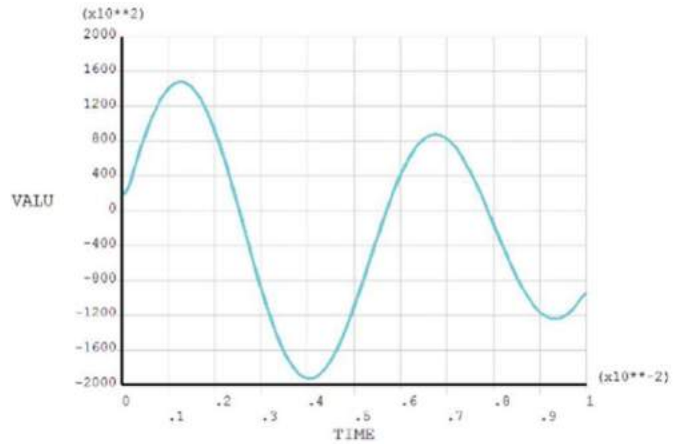


Figure 4.11 Structural deformation displacement nephogram (maximum displacement: 0.975mm)

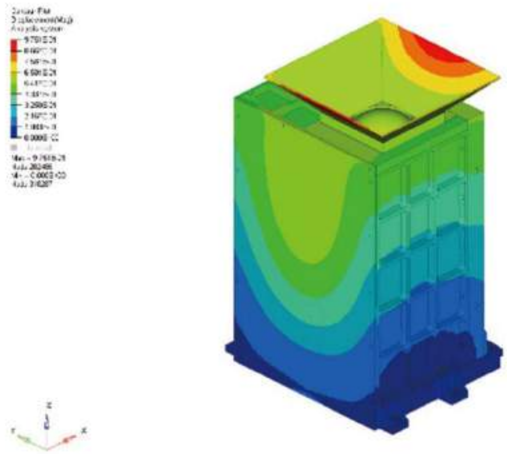
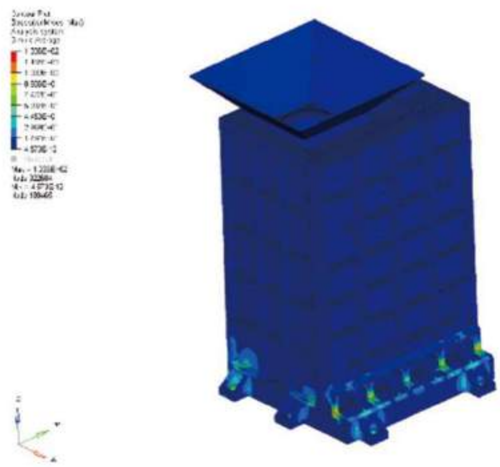


Figure 4.12 Structural stress nephogram (maximum stress: 133.6MPa)



4.3 Frequency Response

4.3.1 Frequency Response Analysis Method

If the structural excitation load changes with frequency, the displacement, stress and acceleration generated by structural responses vary with frequency accordingly.

A direct method for frequency response analysis

$$[-\omega^2 M + i\omega B + K]\{u(\omega)\} = \{P(\omega)\} \qquad (4.16)$$

For each frequency value ω, the coefficient matrix on the left of the dynamic equation (4.16) is complex, so that the equation can be solved by a complex algorithm, which is similar to the static problem.

A modal method for frequency response analysis

Transform to the modal coordinate space and solve the decoupled single-degree-of-freedom equation:

$$\xi_i = \frac{p_i}{-m_i\omega^2 + ib_i\omega + k_i} \qquad (4.17)$$

The computation of the modal method is much faster than the direct method. In order to decouple the equation, damping may be ignored or modal damping can be applied. If damping has to be considered and there is no modal damping, the direct method shall be used in the modal coordinate space. This is because the modal coordinate matrix is small with high computational efficiency.

4.3.2 Frequency Response Examples

Modal analysis examples are utilized to compute frequency responses, and the sinusoidal vibration load given in Table 4.3 is applied on this basis. The response curve of acceleration at a point on the structure as a function of frequency is shown in Figure 4.14. The distribution nephograms of acceleration, deformation displacement and stress of the structure at a frequency point are shown in Figure 4.13, 4.15 and 4.16, respectively.

Table 4.3 Sinusoidal vibration acceleration

Frequency (Hz)	5-12	12-25	25-35	35-60	60-65	65-100
Magnitude	3.88mm	2.25g	Transition to 5.25g	5.25g	Transition to 3.0g	3.0g
Rate	2oct/min					
Direction	X direction					

Figure 4.13 Structural acceleration nephogram (maximum acceleration: 9.54e4mm/s^2)

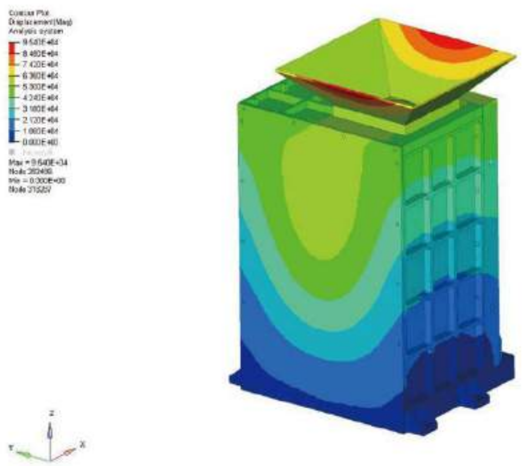


Figure 4.14 Node106039 acceleration response curve

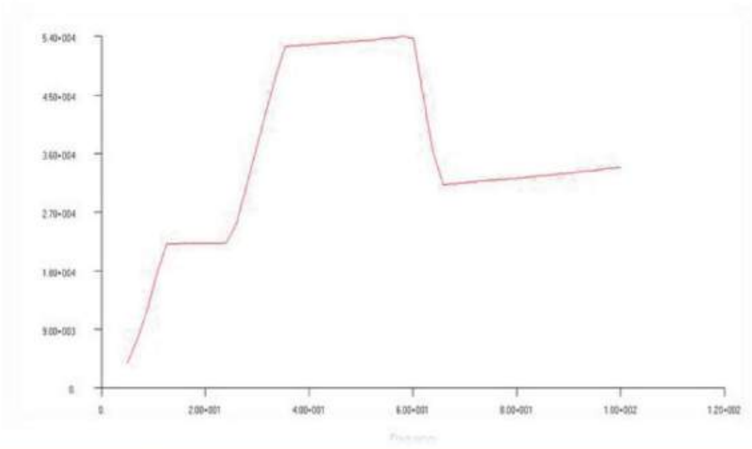


Figure 4.15 Structural deformation displacement nephogram (maximum displacement: 0.07mm)

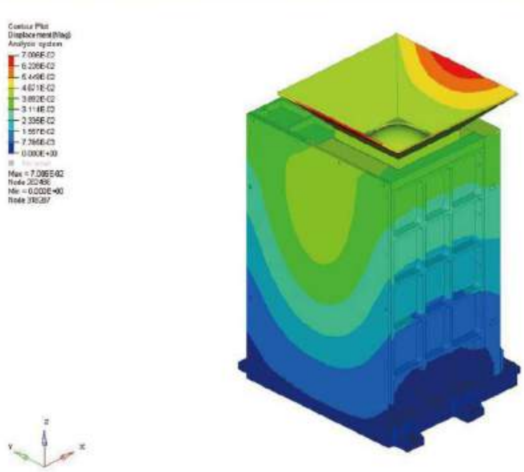
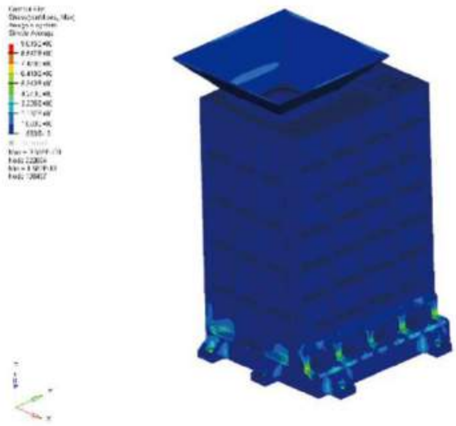


Figure 4.16 Structural stress nephogram (maximum stress: 9.6MPa)

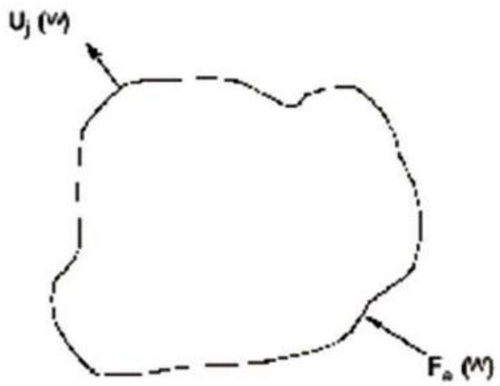


4.4 Random Response

4.4.1 Random Response Analysis Method

The response is random when the structure bears random loads. A random response is computed based on the calculation of a frequency response. A transfer function is obtained from the frequency response computation, and then the input power spectral density is applied to compute the output power spectral density of the response.

Figure 4.17 Response input and output



According to the frequency response analysis,

$$uj(\omega)=Hja(\omega)\bullet Fa(\omega) \qquad (4.18)$$

Where, Hja(ω) is the transfer function, uj is the output, and Fa is the input.

If there are multiple inputs, then

$$uj(\omega)=Hja(\omega)Fa(\omega)+Hjb(\omega)Fb(\omega)+... \qquad (4.19)$$

Writing the equation in the form of a matrix

$$u_j(\omega) = [H_{ja}(\omega) H_{jb}(\omega) \cdots] \begin{Bmatrix} F_a(\omega) \\ F_{b(\omega)} \\ . \\ . \end{Bmatrix}$$

The output auto-power spectrum is

$$S_{ujuj} = T[H_{ja} H_{jb} \cdots] \begin{Bmatrix} F_a(\omega) \\ F_b(\omega) \\ . \\ . \end{Bmatrix} [F_a^*(\omega) F_b^*(\omega) \cdots] \begin{Bmatrix} H_{ja}^* \\ Hjb^* \\ . \\ . \end{Bmatrix}$$

The spectrum for each input is

$$T\overline{F_a(\omega) F_a^*}(\omega) = S_{aa}(\omega)$$

$$T\overline{F_a(\omega) F_b^*}(\omega) = S_{ab}(\omega)$$

$$T\overline{F_b(\omega) F_b^*}(\omega) = S_{bb}(\omega)$$

The spectral relation of multiple inputs-outputs is

$$S_{ujuj}(\omega) = [H_j]^T \begin{bmatrix} S_{aa} & S_{ab} \\ S_{ba} & S_{bb} \\ . & . \\ . & . \\ . & . \end{bmatrix} [H_j^*]$$

Where

$$[H_j]^T = [H_{ja} H_{jb} \cdots] \quad \text{and} \quad [H_j^*] = \begin{Bmatrix} H_{ja}^* \\ H_{jb}^* \\ . \\ . \\ . \end{Bmatrix}$$

The input cross-spectral matrix is

$$[S]_{in} = \begin{pmatrix} S_{aa}(\omega) & S_{ab}(\omega) & \cdots \\ S_{ba}(\omega) & S_{bb}(\omega) & \cdots \\ . & . & \cdots \\ . & . & \cdots \end{pmatrix}$$

And which has the following characteristics

$$S_{ab}(\omega) = S_{ba}^{*}(\omega)$$

$$S_{aa}(\omega),\ S_{bb}(\omega) = real \geq 0$$

Common specific cases

Analysis of single input

$$S_{ujuj}(\omega) = \left|H_{ja}(\omega)\right|^2 S_{aa}(\omega)$$

Analysis of multiple irrelevant inputs

$$S_{ujuj}(\omega) = \left|H_{ja}(\omega)\right|^2 S_{aa}(\omega) + \left|H_{jb}(\omega)\right|^2 S_{bb}(\omega) + \cdots$$

4.4.2 Random Response Examples

Modal analysis examples are utilized to compute random responses, and the random vibration load given in Table 4.4 is applied on this basis. The power spectral density curve of acceleration at a point on the structure is illustrated in Figure 4.19. The Root-Mean-Square (RMS) distribution nephograms of acceleration, deformation displacement and stress of the structure are shown in Figure 4.18, 4.20 and 4.21, respectively.

Table 4.4 Random vibration load

Frequency range (Hz)	20-100	100-600	600-2000
Power spectral density	+3dB/oct	$0.09g^2/Hz$	-9dB/oct
Total RMS acceleration	$8.6g_{r.m.s}$		
Test direction	X direction		
Test duration	2min		

Figure 4.18 Structural acceleration RMS nephogram (maximum acceleration: 8.919e5mm/S^2)

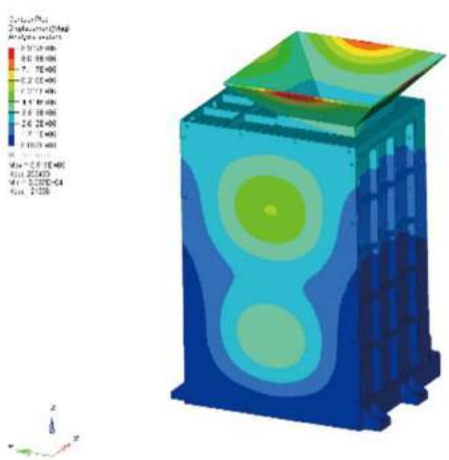


Figure 4.19 Node106039 acceleration power spectral density

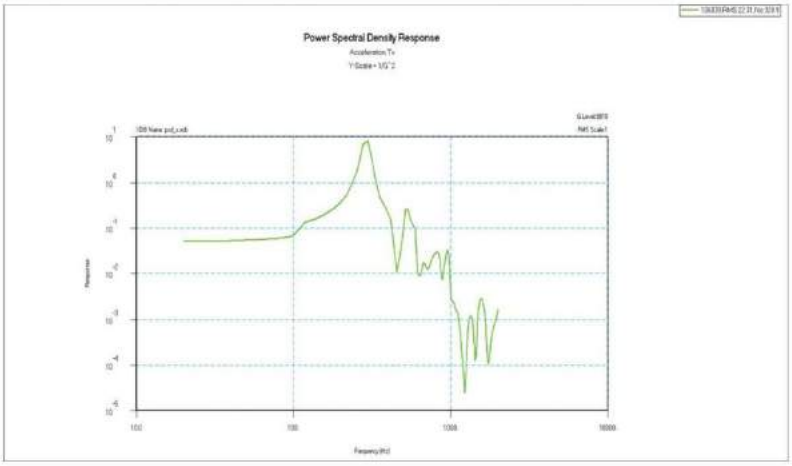


Figure 4.20 Structural displacement RMS nephogram (maximum displacement: 0.4151mm)

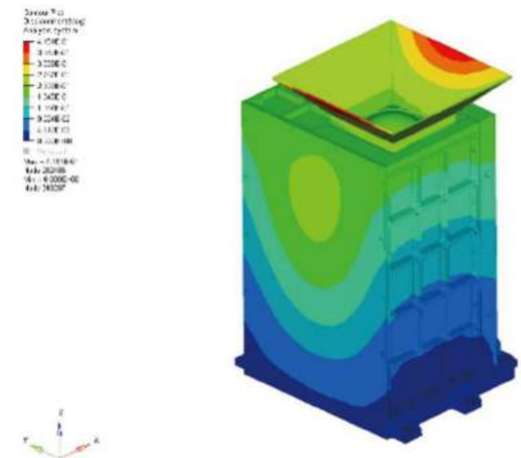
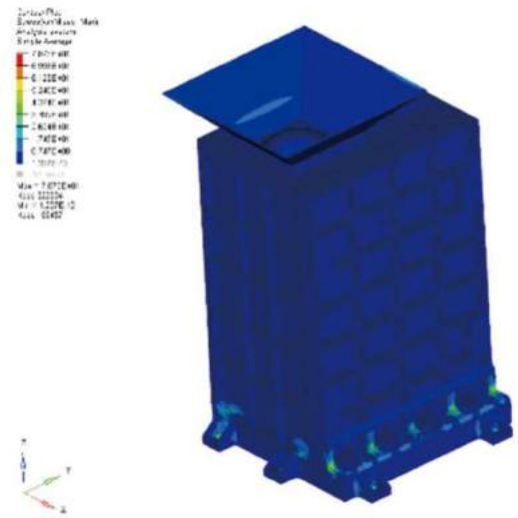


Figure 4.21 Structural stress RMS nephogram (maximum stress: 78.7MPa)



CHAPTER 5

Thermal Design of Products

CHAPTER 5
Thermal Design of Products

A number of products will produce heat during service, and some products are used at high or low temperature. Heat has impact on material properties, product reliability and service life. Therefore, thermal design of products is required.

5.1 Thermal Analysis

According to the heat transfer theory, heat conducts in and along the structure from the high temperature to the low temperature, and also exchanges with the environment in the form of convection or radiation.

The governing equation of heat conduction in a 3D temperature field is

$$\rho c \frac{\partial T}{\partial t} = \left[\frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) \right] + Q \qquad (5.1)$$

Where

k,r,c represent thermal conductivity (W/(m×K)), density (kg/m³) and specific heat (J/(kg×K)) of the material.
Q represents internal heat source (W/m³).

If the temperature field does not change with time, the item on the left of the equation above is 0, thus the equation turns into a steady-state thermal analysis problem. The boundary conditions of heat transfer can be classified into four categories. In other words, four different boundary conditions can normally be created on the structure surface ***G***.

a) Given temperature on the surface G_r

$$T = T(x_i, t)$$

b) Boundary conditions for given heat flux density on the surface G_q

$$\bar{q}(x_i, t) = \lambda_n \frac{\partial T}{\partial n}$$

Where, n is the outer normal direction of G_q, and $\bar{q}(x_i, t)$ is the given heat flux density as a function of spatial position and time.

c) Boundary conditions for given convection on the boundary ***G***

$$\bar{q} = h(T_G - T_\infty)$$

Where, h is the surface convective heat transfer coefficient, and T_G and $T_¥$ are the temperature of the surface and the ambient media.

d) Boundary conditions for given thermal radiation on the boundary ***G***

$$\bar{q} = \sigma\varepsilon(T_G^4 - T_\infty^4)$$

Where, ***s*** is a *Stefan-boltzmann* constant, and ***e*** is the surface radiation efficiency.

In addition to the four categories of boundary conditions mentioned above, the temperature distribution of the structure at the initial moment shall also be given, that is, the initial condition:

$$T(\boldsymbol{x}_i,0)=\boldsymbol{T}_0$$

5.2 Thermal Stress Analysis

When the temperature of an object changes, the object produces linear strain αT due to expansion, where α is the linear expansion coefficient of the material, and T is the temperature change value at any point in the elastic body (counted from the initial uniform temperature of the entire object). If the thermal deformation at each part of the object is not subject to any constraints, then stress will not be caused despite deformation. However, if the temperatures at various parts of the object are uneven, or the surface is in contact with other objects, that is, the object is subject to certain constraints, then the thermal deformation cannot proceed freely, thus resulting in the production of stress forces. This kind of stress caused by temperature change is called "thermal stress" or "temperature stress".

The thermal stress problem is mainly different in the stress-strain relationship compared with general stress analysis problems. If thermal stress is considered, the physical equation will be expressed as follows:

$$\{\sigma\}=[D](\{\varepsilon\}-\{\varepsilon_0\}) \qquad (5.2)$$

Where, $\{\varepsilon_0\}$ is the thermal strain caused by temperature variation.

$$\{\varepsilon_0\}=\alpha T[1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0]^T$$

Where, α is the linear expansion coefficient of the material, and T is the temperature variation.

5.3 Finite Element Method for Thermal Analysis

According to the variational principle, the following finite element matrix equation for thermal analysis can be derived from the equation 5.1:

$$[B]\{\dot{T}\}+[K]\{T\}=\{F\} \qquad (5.3)$$

Where, [B] and [K] are the heat capacity matrix and heat conduction matrix, respectively, and {T} and {F} are the temperature and heat load vector, respectively.

The matrix equation (5.3) is transformed to the following equation by the steady-state thermal analysis in MSC Nastran.

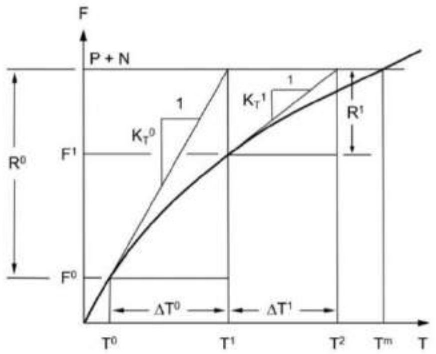
$$[K]\{T\}+[\Re]\{T+T_{abs}\}^4=\{P\}+\{N\} \qquad (5.4)$$

Where, [R] is the thermal radiation matrix, {Tabs} is the temperature deviation from the absolute temperature during thermal radiation calculation, {P} is the constant heat flow vector, and {N} is the temperature-dependent heat flow vector.

This is a nonlinear matrix equation and can be solved by the Newton-Raphson iteration method. The residual vector in the iterative computation is defined as the difference between the external thermal load vector and the internal thermal load vector of the element.

$$\{R\}=(\{P\}+\{N\})-([K]\{T\}+[\Re]\{T+T_{abs}\}^4) \qquad (5.5)$$

Figure 5.1 Newton-Raphson iteration method



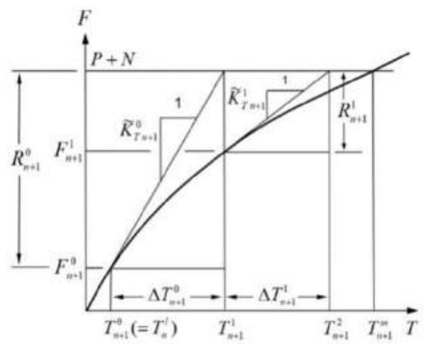
The matrix equation (5.3) is transformed to the following equation by the transient thermal analysis in MSC Nastran.

$$[B]\{\dot{T}\} + [K]\{T\} + [\Re]\{T + T_{abs}\}^4 = \{P\} + \{N\} \qquad (5.6)$$

This is a dynamic nonlinear matrix equation and can be solved by the Newton-Raphson iteration method at each time step, as shown in Figure 5.2. The residual vector in the iterative computation is defined as the difference between the external thermal load vector and the internal thermal load vector of the element. The internal thermal load vector of the element is not only related to temperature, but also to temperature change over time.

$$\{R(t)\} = (\{P\} + \{N\}) - ([B]\{\dot{T}\} + [K]\{T\} + [\Re]\{T + T_{abs}\}^4) \qquad (5.7)$$

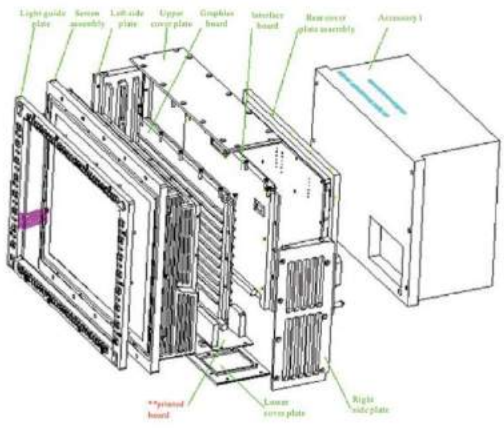
Figure 5.2 Newton-Raphson iteration method at the Tn+1 step



5.4 Thermal Analysis of Electronic Devices

5.4.1 Problem Description

Figure 5.3 Electronic cabinet structure

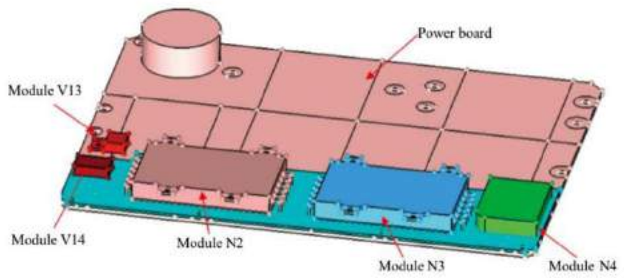


The structure of an electronic cabinet is illustrated in Figure 5.3. The main components include a screen assembly, a graphics board, an interface board, a power board and an enclosure. The screen assembly, graphics board, interface board and power board are heating components in the electronic cabinet.

In the screen assembly, the screen is surrounded by heating elements, with the heating power consumption being 20W. Assuming that the heat is distributed uniformly, the graphics board has a heating power consumption of 4W.

Heating elements of the interface board include CPU (U5) and FPGA (U4). CPU (U5) has a power consumption value of 656mW, and the heating power consumption is 10% of the power consumption 656mW. FPGA (U4) has a power consumption value of 500mW, and the heating power consumption is 10% of the power consumption 500mW.

Figure 5.4 CAD model of power board



A CAD model of the power board is illustrated in Figure 5.4, in which the modules N2, N3, N4, N13 and N14 are heating elements, with respective heating power shown in Table 5.1.

The temperature status of the electronic cabinet during service is analyzed, the temperature and heat flux distribution of the screen assembly, graphics board, interface board, power board and enclosure are computed, and the ambient temperature of the electronic cabinet is 65℃.

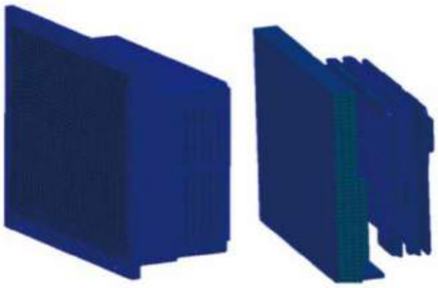
Table 5.1 Parameters of heating elements of power board

S/N	Code	Heating power consumption (W)
1	V13	1.8
2	V14	0.37
3	N2	5.8
4	N3	5.6
5	N4	1.14

5.4.2 Finite Element Model

Figure 5.5 shows the finite element model of the electronic cabinet, and the model adopts a three-dimensional solid element. On the right of the Figure 5.5, there is the finite element model of the screen assembly, graphics board, interface board and power board in the cabinet. During the finite element modeling process, the model is simplified as appropriate without considering effect of the cabinet accessory.

Figure 5.5 Finite element model of electronic cabinet



5.4.3 Material Properties

As for the coefficient of heat conduction of materials, the printed board is 2.6W/(m.℃), the modules V13 and V14 are 88.2W/(m.℃), the modules N2 and N3 are 88.2W/(m.℃), the module N4 is 88.2W/(m.℃), the cabinet screen is 88.2W/(m.℃), and the cabinet enclosure is 204W/(m.℃).

5.4.4 Load and Boundary Conditions

The electronic cabinet exchanges heat with the surrounding environment in the form of convection during service. The heat of the electronic components in the cabinet is dissipated to the surroundings through the heat transfer of solid devices, and to the surrounding space in the cabinet in the form of convection. The electronic cabinet will reach a thermal balance state with the environment after operating for a period of time, so that the computation can be performed by steady-state thermal analysis.

The electronic components produce thermal load due to heat generation. In the finite element model, the thermal power is converted into heat flux density (W/m^2) to define the thermal load, as shown in Figure 5.6, 5.7, 5.8 and 5.9.

Figure 5.6 Thermal load of power board

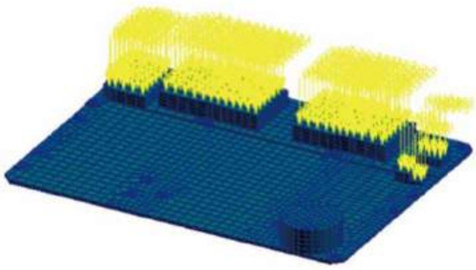


Figure 5.7 Thermal load of interface board

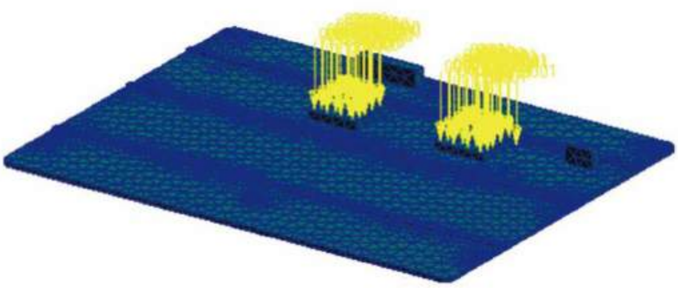


Figure 5.8 Thermal load of graphics board

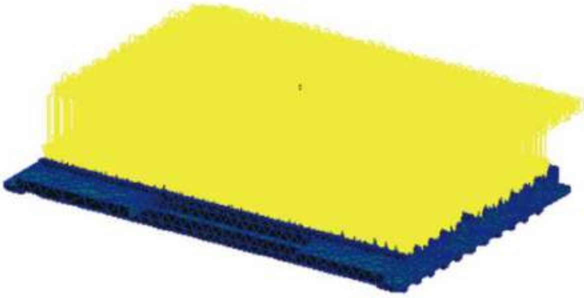
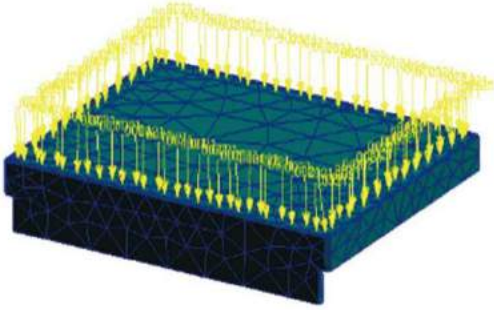


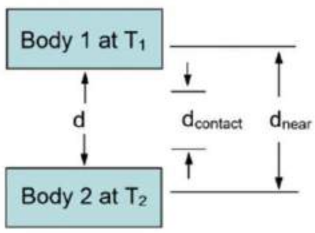
Figure 5.9 Thermal load of cabinet screen



Heat exchange between the electronic cabinet and the surrounding environment during service can be defined as the convection boundary condition. The convection coefficient is 30W/(m2.℃), and the ambient temperature is 65℃.

There are two types of heat transfer in the cabinet: one is heat conduction along the solid devices, and the other is heat transfer in the form of convection between the screen assembly, graphics board, interface board, power board and enclosure. The heat transfer in the cabinet can be defined as thermal contact.

Figure 5.10 Thermal contact



As illustrated in Figure , the thermal contact is computed as solid heat conduction when $d < d_{contant}$, i.e. no gap between the two objects;

The two objects transfer heat by convection and radiation when $d_{contant} < d < d_{near}$, i.e. a gap existing between the two objects; and $d_{near} < d$.

The two objects transfer heat by convection and radiation and transfer heat to their surroundings when .

In this computation, there are two forms of thermal contact, namely heat conduction and convection. The coefficient of heat conduction is 204W(m.℃), and the coefficient of heat convection is 30W/(m2.℃).

Therefore, the load and boundary conditions in this computation are classified into three categories: heat source, heat convection between the enclosure and surroundings, and contact heat transfer in the cabinet.

5.4.5 Thermal Analysis Results

The temperature distribution and heat flux distribution of the power board, interface board, graphics board and screen in the cabinet are shown in Figure 5.11 and 5.12, respectively. The maximum temperature is 84.40℃, and the maximum heat flux density is 0.0181W/mm2, both of them are observed at the module V13 on the power board. This is mainly caused by the small volume of the module V13 and the large thermal power per unit volume.

Figure 5.11 Temperature distribution in the cabinet

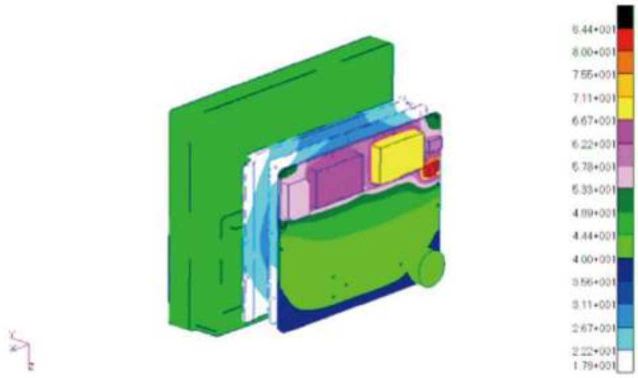


Figure 5.12 Heat flux distribution in the cabinet

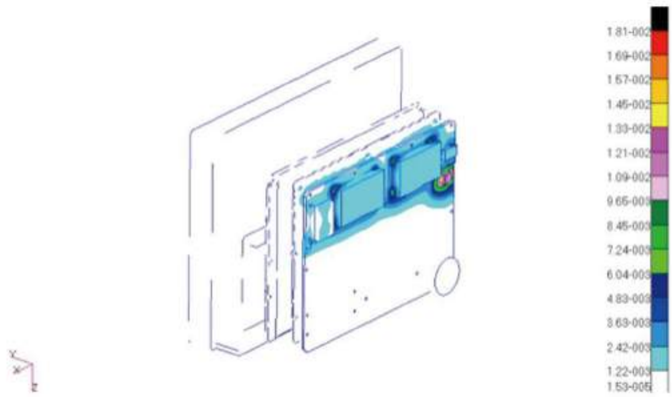


Figure 5.13 shows the temperature distribution of the electronic cabinet enclosure. The maximum temperature is 76.60 ℃, and the temperature of the rear cover plate is higher due to the influence of the power board, which exactly indicates the excellent heat dissipation effect of the rear cover plate. Figure 5.14 is the heat flux distribution of the enclosure. The maximum value is 0.0314W/mm2, which is also observed on the rear cover plate.

Figure 5.13 Temperature distribution of the enclosure

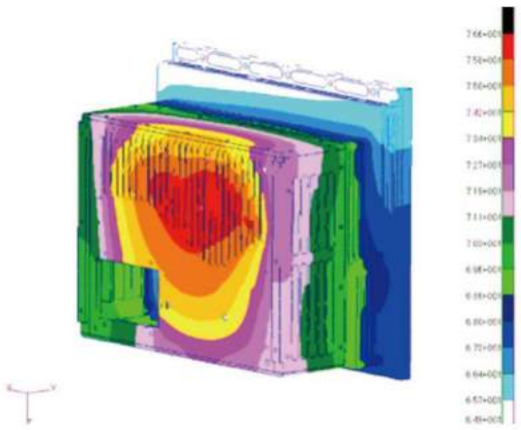
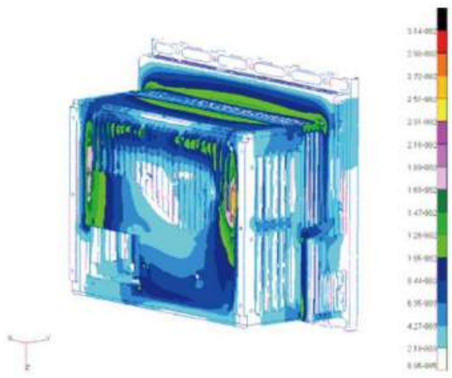


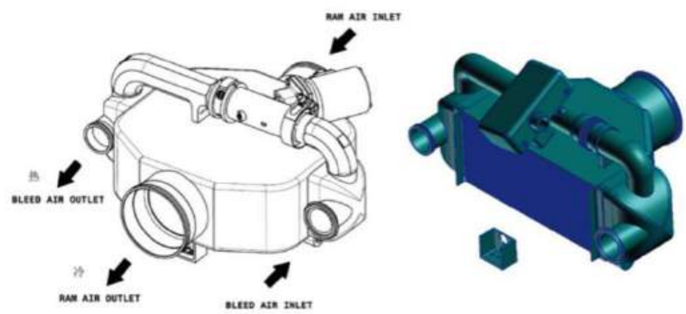
Figure 5.14 Heat flux distribution of the enclosure



5.5 Thermal Analysis of Radiator

5.5.1 Overview

Figure 5.15 Radiator structure



The structure of a radiator is shown in Figure 5.15. The material property parameters of the radiator core and fluid media are given in Table 5.2 and 5.3.

The working parameters of the radiator are given in Figure 5.4. The temperature of the bleed air inlet is constant at 225 ℃. The ram air inlet temperature curve is illustrated in Figure 5.16, in which the initial temperature is 55℃ from T3. The temperature field of the radiator varies, while this computation adopts transient thermal analysis.

Table 5.2 Thermo-physical properties of materials

Material	Coefficient of heat conduction (W/m K)	Specific heat (J/kg·K)	Density (kg/m³)	Coefficient of dynamic viscosity (Kg/m·sec)
Core	193	893	2730	/
Air	0.02622	1004.85	1.388	0.00001841

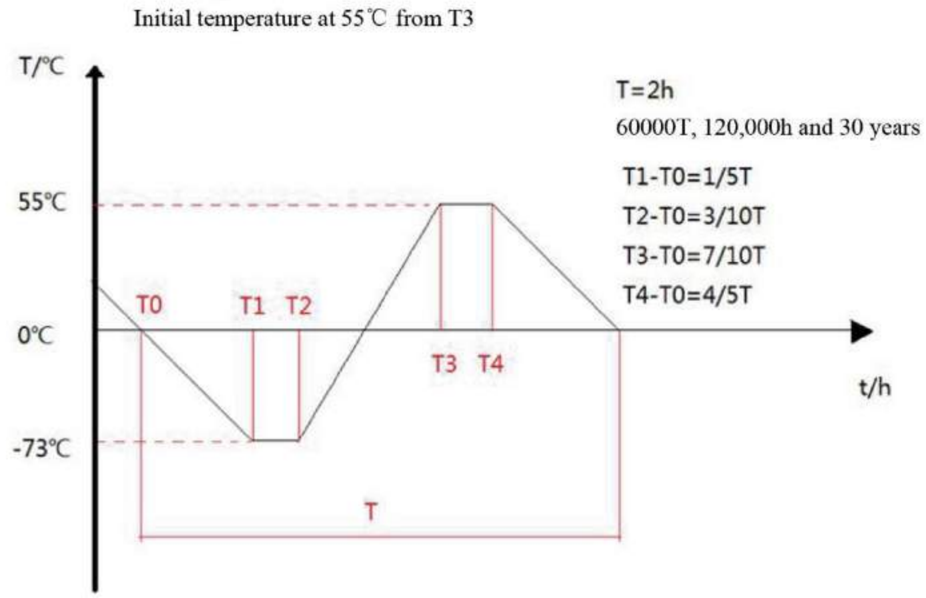
Table 5.3 Mechanical properties of materials

Material	Temperature ℃	Young's modulus (MPa)	Poisson's ratio	Thermal expansion coefficient (μm/m·K)	Yield strength (MPa)	Tensile strength (MPa)
Core	20	70000	0.33	24.1	57	110
	90	64197	0.33	24.1	52	94.5
	100	63368	0.33	24.1	51.6	93
	150	59315	0.33	24.1	48.3	83
	175	57350	0.33	24.1	46.7	74
	200	55263	0.33	24.1	45	69
	250	43328	0.33	24.1	35.2	54

Table 5.4 Working parameters of radiator

	Flow rate (Kg/s)	Inlet temperature (℃)	Outlet temperature (℃)	Pressure (Pa)	Convection coefficient (W/m2·℃)
Hot BLEED	0.0415	225	66	411600	162.16
Cold RAM	0.1284	55	83	101400	145.36

Figure 5.16 Cold inlet temperature curve

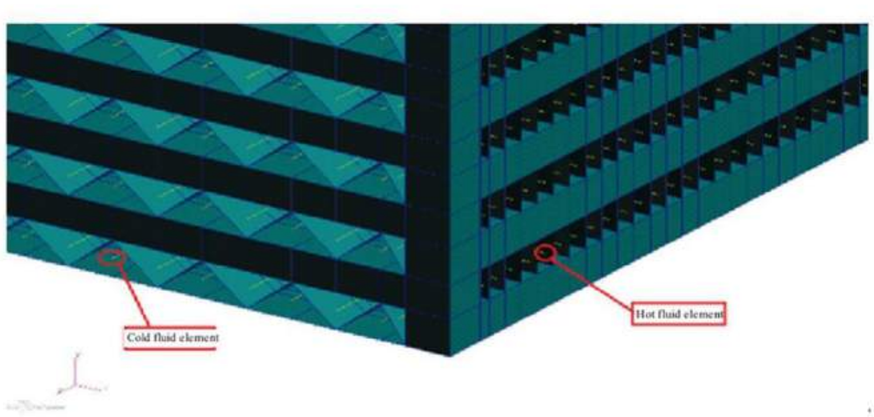


5.5.2 Finite Element Model

The finite element models of the radiator core structure and fluid media are shown in Figure 5.17 and 5.18, respectively. The finite element modeling of the core structure is based on 1/4 of the core structure according to its symmetry, with quadrilateral plate elements and hexahedron elements used. The fluid media is a 1D fluid element.

Figure 5.17 Finite element model of radiator core

Figure 5.18 Finite element model of radiator core fluid media



5.5.3 Thermal Analysis Boundary Conditions

Thermal analysis boundary conditions include the temperature of the bleed air inlet at 225℃ and bleed air outlet at 66℃, the temperature of ram air inlet at 55℃ and ram air outlet at 83℃, convective heat exchange between bleed air and fins, and convective heat exchange between ram air and fins.

Figure 5.19 Bleed air inlet and outlet temperature of the core

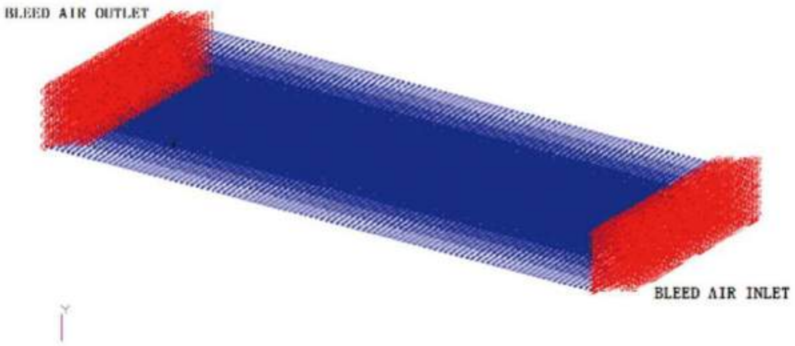
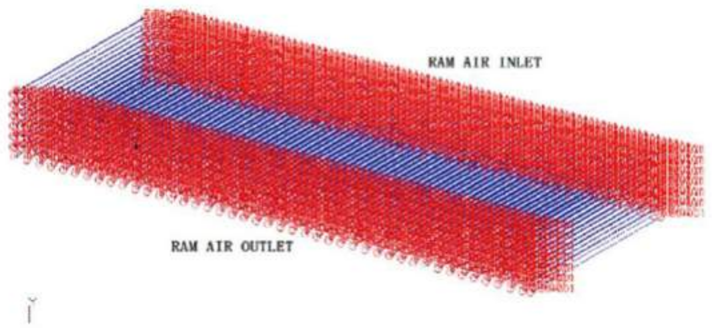


Figure 5.20 Ram air inlet and outlet temperature of the core



5.5.4 Stress Analysis Boundary Conditions

As shown in Figure 5.21, there are translational displacement constraints in the Y direction on the bottom surface, in the X direction at the seal position around the bleed air outlet, and in the Z direction at the seal and side plate positions around the ram air outlet. The load is subject to the temperature field and the bleed and ram air pressure.

Figure 5.21 Displacement constraint boundaries

5.5.5 Thermal Analysis Results

The temperature distribution of the radiator core is illustrated in Figure 5.22. The maximum temperature of the core is 176℃, and the temperature is relatively high in the areas adjacent to the bleed air inlet and ram air outlet of the core.

Figure 5.22 Temperature field distribution of the core

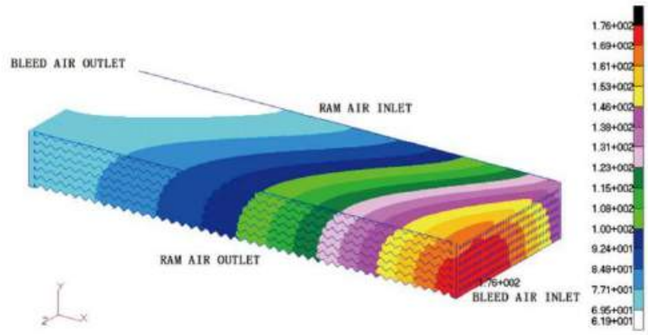


Figure 5.23 Bleed air temperature

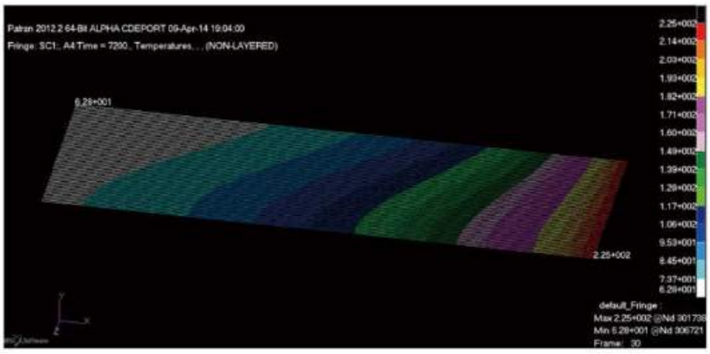
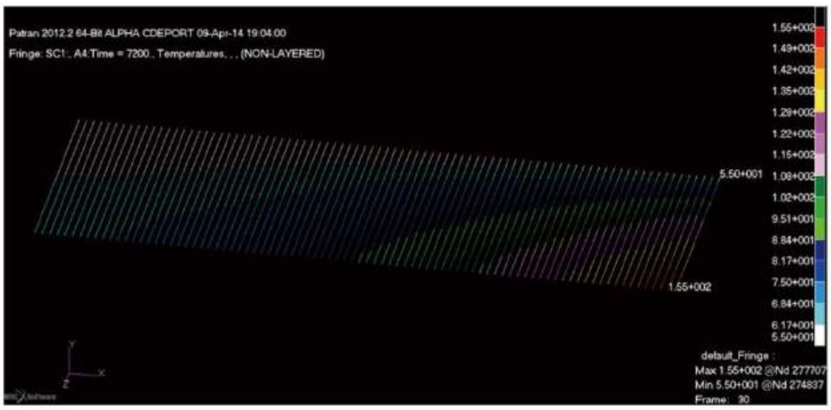


Figure 5.24 Ram air temperature



5.5.6 Stress Analysis Results

The temperatue distribution of the entire core is uneven during operation of the radiator, resulting in the production of uneven thermal deformation and generation of thermal stress. In this analysis, the stress of the core under thermal load and internal air pressure is computed. The thermal load is the temperature field computed in Section 5.5.5. The initial reference temperature is 20℃. The bleed air pressure is 411,600Pa, and the ram air pressure is 101,400Pa.

The maximum stress of the radiator core is 33.5MPa, and is observed at the bleed air inlet of the ram air seal, as shown in Figure 5.25.

Figure 5.25 Stress of bleed and ram air seals (Pa)

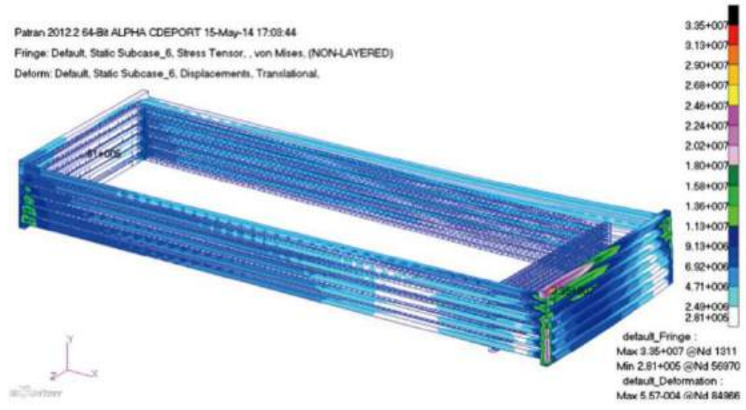


Figure 5.26 Stress of partition and side plates (Pa)

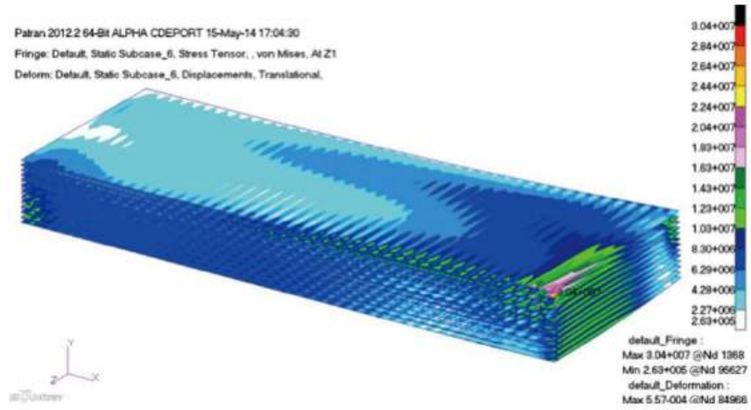


Figure 5.27 Stress of bleed air fins (Pa)

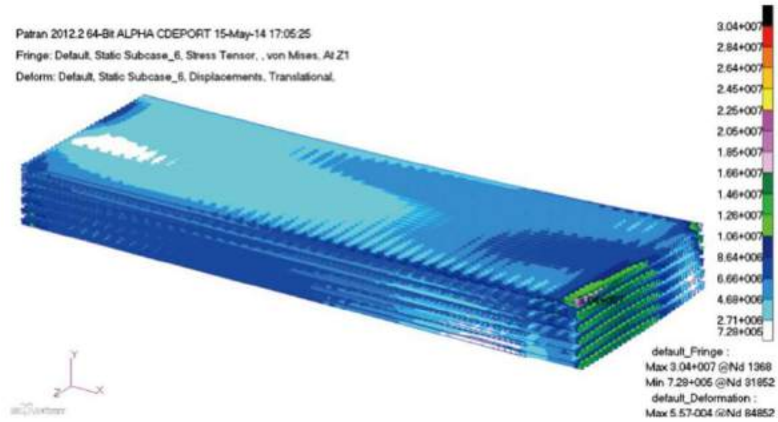
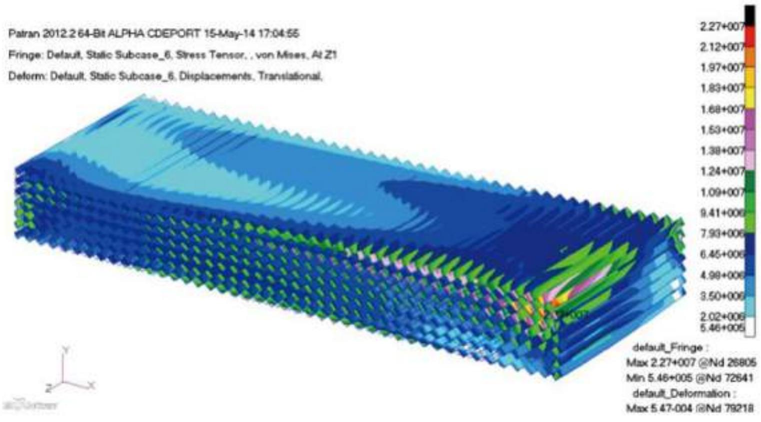


Figure 5.28 Stress of ram air fins (Pa)



CHAPTER 6

Product Life Design

CHAPTER 6
Product Life Design

Fatigue failure is one of the main causes for the failure of engineering structure and machinery. The peak of cyclic load causing the fatigue failure is usually much lower than the safe load estimated based on the static fracture analysis. Therefore, the research on fatigue has significant implication. As a branch of solid mechanics, fatigue research is focused on the strength of materials or structures under alternating loads and the relationship between the stress states and lives of the materials or structures.

6.1 Basic Concept of Fatigue

6.1.1 Definition

A material or structure would be damaged under the action of a load changing repeatedly, even if the stress does not exceed the ultimate strength of the material, or is lower than its elastic limit. The damage of material or structure occurring in the presence of repeated alternating loads is called fatigue failure.

The failure of engineering structures and components is mainly caused by fatigue and fracture. What is fatigue? As stated by ASTM in the Definitions of Terms Relating to Fatigue Testing and the Statistical Analysis of Fatigue Data (AASTM E206-72), the definition of fatigue is as follows: "The process of progressive localized permanent structural change occurring in a material subject to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations."

The typical alternating loads on all machines and equipment are collectively called fatigue load, and the stress is called alternating stress or fatigue stress, correspondingly. The progressive change of the alternating load with time is called load spectrum which may be irregular, disordered or may show some regularity. The loads with periodic alternating feature are called cyclic loads. It is deducible that every single cycle is composed of a complete fluctuation cycle of load and corresponding stress.

6.1.2 Classification

Fatigue can be classified on different bases. According to objects of study, fatigues consist of material fatigue and structural fatigue. The material fatigue research is characterized by testing standard specimens to research failure mechanism, effects of chemical composition and microstructure on fatigue strength of materials, fatigue test method and data processing method of standard specimens, basic fatigue properties of materials, effects of environment and working conditions, macro- and micro-appearance of fatigue fracture.In the structural fatigue research, parts, connectors and even the complete machines are studied for their fatigue performances, anti-fatigue design methods, life estimation methods and fatigue test methods, impacts of shapes, sizes and process factors; and methods for improving their fatigue strengths.

Fatigues can be divided into high-cycle fatigue and low-cycle fatigue according to number of fatigue cycles (i.e., life) experienced by the material before fatigue failure. The high-cycle fatigue means that more than $1'10^5$~$1'10^7$ cycles (N_f) are needed before final rupture of the material which is under an alternating stress far lower than the yield limit of the material (or as low as one third of the yield limit). Stress-Life (S-N) Curve is usually used to represent the fatigue properties of the material. The low-cycle fatigue is a term used to designate the situation that less than $1'10^4$~$1'10^5$ cycles are required before final rupture of the material which is under an alternating stress approaching or exceeding the yield limit of the material. The high-cycle fatigue mainly differs from the low-cycle fatigue in plastic strains. The high-cycle fatigue is normally caused by a relatively low stress and material is elastic, so the stress is proportional to the strain. Conversely, when the low-cycle fatigue occurs, the material usually undergoes a large plastic deformation under a stress exceeding its elastic limit, so the stress is disproportional to the strain. Generally, the fatigue refers to high-cycle fatigue because it is the most common form of fatigue for various machines.

According to stress states, fatigues can be divided into uniaxial fatigue and multi-axial fatigue.The uniaxial fatigue refers to fatigue under the action of a unidirectional cyclic stress, and parts are only subject to unidirectional normal stress or unidirectional shearing stress in that case. For example, the parts are only subject to unidirectional tensile-compressive cyclic stress, bending cyclic stress or torsional cyclic stress. The multi-axial fatigue refers to fatigue under the action of multiaxial stresses, and is also known as combined fatigue, including combined bending-torsional fatigue, biaxial tensile fatigue and triaxial stress fatigue.

According to amplitude and frequency of load, fatigues can be divided into constant-amplitude fatigue, variable-amplitude fatigue and random fatigue. The constant-amplitude fatigue is under an alternating stress with constant amplitude and frequency. The variable-amplitude fatigue means that the alternating stress changes in amplitude rather than frequency. The random fatigue means that the stress randomly changes in both amplitude and frequency.

According to load cases and working environment, fatigues can be divided into conventional fatigue, high- and low-temperature fatigues, mechanical fatigue, thermal fatigue, thermal-mechanical fatigue, corrosion fatigue, contact fatigue, fretting wear fatigue and impact fatigue:

◆the fatigues occurred at room temperature and in air medium are called conventional fatigues;

◆the fatigues occurred at a temperature lower/higher than the room temperature are called low-temperature fatigues/high-temperature fatigues;

◆the fatigues only attributable to the alternating stress or strain fluctuation are called mechanical fatigues;

◆the fatigues generated by thermal stress due to cyclic temperature variation are called thermal fatigues

◆the fatigues resulting from the combined actions of temperature cycle and strain cycle are called thermal-mechanical fatigues;

◆the fatigues caused by cyclic alternating stress in corrosion environment are called corrosion fatigues, and further consist of gas-phase fatigues and aqueous medium fatigues;

◆the fatigues caused by repeated load actions in combination with the sliding and rolling contacts among materials are called contact fatigues;

◆the fatigues occurred in the presence of wear and fatigue caused by the micro relative vibrations between contact surfaces are called fretting wear fatigues; and

◆the fatigues resulting from the repeated impact loads are called impact fatigues.

Most failures of the machinery or structural components occur in case of one of the above mentioned fatigues.

6.1.3 Fatigue Strength, Fatigue Limit and Fatigue Life

Fatigue performances of materials or components are measured in terms of fatigue strength, i.e., strengths of the materials or components under the action of alternating loads.

The fatigue strength is further measured in terms of fatigue limit. The fatigue limit, generally expressed by S_r, is defined as the maximum stress S_{max} at which the fatigue failure never occurs to a material or component with a cyclical characteristic R. As the fatigue limits of materials vary with the loading methods and stress ratios, the fatigue limit under symmetrical cyclic load is regarded as the basic fatigue limit of a material in most cases.

The fatigue life is defined as the number of stress (strain) cycles of a material undergoing before failure occurs, and normally expressed by N. The fatigue life of a specimen depends on the mechanical capacity of the material and the applied stress. In general, the higher the ultimate strength of the material, the lower the applied stress, and the longer the fatigue life of the specimen will last; otherwise, the shorter the fatigue life of the specimen will last. The curve describing the relationship between the applied stress and the fatigue life of the standard specimen is called material S-N curve.

6.2 Fatigue Design Method

Fatigue design is a basic way to handle dynamic stress and resulting failure mode. For aviation architectures or mechanical products, a reasonable fatigue design is important and necessary for improving the design level and product quality.

As the fatigue failure is one of the most frequent destructions of modern industrial equipment, fatigue strength must be included in the design of all engineering components and aviation architectures in addition to the necessary static strength. That is, these architectures must be subject to fatigue analysis and designed in point of fatigue.

6.2.1 Infinite Life Design

The infinite life design is the earliest fatigue design method that brings the design stresses of parts and components below their fatigue limits to allow these parts and components to have infinite life. Infinite life design is still a simple and reasonable method for engineering parts and components undergoing infinite cycles (>10^7 cycles), including cylinder valves, push rods, springs and long-running axles of engines.

However, the components designed with the method are often heavy and bulky. With the development of the modern industry, especially aviation industry, aircrafts are designed to have high speed, high performance and low weight. To make full use of the potential bearing capacities of materials, the design stress level is increasing, and the fatigue design method is improved to match with the finite life design process.

6.2.2 Safe Life Design

The safe life design derived from the infinite life design method belongs to the finite life design and is also based on the S-N curve obtained from tests. The safe life design method only guarantees the safe use of parts and components within the specified service life. Therefore, the method allows these parts and components to work under a stress exceeding their fatigue limit to reduce their dead load. The method takes up a leading status in the design of many mechanical products. The method is widely used in the design of products with strict requirements for dead load, including aircraft engines and automobiles.

Safety factor must be considered in the safe life design to take the influence of fatigue data dispersibility and other unknown factors into consideration. The safety factor can be set for the stress, life or both in a design. The safe life can be designed according to the S-N curve or e-N curve. The former is called nominal stress finite life design, and the latter is local stress-strain method.

6.2.3 Fail-Safe Design

Higher safety and reliability of the fatigue design is expected with the unprecedented development of modern industry, especially in the fields of aircrafts, rockets, ships and vehicles, as well as from a historical perspective the record number of accidents caused by fatigue failures since the World War II. The fail-safe design method is newly developed against the background.

The essence of the fail-safe design method is to allow generation and growth of fatigue cracks on structures within the specified service life, providing that the residual intensity exceeds the load limit. Further, fracture control measures should be taken in the design to prevent structural failure before the detected cracks are repaired, including multi-channel design and rip-stop doublers. Leak before break (LBB) in pressure vessel design is an embodiment of the design criteria.

6.2.4 Damage Tolerance Design

The damage tolerance design presents and improves the fail-safe design method. The design assumes that the parts and components have initial cracks, and the fracture mechanics is adopted to estimate their residual lives which are checked through tests to avoid failures caused by crack growth during their service lives, so that the parts and components with cracks can be safely used during their service lives. The design is applicable to materials with slow crack propagation and high fracture toughness.

6.3 Major Factors Affecting Fatigue Strength

The S-N curves and fatigue limits of materials only represent the fatigue performances of the standard smooth specimens. The actual parts varying in size, shape and surface condition are quite different from the standard specimens. Fatigue strengths of mechanical parts depend on size, shape, surface condition, mean stress, combined stress, corrosive medium and temperature and other factors. This chapter mainly discusses the effects of stress concentration, size, surface finishing and other factors on fatigue strength.

6.3.1 Effect of Stress Concentration

To fulfill structural requirements, mechanical parts are inevitably configured with grooves, shaft shoulders, holes, corners, notches or other discontinuous sections, resulting in sudden changes in cross sectional shapes, and the phenomenon that local stress is far beyond the nominal stress due to discontinuity of geometries of parts or components is called "stress concentration".

Under the considerable and main impact of the stress concentration, fatigue strengths of parts and components are significantly decreased. The fatigue strength-decreasing effect of stress concentration can be represented by fatigue notch factor. The fatigue notch factor K_f is the ratio of fatigue limit S_{-1} of smooth specimen to the fatigue limit S_{-1k} of notch specimen with the same net sectional size and finishing method, i.e.:

$$K_f = \frac{S_{-1}}{S_{-1k}}$$

The fatigue notch factor mainly depends on theoretical stress concentration factor K_t and is affected by the material properties as well as notch form, radius and depth. The K_t has a far more effect than other factors. Apparently, fatigue test is the most direct and reliable way to determine K_f, and it is expensive and time-consuming. The test reveals the association between K_f and specimen size. The K_f obtained from a specimen cannot be directly applied to other specimens of the same material but different in size. In addition, K_f cannot be directly obtained by tests due to the stress concentration sensitivity varying with materials.

6.3.2 Size Effect

The fatigue strengths of specimens and parts are also affected by their sizes. In general, fatigue strengths decrease with increasing sizes of parts and specimens. The phenomenon that the fatigue strength decreases with the increase of part size is called fatigue size effect (also known as size effect).

The size effect on fatigue strength is mainly due to the following three reasons:

(a) Mechanical properties (including fatigue performance) of materials decrease with their increasing cross sections. The phenomenon is even more obvious for alloy steel having high strength. The phenomenon is apparently related to metallurgical processes, hot working processes and metallographic structures of materials and determined by the inherent natures of the materials, and has nothing to do with structures, loads and cold working processes of parts.

(b) Stress gradients of parts are the main cause of size effect. If specimens with different sizes under the same stress conditions have equal peak stress at dangerous points, large components have low fatigue strengths due to small stress gradients, and small specimens have high fatigue strengths due to great stress gradients.

(c) For specimens taken from the same blank and different in size and cross section, the fatigue strengths of large specimens are lower than those of small specimens. The decrease in fatigue strengths of large specimens can be attributed to highly potential crack initiation due to more sources of fatigue damage in large specimens.

The size effect is represented by size factor e, which is defined as the ratio of the fatigue limit S_{-1d} of a specimen or part in size d to the fatigue limit S_{-1} of a geometrically similar specimen in standard size subject to the same stress concentration and processing method, i.e.:

$$e = \frac{S_{-1d}}{S_{-1}}$$

The size factor is less than 1 and is designated in the design manual.

6.3.3 Effect of Surface Condition

Most of fatigue cracks initiate from surfaces of specimens because the outside surfaces are most commonly exposed to stresses. In addition, the materials at surface layers are less constrained and slip bands are the most easily to be opened. Therefore, surface conditions of parts and components have significant influences on their fatigue strengths, and the influence is represented by surface sensitivity coefficient, i.e.:

$$b = \frac{\text{Fatigue strength of a finished specimen}}{\text{Fatigue strength of standard smooth specimen}}$$

Fatigue strengths or fatigue lives of materials are normally obtained from standard smooth specimens. When estimating the fatigue strengths or fatigue lives of parts and components based on these resulting data, the surface sensitivity coefficient shall be corrected. As most of the critical fatigue nodes in structures or machinery are the stress concentrated nodes, the surface sensitivity coefficient shall be corrected according to the surface conditions.

The surface conditions mainly include surface roughness b_1, surface microstructure b_2 and surface stress state b_3, and

$$b = b_1 b_2 b_3$$

a) Surface roughness b_1

A large number of tests show that surface roughness has a great influence on fatigue strength, because surface defects of the finished surface of parts and components bring about stress concentration. Particularly, any small defect on the surface of high-strength materials would become a dangerous sharp notch and result in stress concentration. The node of stress concentration often forms a fatigue source that generates cracks under the action of alternating stress. These cracks will grow continuously and greatly reduce the fatigue strength. In most cases, the fatigue strength increases with the decrease of surface roughness. On the micromechanical level, surface roughness indicates intrusions and extrusions on the surface that shorten the fatigue crack initiation life and reduce the fatigue strength. On the macro level, the surface roughness leads to microscopic stress concentration and decreases the fatigue strength.

b) Surface microstructure b_2

Fatigue strengths of parts are significantly affected by surface layers of these parts. Therefore, multiple surface treatment technologies are taken to increase the surface fatigue strength, mainly including surface carburization, nitriding, cyanidation, surface hardening and laser surface treatment. These treatment methods essentially change microstructure of the surface layer. Generally, the fatigue strength is improved (b_2 is greater than 1) with these methods to increase the fatigue strength of parts. The b_2 is completely defined by test. However, b_2 varies with process parameters.

c) Surface stress state b_3

As one of the effective ways improving fatigue strengths of parts, surface cold deformation is mainly realized by rolling, shot peening and extrusion. The surface cold deformation essentially changes stress states of surface layers of parts and physically changes the surface microstructure.

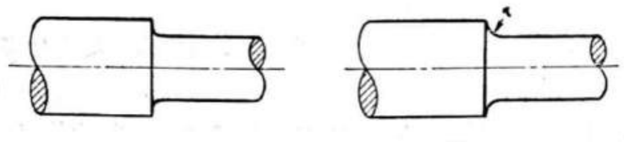
6.4 Measures for Increasing Fatigue Strengths of Components

Fatigue failure is caused by crack growth, and cracks are mainly initiated at stress concentration sites and on surfaces of components. In order to improve the fatigue strength, it is necessary to decrease the stress concentration and improve the surface finish.

6.4.1 Decrease in Stress Concentration

The stress concentration is the main cause of fatigue failure. To improve the fatigue strength of components, the stress concentration should be minimized or eliminated. If possible, the components should be designed without any square or sharp-angled openings and grooves. Transition fillet with sufficient radius shall be configured to any site with a sudden change in section size (e.g. shaft shoulder of a stepped shaft) to reduce stress concentration. For example, comparing two cases in Figure 6-1, the stress concentration of the stepped shaft with a larger transition fillet radius r is much lower than the other one. The stress concentration decreases dramatically with the increase of r.

Figure 6-1 Transition fillet



In case it is difficult to structurally increase the transition fillet radius, partial large-diameter shaft can be configured with unloading groove (Figure 6-2) or relief groove (Figure 6-3) to significantly reduce stress concentration.

Figure 6-2 Unloading groove

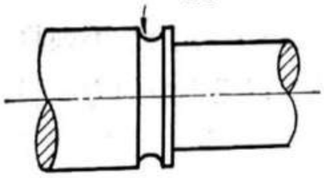
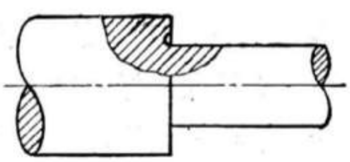


Figure 6-3 Relief groove



Apparently, stress is concentrated at the edge of the fitting surface of the hub and shaft in tight fit. The stress concentration at the edge of the fitting surface can be reduced if an unloading groove is formed in the hub and the mating portion of the shaft is thickened (Figure 6-4) to reduce stiffness difference between the hub and the shaft. The stress concentration of a fillet weld subject to groove welding as shown in Figure 6-5 (a) is much less severe than that of the one without groove welding (Figure 6-5 (b))

Figure 6-4 Stiffness matching

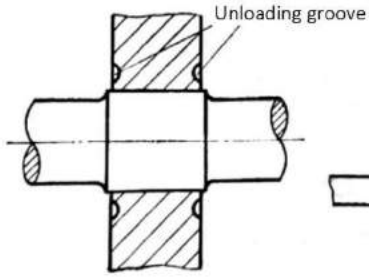
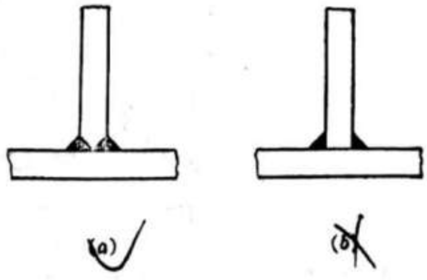


Figure 6-5 Groove welding



6.4.2 Improvement of Surface Finish

Surface layers of components are generally under large stresses. For example, when a component is bent or twisted, its surface is under the maximum stress. Further, stress concentration caused by tool marks or damages on the surface easily induces fatigue cracks. Therefore, surface finish has a great influence on the fatigue strength of components, and the components requiring high fatigue strengths should have good surface finish. High-strength steel is particularly sensitive to surface finish, and its high strength property can only be maximized by fine finishing. Otherwise, the fatigue limit will be greatly reduced, and the use of high-strength steel will be less rewarding. Mechanical damages (e.g., scratch and impact abrasion) or chemical damages (e.g., corrosion and rusting) to surfaces of components should also be minimized during the use of these components.

6.4.3 Increase of Surface Strength

Surface layers of components can be strengthened with heat treatment or chemical treatment methods, including high-frequency quenching, carburization and nitridation of surfaces, by significantly improving their fatigue strengths. These methods should be used under a strictly controlled process to avoid microcracks on the surfaces which will reduce the fatigue limit. Mechanical methods can also be used to strengthen the surface layer, such as rolling, shot peening, etc., so that a layer of pre-compressive stress can be formed on the surfaces of components to reduce tensile stresses which will easily generate surface cracks, and to improve the fatigue strength.

6.5 Examples of Wheel Fatigue Life Design

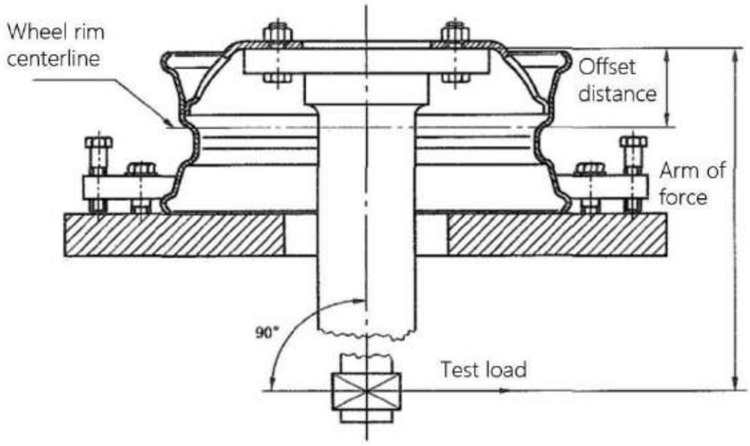
Wheels are important safety components in automobile driving systems. Driving forces of automobiles are transmitted through wheels. Therefore, the structural performance of these wheels has an important effect on the safety and reliability of the entire automobiles. In order to meet strength and fatigue requirements, Performance Requirements and Test Methods of Commercial Vehicles Wheels (GB/T 5909-2009) stipulates that commercial vehicle wheels must be subject to bend tests and radial rolling fatigue tests. A 22.5×9 commercial vehicle wheel is taken as an example here for the fatigue life analysis, through which the fatigue life of wheel products is designed.

6.5.1 Simulation Analysis of Bending Fatigue

6.5.1.1 Problem description

The wheel rim is firmly clamped to the test fixture, as shown in Figure 6-6. The connection surfaces of the testing machine shall have the same mounting dimension characteristics as the connectors commonly used in vehicles. The connection surfaces of the test bench and the mounting surfaces of the wheels shall be free from scratches and abrasions, and paint sagging, dust or foreign matters shall be removed. The loading arm and the connector are reliably connected with the wheel mounting surface with non-lubricated studs or nuts under the mounting conditions equivalent to the actual working conditions when they are installed on the vehicle. Before the test starts, wheels are mounted and fixed according to the torque specified by the vehicle or wheel manufacturer. The wheel bolts or nuts probably need to be tightened again during the test.

Figure 6-6 Diagram of dynamically repeated bend test with load



The standard specifies that the test load (bending moment) is determined by the following equation:

$$M = (nR + \mathrm{d})F_v S$$

Where,

M: the bending moment in N.m;

m : a preset friction coefficient between the tire and pavement;

R: the static loaded radius (m) of the maximum tire provided for the wheel as specified by the vehicle or wheel manufacturer;

d: the inner offset distance (positive value, m) or outer offset distance (negative value, m). If both the inner offset and the outer offset distances are applicable to the wheels, the inner offset distance should be adopted.

Fv: the rated wheel load (N) as specified by the vehicle or wheel manufacturer; and

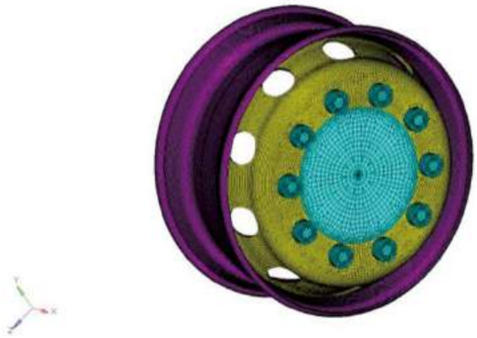
S: the intensified test coefficient.

As specified in the standard, if the inner offset distance or outer offset distance of steel wheels is greater than 101.6mm, the corresponding friction coefficient is 0.7, the intensified test coefficient is 1.1, and the minimum number of cycles is 300,000.

6.5.1.2 Finite element model

The wheel model for bending fatigue analysis consists of four parts: spokes, rim, hub and bolts. Since the spokes are designed to be variable in thickness and the contact and application of bolt pre-tightening force should be considered, hexahedral finite elements are adopted for meshing. The overall mesh sizes are 3.5mm to ensure consistency of all meshes, and 4 layers of meshes are configured along the thickness direction. There are 350,706 final elements and 437,659 nodes in all. The mesh model for wheel bending fatigue analysis is shown in Figure 6-7.

Figure 6-7 Finite element model for bending fatigue analysis



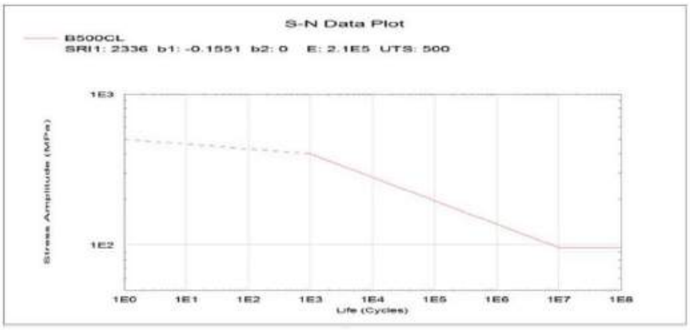
The spokes and rim are made of B500CL, and mechanical parameters of the material are shown in Table 6-1.

Table 6-1 Mechanical parameters of the material

Material	Modulus of elasticity/GPa	Poisson's ratio	Density/(kg/m^3)	Yield strength/MPa	Tensile strength/MPa
B500CL	210	0.3	7850	345	500

The S-N curve of B500CL is shown in Figure 6-8.

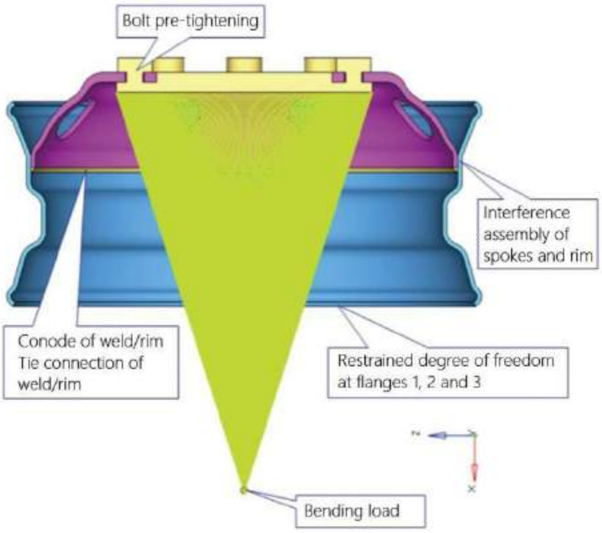
Figure 6-8 S-N curve of B500CL



6.5.1.3 Loads and constraints

As shown in Figure 6-9 below, the translational degrees of freedom in X, Y and Z directions of the wheel flange are restrained. The main influencing factors in the bending test process are bolt pre-tightening force and bending load. Analysis reveals that the effect of centrifugal force is negligible.

Figure 6-9 Diagram of boundary conditions for bending fatigue analysis



a). Bolt pre-tightening force: The nut torque applied in the test is 610N.m, so the bolt pre-tightening force should be 1.4E5 N according to related computing method of the mechanical design principle.

b). Bending load: The load is 22,569N.m. As orientation of force action changes constantly throughout the test, the bending load can be decomposed into $M_y = M \times \sin(\omega t)$ and $M_z = M \times \cos(\omega t)$.

$$
\begin{aligned}
M &= (\mu R + d) \times F_V \times S \\
&= (0.516 \times 0.7 + 0.1622) \times 4000 \times 1.1 \times 9.8 \\
&= 22569 \quad N.m
\end{aligned}
$$

6.5.1.4 Stress response analysis

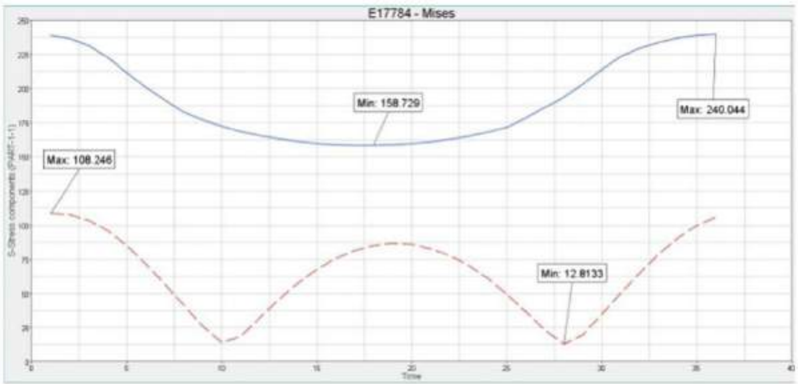
When the wheel is subject to a bending torsional force, the stress nephogram of the wheel at a given moment is shown in Figure 6-10.

Figure 6-10 Stress nephogram of wheel under bending load

As shown in the nephogram, the bolt holes undergo the maximum stress in the presence of bending load and bolt pre-tightening load, and the peak stress is 242MPa, followed by 108MPa at the air vent.

A cycle is one rotation of the loading shaft. A cycle is divided into 36 steps for analysis presented herein. The changes of stress at the bolt holes and air vent are as shown in Figure 6-11.

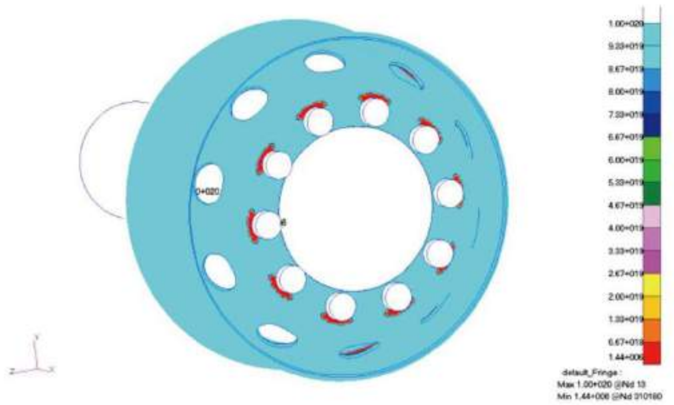
Figure 6-11 Diagram of stress response at bolt holes and air vent



6.5.1.5 Fatigue life analysis

Fatigue life nephogram of the wheel can be obtained by computation on the basis of the material S-N curve in the presence of the bending load cycle, as shown in Figure 6-12.

Figure 6-12 Bending fatigue life nephogram of wheel



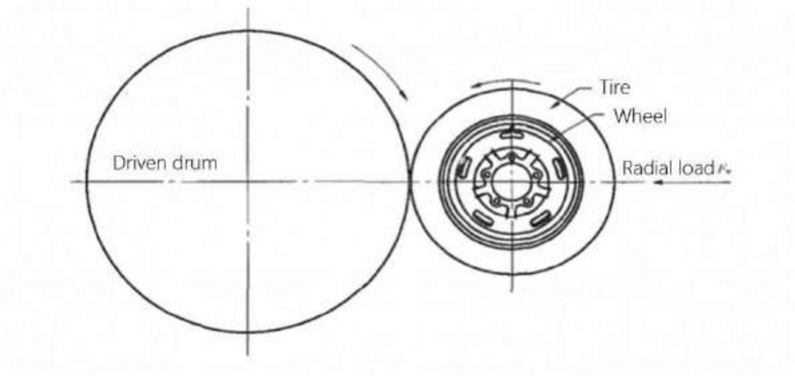
As shown in the fatigue life nephogram, under the cyclic bending load, the dangerous point is located at the bolt hole of the wheel with a minimum fatigue life of 1.44 million times, followed by the air vent with a fatigue life of 5.77 million times. Both of their lives exceed the minimum cycles of 300,000 times and meet the fatigue life design requirements of the wheel.

6.5.2 Radial rolling fatigue analysis

6.5.2.1 Problem description

A device should be mounted on the testing machine to apply a constant radial load when the wheel rotates in the radial rolling fatigue test, as shown in Figure 6-13. The machine should be provided with a driven rotatable drum with a smooth surface wider than the section of bearing test tire. The recommended minimum outer diameter of the drum is 1700mm. The wheel (single wheel) and tire test device shall keep the loading direction perpendicular to the outer surface of the drum and is radially aligned with the center line of the test wheel and drum. The drum and the test wheel shall be axially parallel.

Figure 6-13 Diagram of radial rolling fatigue test



As stipulated in the standard, radial rolling load Fr is determined by the following equation:

$$Fr=FvK$$

Where,

Fr: radial load (N);

Fv: rated load (N) of wheel, as specified by the vehicle or wheel manufacturer; and

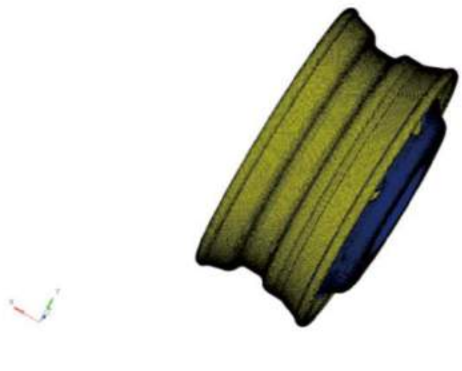
K: intensified test coefficient.

According to relevant standards, the intensified test coefficient for the steel wheel analyzed herein is 2.0, and the minimum number of cycles is 500,000.

6.5.2.2 Finite element model

In order to simplify computation, the radial rolling fatigue analysis model of wheel only consists of the spokes and rim, and the effect of tire is ignored. Since the spokes are designed to be variable in thickness, hexahedral finite elements are adopted for meshing. The overall meshes are 4mm sized to ensure consistency of all meshes, and 4 layers of meshes are configured along the thickness direction. There are 352,928 final elements and 446,197 nodes in all. The mesh model for radial rolling fatigue analysis of wheel is shown in Figure 6-14.

Figure 6-14 Finite element model diagram for radial rolling fatigue analysis of wheel



6.5.2.3 Loads and constraints

The translational degrees of freedom in X, Y and Z directions of the bolt holes on spokes are restrained. The main influencing factors in the radial rolling fatigue test are tire inflation pressure and radial rolling load. The analysis reveals that the effect of centrifugal force is negligible.

a) Tire inflation pressure: The pressure is 1MPa throughout the test.

b) Radial rolling load: According to findings of John C.Stearns, Ph.D., University of Akron, stress distribution of rim is approximate to the cosine function distribution when the wheel undergoes radial rolling load. The affected angle ɵ0 of the load ranges from 0° to 40°, and the angle is set to 36° herein.

6.5.2.4 Stress response analysis

Stress condition of the rim is focused on because it is the most vulnerable part in the radial rolling fatigue test of the wheel. When the wheel undergoes tire pressure and radial rolling load, stress nephogram and displacement nephogram of the rim at a given moment are shown in Figures 6-15 and 6-16, respectively.

Figure 6-15 Rim stress nephogram

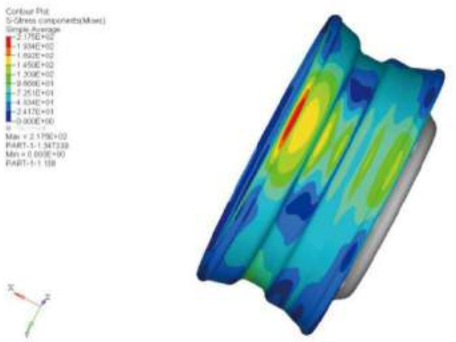
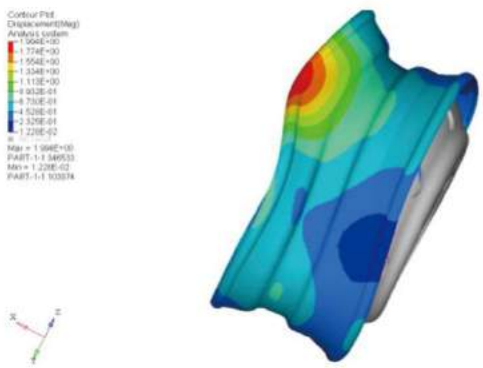


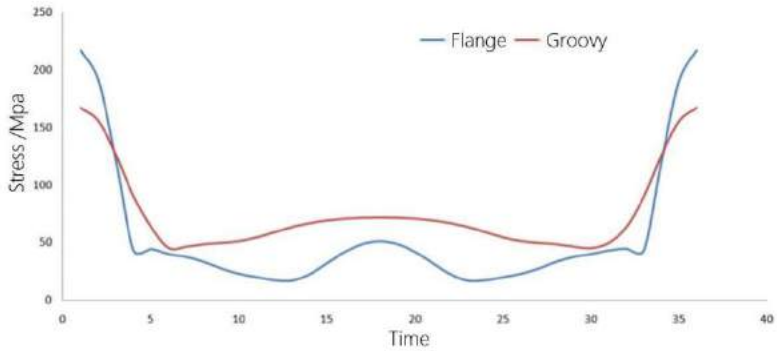
Figure 6-16 Rim displacement nephogram



According to these nephograms, the maximum stress of the rim is located at the flange with a stress value of 217.4MPa, followed by the groove R corner with a maximum stress of 167.4MPa, and amount of deflection of the rim is 1.994mm.

A cycle is one rotation of the wheel. A cycle is divided into 36 steps in the analysis. The stress changes at the flange and groove are shown in Figure 6-17.

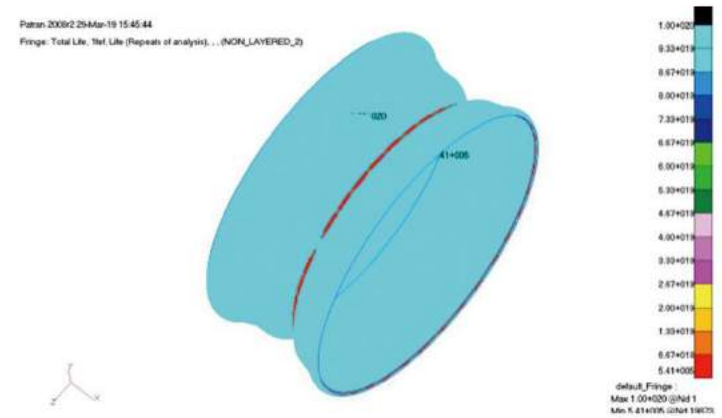
Figure 6-17 Diagram of stress responses of flange and groove under radial rolling load



6.5.2.5 Fatigue life nephogram

The fatigue life nephogram of the wheel rim can be obtained by computation on the basis of the material S-N curve in the presence of the radial rolling load cycle, as shown in Figure 6-18.

Figure 6-18 Radial rolling fatigue life nephogram of the wheel



As shown in Figure 6-18, under the cyclic radial rolling load, the dangerous point of the wheel is located at the flange of the rim with a minimum fatigue life of 541,000 times, which is followed by the groove R with a life of 825,000 times. Both of their lives exceed the minimum cycles of 500,000 times and meet the fatigue life design requirements of the wheel.

CHAPTER 7

Working Out the Optimum Product Design Scheme with Optimization Technology

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7.1 Optimization Problem in Product Design

To meet requirements for performance and function in structural designs of products, design engineers should configure reasonable structures to meet the required properties and functions as well as conditions in terms of strength, vibration, heat dissipation, electromagnetic field and fatigue life of the products in use. As outlined in the previous chapters, we can verify whether the design products meet required conditions by using CAE simulation software and modify designs accordingly. However, a qualified design engineer should not only design the product according to the known function and performance requirements, but also consider its market competitiveness. That is, we need to design competitive products that are among the most popular ones in the market. What variables can be improved: performance, function, cost or appearance? If the product you designed has not been top of the market, you must investigate the best one and design a product superior to it. When your product is already the best offering in the market, you should seek to design beyond yourself. In brief, product design is a process of constantly transcending and searching for the optimum design.

Mathematically, we call this process optimization. We can discuss a practical issue as follows:

Case 1: optimization design of round-bottomed cup

Assume that you are required to design a 300ml water cup with circular top and bottom in the same diameter. How to determine the height h and diameter d of the cup to meet these requirements with minimum materials?

Design parameters: Height h and diameter d of the cup.

Design objective: minimum area S of the cup material: $\min S = h*\pi d + \pi*(d/2)^2$

(Circumference = $2\pi r$ r is radius of the circle)

(Area of the circle = πr^2)

Constraint: Cylinder volume = 300ml, i.e., $V=\pi r^2 h$ ($r>0$, $h>0$)

According to Lagrange multiplier method:

$F(r,h,m)= 2\pi rh+\pi r^2-m(\pi r^2 h-300)$

The partial derivatives of these three variables r, h and m are solved to be 0 respectively, to obtain the following three equations:

$2\pi h+2\pi r-2\pi mhr=0$

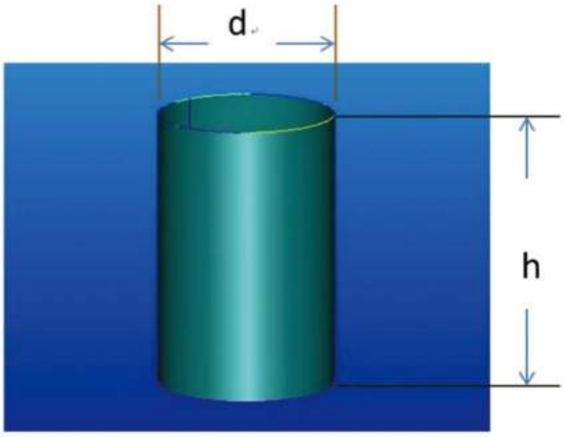
$2\pi r-\pi m r^2=0$

$\pi r^2 h-300=0$

$r = h = 4.57...$

That is, the size for the most material-saving water cup with a capacity of 300ml should be designed as: $r = h = 4.57...$

Figure 7.1 Design of cylinder cup



7.2 Development History of Optimization Design

The earliest recorded optimization issue can be traced back to Euclid, an ancient Greek mathematician (around 300 BC). He pointed out that among all rectangles with the same perimeter, the one with the largest area is a square. The establishment of calculus in the 17th and 18th centuries provided some criteria for finding the extrema of functions as well as some theoretical basis for optimization. However, the development of optimization technology slowed down in the following two centuries.

In the 17th century, Newton & Leibniz raised the issue of extremum for function, and then the Lagrange multiplier method was developed.

In 1847, Cauchy studied the direction in which the function value decreased at the most rapid speed and proposed the steepest descent method.

In 1939, the Soviet mathematicians proposed the solutions for the linear programming problems of cutting stock and transportation.

In 1947, Dantzig proposed the simplex method to solve the linear programming problem, and the method is called "one of the greatest creations in the 20th century".

In 1948, Fritz John proposed the optimality conditions.

In 1951, Kuhn and Tucher proposed the optimality conditions and did the groundwork for non-linear programming.

In the early 1940s, the operational research was born out of military necessity, and the optimization techniques were firstly used to solve practical problems in war, including the design of optimal diving trajectory of bombers.

At the end of the 1950s, mathematical programming approach was firstly adopted for structural optimization and became the theoretical basis of optimization methods in the optimization design. The mathematical programming approach is a new branch of mathematics developed during World War II, and is mainly composed of linear programming and non-linear programming.

The optimization theory and algorithm have been developed rapidly and applied to more and more aspects in recent decades, and have become a vast field of study. In a narrow sense, the optimization mainly refers to contents related to the non-linear programming problems; and in a broad sense, it covers linear programming, non-linear programming, dynamic programming, integer programming, geometric programming, multi-objective programming, stochastic programming, and even variation and optimal control.

Modern optimization design is developed on the basis of the mathematical programming approach, which is an effective design method gradually formed after the introduction of electronic computers into the field of structural design in the early 1960s. The application of this method can consumedly shorten the design cycle and improve the computational accuracy, and further solve the complex optimization design problems for which the traditional design methods are ineffective. With the emergence of mainframe computers, the optimization method and relevant theory develop vigorously into an important branch of the applied mathematics, and are applied in various fields regarding science and technology.

During the last two decades, the optimization design method has been applied to architectural structure, chemical industry, metallurgy, railway, aerospace, shipbuilding, machine tool, automobile, automatic control system, power system as well as engineering design such as motor and electrical appliance, and achieved significant results. Plentiful achievements have been obtained with the method although its application to mechanical design is still at an early stage. In general, for engineering design problems, the more factors or variables involved, the more complex the problem is, the greater benefits will be through the application of design optimization.

In conclusion, the development of optimization design can be divided into the following four stages:

Stage 1: Human intelligence optimization: The process synchronizes with the human history and directly relies on human intuition or logical thinking ability, and relevant methods include golden section method, method of exhaustion and local optimization.

Stage 2: Optimization of mathematical programming approach: The mathematical programming approach was born since Newton invented calculus over three hundred years ago, and rapidly developed with the emergence of electronic computers in the last 50 years.

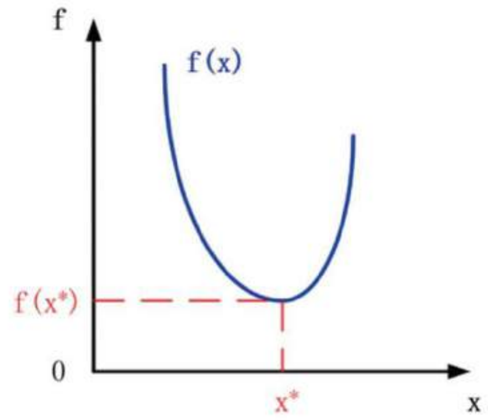
Stage 3: Engineering optimization: In the last two decades, the developing computer technology provides new possibilities for solving the complex engineering optimization problems. Non-mathematical experts developed some engineering optimization methods to cover the gap left by conventional mathematical programming approach in the engineering optimization field. The methods based on experience and intuition are relatively popular in solving the multi-objective engineering optimization problems. The optimization process and methodological research have attracted attention, especially the research on modeling strategy, and lead to a new way to improve the engineering optimization efficiency.

Stage 4: Modern optimization methods, including genetic algorithm, simulated annealing algorithm, ant colony algorithm and neural network algorithm. With these methods, the expert system technology is used to automatically select the optimization strategy and control the optimization process, and the intelligent optimization strategy develops rapidly.

7.3 Classification of Optimization Techniques

The term "Optimization" originally refers to a process of finding the best solution, i.e., the process of finding the maximum or minimum of a given function in a constrained space.

Figure 7.2 Extremum of function



As shown in the figure above, for the function f(x) with a variable x, what is the value of x at the minimum f(x)?

Further, the condition for solving the minimum of one-dimensional function f(x) is: if x is x*, f(x) can reach its minimum value f(x*).

Practical problems can be expressed into various functions:

Deterministic and non-deterministic functions;

Linear and non-linear (quadratic, higher-order, transcendental) functions.

Variables of different types are involved, include:

Continuous, discrete and random variables.

Many optimization algorithms are generated, including:

Unconstrained optimization and constrained optimization;

Single-objective function optimization and multi-objective function optimization;

Continuous variable optimization, discrete variable optimization and random variable optimization.

Optimization is an important branch of mathematics, and has wide application and strong practicability. In brief, the optimization is a discipline to choose an appropriate scheme from all of the possible ones to achieve optimal goals.

Scheme for reaching the optimal objective is called optimal scheme.

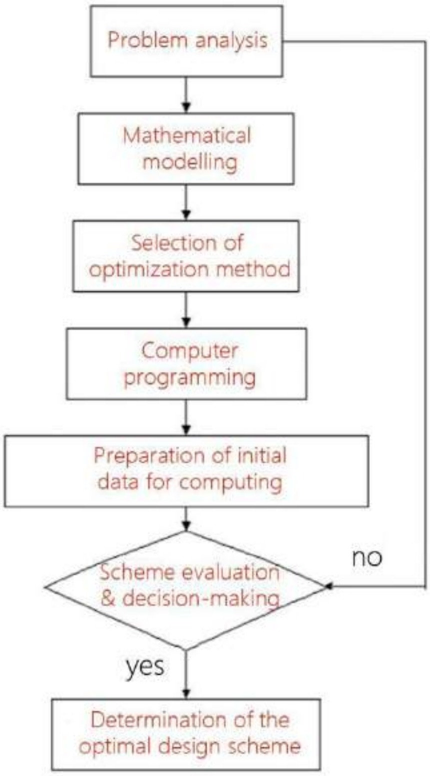
Method for searching for the optimal scheme is called optimization method.

Mathematical theory of the method is called optimization theory.

7.4 Process of Optimization Design for Engineering Problems

The figure below describes the main flow of optimization design for general engineering problems:

Figure 7.3 Optimization design process

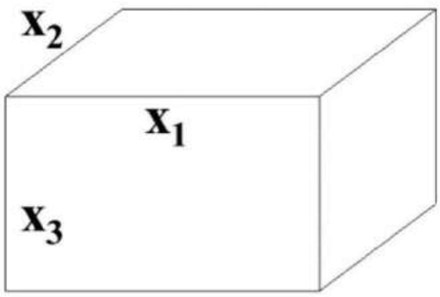


Optimization design is a process of seeking optimal design schemes for engineering problems based on optimal numerical computation method and computer technology. Therefore, the first step is to mathematically describe a problem of engineering optimization design for mathematical modeling, and the second step is to select a suitable optimal numerical method and a computing program to obtain the optimal solution, thus determining the optimal design scheme.

Example 1: Optimization design of a box

If: A 100m3 uncovered box with a length not less than 5m should be made, try to determine the length x1, width x2 and height x3 of the box to minimize the required materials.

Figure 7.4 Box diagram



Analysis:

a) Expression of surface area of the box;

b) Determination of design parameters: length x1, width x2 and height x3;

c) Design constraints:

(i) Volume requirement;

(ii) Length requirement:

Mathematical model:

Design parameters: x1, x2, x3

Design objective: minS= x1x2+2(x2x3+ x1x3)

Constraint: x1≥5

x2≥0

x3≥0

x1x2x3=100

Example 2: production resources allocation for maximum output

If a factory produces products A and B, with unit price of PA (10,000 yuan) for product A and PB (10,000 yuan) for product B. The production of a unit of product A needs aC tons of coal, aE k/h of electricity and aL man-days; and the production of a unit of product B needs bC tons of coal, bE k/h of electricity and bL man-days. The available production resources include C tons of coal, E k/h of electricity and L man-days.

The optimal allocation scheme should be determined to maximize the output.

Analysis:

a) Expression of output;

b) Determination of design parameters: xA for product A and xb for product B;

c) Design constraints:

(i) Constraint on coal resource for production;

(ii) Constraint on electricity resource for production;

(iii) Constraint on labor resource for production;

Mathematical model:

Design parameters: xA,xB

Design objective: $\max P = P_A x_A + P_B x_B$

Constraint: $a_C x_A + b_C x_B \leq C$

$a_E x_A + b_E x_B \leq E$

$a_L x_A + b_L x_B \leq L$

7.5 Mathematical Model of Optimization Design

Mathematical models of optimization design are mathematical expressions describing the design contents, variable relations, relevant design conditions and intentions of actual optimization problems. They describe the internal relations of major factors of physical phenomena and contributes to further optimization design.

7.5.1 Design Variables

A design scheme can be numerically represented by a set of basic parameters, and the basic parameters include geometric quantities (e.g. member size), physical quantities (e.g. mass) and derived quantities (e.g. stress and deformation that represent service behaviors).

Design variables refer to independent parameters that can be changed and optimized in optimization design.

All design variables refer to a set of variables that can be represented by a column vector.

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \cdot \\ \cdot \\ \cdot \\ x_n \end{bmatrix}$$

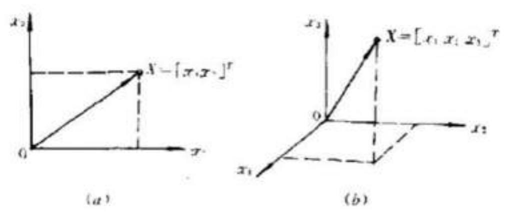
A real space formed by coordinates consisting of n design variables (x1, x2, ..., xn) is called design space. A "design" can be represented by a point in the design space.

The number of design variables is called the dimensions of optimization design. For example, a design involving n design variables is called a n-dimensional design problem.

According to the characteristics of product design variables, design variables can be divided into continuous variables (e.g. axle diameter and overall dimensions) and discrete variables (e.g. various standard specifications).

Two-dimensional design problems only involving two design variables can be represented by the rectangular plane coordinates shown in the figure below. Three-dimensional design problems involving three design variables can be represented by the space rectangular coordinates as shown in Figure 7.5(b).

Figure 7.5 Design space composed of design variables



(a) two-dimensional design problem, (b) three-dimensional design problem

The dimensions of design spaces represent the degree of freedom in design. The design variables can be increased to improve the degree of freedom in design and number of available alternatives to realize a flexible design. However, increasing variables will also increase the difficulty and complexity of solving the problem.

Small design problem normally involves 2 to 10 design variables.
Medium-scale design problem involves 10 to 50 design variables.
Large-scale design problem involves more than 50 design variables.
At present, it is possible to solve the large-scale optimization design problem involving 200 design variables.

With the continuous improvement of optimization algorithms and the emergence of new algorithms, computing problems in larger scale (e.g. problems involving thousands of design variables) can be theoretically solved with appropriate algorithms by combining computers with reliable hardware performance (e.g. high-performance computers) and cluster computing, parallel computing and other technologies.

U.S. Boeing optimized the structures of large wings with 138 design variables, which reduced the weight by one third. The large transport ships are optimized with 10 variables, which reduced the cost by about 10%.

Figure 7.6 Boeing aircraft

The practice has proved that optimization design is an effective design method to guarantee excellent performance, reduce dead weight or volume and lower product cost. In addition, designers can get rid of lots of cumbersome and repetitive calculations, which enable them to focus on creative design and greatly improve design efficiency.

How to select design variables?

Every product is an integration of structural dimensions specified by variables. The number of variables is proportional to the degree of elaboration of the product structure. However, the more variables the produce has, the more difficulties it has as well in modeling and optimization. Therefore, the following aspects should be noted when selecting the design variables:

a) Focus on main problems rather than minor issues.

Parameters having a significant influence on product performance and structure should be taken as design variables, while those having a slight influence can be taken as tentative constants based on experience or directly ignored.

b) Select design variables according to the particularity of the design problem.

For instance, there are 4 design variables for a cylindrical helical tension/compression spring, namely diameter d of steel wire, pitch diameter D of spring, number of effective coils n and free height H. In the design process, the allowable shearing stress and shear modulus G of a material are taken as design constants. If the spring is designed in a given radial space, the pitch diameter D can be taken as a design constant.

7.5.2 Constraint Conditions

The design space is a collection of all design schemes, including those unacceptable in engineering conditions. A feasible design refers to a design that meets all the necessary requirements.

A feasible design must meet some design restrictions, and these design restrictions are called constraint conditions, or constraints for short.

Constraints can be divided into equality constraints and inequality constraints according to their mathematical expressions:

(a) Equality constraint: $f(x)=0$

(b) Inequality constraints: $f(x)\geq 0$

According to nature of constraints, constraints can be divided into:

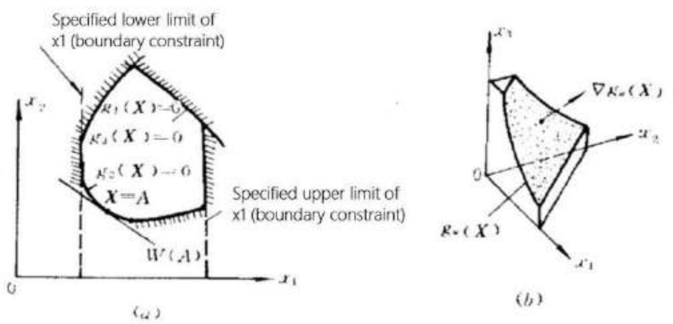
Performance constraints, referring to constraints proposed to meet performance requirements. For example, some structures must be selected to meet the requirements regarding strength, rigidity or stability under stress.

Boundary constraints, referring to constraints limiting the value range of design variables. For example, the size range for the machine tool spindle and the limited range of axle length are boundary constraints.

Explicit constraints and implicit constraints.

Some constraint functions can be explicitly expressed to reflect the obvious functional relationship among design variables, while others can only be expressed in implicit form. For instance, the performance constraint functions (deformation, stress and frequency) of complicated structures in this example are expressed in implicit form and need to be solved by the finite element method and the like.

Figure 7.7 Constraint surface (or constraint line) in the design space

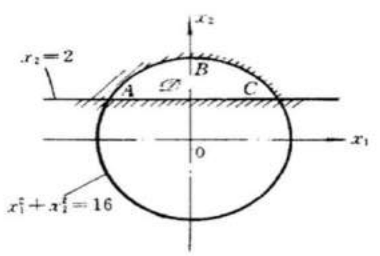


(a) Constraint line in a two-variable design space (b) constraint surface in a three-variable design space

Feasible region means a space composed of design points meeting all constraints in the design space.

For example, the feasible region D of a two-dimensional design problem meeting two constraints
g1(X)=x12+x22—16 ≤ O and g2(X)=2—X2≤0 is shown as follows:

Figure 7.8 Feasible region D defined by constraints



7.5.3 Objective Function

To quantitatively evaluate the design, an evaluation function containing design variables must be constructed. The evaluation function is an optimization objective (also known as an objective function), and expressed by F(X).

F(x)=F(x1,x2,... ....,xn)

In the optimization process, the design variables are automatically adjusted to improve the F(X) value continuously, and finally, solve an X value that is the best or most satisfactory for the F(X). When the objective function is constructed, all necessary design variables must be included in the objective function and constraint function, respectively. The following objective functions can be referred to in mechanical design:

Minimum volume, minimum weight, highest efficiency, maximum bearing capacity, highest structural motion accuracy, minimum amplitude or noise, minimum cost, minimum energy consumption, minimum dynamic load, etc.

An optimization design problem can be involved with only one objective function, i.e., single-objective function. A design problem with multi-objective functions is called the optimization problem of multi-objective function. The multi-objective function is common in general mechanical optimization design. The objective functions can be increased to improve the comprehensive effect of design, but this complicates the solution to the problem.

Some objectives of a multi-objective function are often contradictory in practical engineering design problems. In that case, designers should be able to correctly handle the relationship among various objective functions.

Contour surface (line) of objective function:

The objective function is a function of n-dimensional variables, and its graphics can only be described in (n+1)-dimensional space. The contour surface is often used to show all changes in an objective function in the n-dimensional design space.

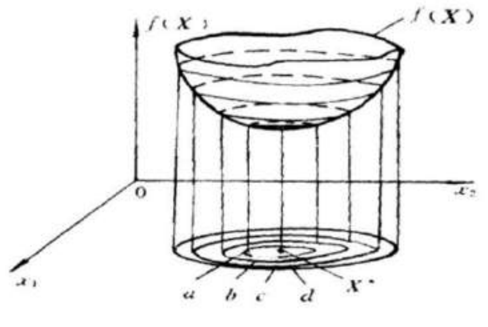
The contour surface (line) of the objective function can be mathematically expressed as:

$$F(x)=c$$

C is a series of constants representing a family of n-dimensional hypersurfaces. For example, in a two-dimensional design space, F(x1, x2)=c represents a family of curves on the x-x design plane.

Plane curves or surfaces consisting of design points with equal objective function values are called contour lines or contour surfaces.

Figure 7.9 Contour lines



The figure above shows the contour lines on the relation surface composed of the objective function f(X) and two design variables x1 and x2. They are plane curves consisting of design points with identical objective function values. When different values are assigned to the objective function, a series of contour lines can be obtained to form a contour line family of the objective function. The contour lines converge to an extremum located at the center of the contour line family. When the objective function value changes with a given range, the sparser the contour lines are, the smoother the change of the objective function value is. The change rule of an objective function can be visually presented with geometric graphics based on the concept of the contour line.

Figure 7.10 Contour lines

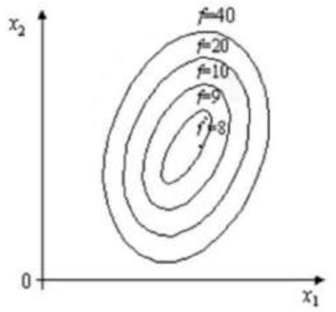


Figure 7.10 is the contour line map of function.$F(x_1,x_2) = 60 - 10x_1 - 4x_2 + x_1^2 + x_2^2 + x_1x_2$.The changes in function values are clearly shown on these contour lines. Contour line of F=40 is the line consisting of all points [x1,x2]T that enable F(x1,x2)=40.

In an objective function of optimization design the goal is to solve its minimum value. If optimal point of an objective function is the maximum value in the feasible region, the objective function can be regarded to solve the minimum value of [-F(X)], because min [-F(X)] is equivalent to maxF(X). The objective function can also be regarded to solve the minimum value of 1/F(X).

For complex problems, it is difficult to establish perfect mathematical models capable of reflecting actual engineering conditions. Sometimes this is even harder than making a solution. In that case, attention should be appropriately paid to key factors rather than minor factors to simplify the problem reasonably and facilitate mathematical modeling. In this way, it can not only save time but sometimes also improve the optimization results.

7.5.4 Basic Solution to Optimization Problem

The basic solutions to the optimization problems are:

a) Analytical method

b) Numerical solution

Analytical method is a method for finding an optimal analytic solution based on necessary and sufficient conditions of extremum of a function (functional) by means of mathematical analysis (calculus and variation). The solution process is applicable to simple objective functions.

Limitation: The objective functions and constraints of engineering optimization problems are often complicated and even cannot be described by mathematical equations. In that case, mathematical analysis methods are inconvenient to use.

Numerical solution is used to numerically compute approximate value and is also known as numerical iteration method. According to the change rule of objective function, people use this method to explore the optimal point of the objective function value in the descending direction of the objective function values at appropriate step size, with the optimal point approximated to or reached. The numerical solution (iteration method) is a basic solution to the optimization design problem.

Optimization methods depend closely on the development of modern electronic computers. The numerical solution is more suitable for the operating features of electronic computers than the analytical method due to the following characteristics of the numerical iteration method:

i) The iteration method is a numerical computation method rather than a mathematical analysis method.
ii) The iteration method has a simple logical structure available for repeated arithmetic computation.
iii) An approximate solution approaching the exact solution is obtained.

These characteristics are in line with the operating features of computers.

The basic idea of the numerical iteration method is to carry out repeated numerical computation to find feasible calculation points where the objective function value decreases continuously until the optimal point with sufficient accuracy is obtained. The optimization process of the method can be generally divided into the following steps:

a) First, select an initial point X(0) as close to the minimum point as possible, find a feasible direction and initial step size according to established principles from X(0), and take a step forward to reach point X(1).

b) Select a new direction along which the function value decreases rapidly and an appropriate step size, take another step from point X(1) to reach point X(2), and so on. In this way, the exploration and numerical computation are repeated until the optimal point of the objective function is obtained.

7.6 Introduction to Multidisciplinary Optimization

Multidisciplinary design optimization (MDO) is a methodology to design complex systems and subsystems by fully exploring and utilizing the interactive cooperation mechanism in engineering systems. The main idea is to organize and manage the design process by integrating the knowledge of various disciplines (subsystems) and applying effective design optimization strategies throughout the process of complex system design. It is mainly intended to obtain the global optimal solution of the system based on synergistic effect generated by the interactions among various disciplines (subsystems), and to shorten the design cycle and improve the product competitiveness by realizing concurrent design. Therefore, the objective of MDO coincides with the concurrent engineering concept in modern manufacturing technology. In actuality, MDO provides a theoretical basis and implementation method for entire product life cycle design based on optimization principle.

The research on MDO includes three main areas:
a) integration of analytical methods and software for design-oriented disciplines;
b) exploration of effective MDO algorithms to realize concurrent design of multiple disciplines (subsystems) and obtain the global optimal solution of the system; and
c) MDO distributed computer network environment.

Multidisciplinary design optimization problem can be mathematically expressed in a simple form, as shown below:
Look for: x
Minimized: f=f(x,y)
Constraint: hi(x,y)=0 (i=1, 2,... ,m) gj(x,y)≤ 0 (j=1 ,2 ,... ,n)

The f is an objective function; x is a design variable; y is a state variable; hi(x,y) is an equality constraint; and gj(x,y) is an inequality constraint. The computation of the state variable y, constraints hi and gj and the objective function involves multiple disciplines. For non-hierarchical systems, the state variable y, objective function f as well as constraints hi and gj should be subject to multiple iterative computations. For hierarchical systems, computations can be performed in a certain order. This computation step is called system analysis.

As science and technology developed rapidly, our products and equipment are improved constantly with a complexity far beyond ordinary imagination, such as airplanes, automobiles, computers and mobile phones. The equipment design requires lots of manpower and knowledge of more than one discipline. For example, aircraft design is involved in hydraulics, transmission, fluid mechanics, computational fluid mechanics, aerodynamics, engine, structural mechanics, heat transfer, thermodynamics, automatic control, electronics, software, computer, reliability, maintainability, supportability, safety, testability and other disciplines. As times progress, every discipline has its own research methods and development ideas. However, these disciplines are islands isolated from each other without effective communication and liaison.

In recent years, the phenomenon of "islanding" on discipline has been noted abroad, and researches on multidisciplinary optimization design are initiated. At present, some multidisciplinary optimization design has realized abroad, and some commercial multidisciplinary optimization software has been developed, such as Isight, OPTIMUS and ModelCenter. The industry in China has kept pace with international development and commenced relevant research, and the optimization algorithm problem has been solved in select sectors.

In the present paper, we make a review on the purpose, significance, algorithm, framework, problems encountered, solutions and achievements of multidisciplinary optimization design as well as introduction to multidisciplinary design software.

7.6.1 Purpose and Significance of Multidisciplinary Optimization Design

The multidisciplinary optimization design mainly aims to:

a) systematize the design process (i.e., the personnel involved in the overall system design are informed of the constraints and optimization objectives of other disciplines to establish a global concept from the start and avoid design contradictions due to misunderstanding among disciplines, so as to reduce design modifications as well as time and expenses required); and

b) penetrate special features design into performance characteristic design (i.e., the personnel of conventionally mechanical, electrical and control disciplines combine other disciplines regarding reliability, maintainability, supportability, safety and testability in the design throughout the system design process, so as to change the phenomenon that these special features were not considered in the design process).

The significances of multidisciplinary optimization design are:

a) Obtaining the global optimal solution of the system by utilizing the synergistic effect generated by the interaction among various disciplines;

b) Shortening the design cycle by carrying out parallel computing and design; and

c) Improving the reliability of design results by using high-precision analysis models.

7.6.2 Multidisciplinary Optimization Design Algorithm

Multidisciplinary optimization design has two difficulties: computation complexity due to multiple iterations of the computation models of disciplines and information exchange complexity caused by organization and management of information exchange among these disciplines. There are many reports on algorithmic research. Main MDO algorithms can be categorized as follows [2]:

a) Single-level optimization

Single-level optimization methods are methods of single-discipline optimization, mainly including:

- standard system-level optimization algorithm;
- CSE-based single-level optimization algorithm; and
- consistency constraint optimization algorithm.

In the optimization design, the analysis and computation of various disciplines are integrated to establish a systematic analysis. The so-called integrated design refers to the algorithm.

b) Sequential optimization

Sequential optimization is to carry out single discipline optimization in a certain order, compute system performance, and repeat these steps to achieve convergence. The selection of objective functions to be optimized in the disciplines during the analysis process should be favorable for objective function of the system.

c) Concurrent subspace optimization

In the concurrent subspace optimization algorithm, design variables and state variables of a system are allocated to subspaces. A large-scale optimization problem is divided into many small optimization problems, and these subspace optimization problems are subject to the constraints and objective functions of the system. These algorithms mainly include:

- concurrent subspace optimization algorithm based on sensitivity analysis;
- improved CSSO algorithm based on sensitivity analysis; and
- CSSO algorithm based on response surface.

d) Collaborative optimization

The collaborative optimization algorithm is used to analyze subspaces for optimization designs, and a design can be temporarily optimized without considering the effect of other subspaces, providing that the constraints of the subsystem are satisfied. The system-level optimization is carried out to coordinate the incompatibility among design optimization results of subsystems. The optimal consistency design is realized through multiple iterative computations between the system level and the subsystem level.

e) Multilayer hierarchical optimization

Multilayer hierarchical optimization algorithm is used to optimize the system based on some concepts and methods of large-scale system control theory. The method represents strong comprehensive capacity of dealing with complex high-order multisystem. A multilayer hierarchical system is decomposed into 3 classes of subsystems: 1) top-layer subsystem, 2) middle-layer subsystem and 3) bottom-layer subsystem. The system runs from top layer to bottom layer to convey the design requirements by layers and design subsystems, then feed information back by layers to modify the design requirements of the previous layer according to the information fed back by the current layer, and optimize targets by layers until convergence.

Some people (Hu Yu and Li Weiji, et al., Northwestern Polytechnical University) were reported to study on the algorithms in detail, and the collaborative optimization algorithm and hierarchical optimization algorithm have been discussed elaborately.

7.6.3 Framework of MOD

The MDO computing framework can be divided into three levels:

Level 1: a general MDO computing framework, e.g. ModelCenter, iSIGHT and OPTIMUS.

Level 2: a computing framework for a specific MDO method, including CSD framework based on concurrent subspace optimization and Caffe framework based on collaborative optimization.

Level 3: a computing framework for specific optimization problems based on a MDO method, such as CJOopt framework developed by U.S. NASA for the preliminary design problems of high-speed civil aircrafts.

Thus, the MDO computing framework shall have the following features and functions:
a) An expression easy to realize various MDO methods;
b) Characteristics of a distributed computing environment;
c) Legacy applications and some commercial software capable of integrating various disciplines;
d) Provision of an optimization algorithm library;
e) Support of the generation of surrogate models;
f) Support of parallel computing;
g) Visualization and monitoring of design process;
h) Storage, management and extraction of data;
i) Support of design optimization based on uncertainty.

7.6.4 Obstacles in MDO and Solutions

Major problems in MDO are described as follows:

a) Investigators of various disciplines put their own design work first. They are unwilling to compromise with others and look down upon MDO.

b) Since the optimal value of a discipline may be the worst to another, the problems arise from coordinating the dependent constraints and optimization objectives among disciplines.

The first problem lies in ideology. We should popularize MDO knowledge to ensure that every employee participating in the work can understand the advantages of implementing MDO, including a shortened design cycle and reduced design changes at later stage due to design conflicts among parties. In this way, relevant employees can form the global and systematic perspectives and participate in the MDO work voluntarily.

The second problem is technology-related and involves the application of decision theory. For the interdependent constraints and optimization objectives, we can select typical test points for multiple scheme computation and evaluation to finally get combination of the optimal constraints and optimization objectives. The evaluation indexes can be economical or technical.

7.6.5 Results of MDO

At present, the MDO mainly focuses on the following aspects:

a) Integrated optimization of aerodynamics and structures[3]

In aircraft design, aerodynamic design is often closely related to structural design. With the traditional design methods, the aerodynamic and structural designs are usually classified as optimization problems at different levels. That is, the aerodynamic design is carried out first, and then the structure is optimized. The aerodynamic design is considered first because its expenses are much higher than that of the structural design. Therefore, work that should be done through two or more designs can be completed in one design with MDO. It has great significance in improving design efficiency and quality.

The aerodynamic optimization is generally implemented by means of a three-dimensional nonlinear model, and the structural optimization is carried out by means of a large-scale finite element model. Considering the asymmetric interaction between aerodynamics and structures, the focus of integrated optimization is to improve the aerodynamic model.

Xue Fei, Yu Xiongqing, et al. of Nanjing University of Aeronautics and Astronautics had discussed whether the collaborative optimization method could effectively solve the optimization problem of integrated aerodynamic/structural design of wing in Preliminary Application of Collaborative Optimization in Integrated Aerodynamic/Structural Design of Wing.Their findings prove that the basic collaborative optimization algorithm cannot effectively solve the integrated optimization problem of wing aerodynamics/structure, and the collaborative optimization based on response surface has good robustness in solving this problem. He Lietang and Zeng Qinghua of the National University of Defense Technology also provided a similar computing method for the multidisciplinary integrated design of aerodynamics and structures of micro aerial vehicles in Aerodynamic Configuration Optimization Design of Micro Aerial Vehicles.

b) Synchronous optimization of aircraft structure and active control[3]

In aircraft design, the structure and active control also need to be designed synchronously for active flutter suppression on structures through the active control. The traditional method is sequentially implemented: first, the structural layout and cross-sectional size are determined, and then a control system is added to eliminate or reduce the undesirable behaviors[3]. Sequential practice is imperfect and its deficiency can be made up by simultaneous optimization of the structure and the system controlling its properties. Integrated structural-control optimization typically adopts a composite objective function (i.e., a weighted sum of structural mass and control force, with a weighting coefficient determined by subjective judgment). However, the body mass and control system mass can always be weighed with a compromise method.

There is still a dispute over related algorithms, and the problem has attracted attentions of many investigators in the world. Some difficult problems need to be solved.

Although many people work on the MDO, there is no great breakthrough except for the results mentioned above. In fact, there is still a long way to go before realizing comprehensive multidisciplinary optimization for such a complex system as aircraft. The research on the application of MDO algorithm in aircraft design should be further developed in terms of extent and depth. For our disciplines, it is necessary to effectively integrate the special feature designs in terms of reliability, maintainability, supportability, testability and safety into the performance design. In conclusion, MOD plays an extremely important role in the development of weaponry, and research on this field is still at infancy in China. Therefore, MDO will have bright prospects in future decades. We can make research on the optimization algorithm to enrich the algorithm database and study the framework design to realize state-owned framework design, and then optimize and classify it to satisfy customized requirements of industries.

c) Weight reduction optimization of automobile design

The automobile industry is also a fiercely competitive industry. Automobile manufacturers are pursuing the design of vehicles with both performance and cost advantages. Automobile design should meet all performance design indexes as well as the collision safety index, load-bearing strength and stiffness indexes, fatigue life index, noise and comfort indexes, design of internal and external aerodynamic flow fields and engine thermal design. Therefore, automobile design is also a complex design involving various disciplines. In these discipline designs, dead weight reduction is a particular concern for each automobile factory. As a design objective of original equipment manufacturers (OEMs), the minimization of dead weight of a finished vehicle satisfying mentioned indexes is also a typical multidisciplinary optimization case.

In fact, optimization technology and multidisciplinary optimization technology can be used in designs from complex products (e.g. airplanes and automobiles) through simple parts and components. The application of optimization technology should be an indispensable method for product designers in finding the optimal product design scheme.

References:

[a] A Study on the Computing Framework of Multidisciplinary Design Optimization, Yu Xiongqing et al., Mechanical Science and Technology, March 2004.

[b] Application and Development of Multidisciplinary Design Optimization in Aerospace Industry, Li Zhe, Spacecraft Recovery & Remote Sensing, September 2004.

[c] New Development in Aircraft Multidisciplinary Design Optimization, Huang Jun, Wu Zhe, Sun Huizhong and Wu Binglin, Acta Aeronautica ET Astronautica Sinica, November 2000.

CHAPTER 8

Reliability and Robustness Design of Products

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8.1 Overview of Robustness

Robustness was a special term in statistics and became popular in theoretical studies on control in the early 1970s. It describes the insensitivity of control systems to disturbance of characteristics or parameters. The robustness quantitatively shows investigators in the fields of economic management and financial decision the basic qualitative descriptions in engineering field, including model errors and decision robustness. In addition, it provides criteria for investigators who design appropriate decision-making rules in the fields of automation and signals processing in case basic requirements (e.g. system detectability) are not met. Science and technology can develop significantly through the substantial integration of different disciplines and fields.

The term “robustness” firstly appeared in a paper of Box (1953). This paper tested the hypothesis of mean and variance and pointed out that the variance test was not robust to the deviation from normality, while the mean test was robust. Meanwhile, Box emphasized that the urgent matter was to develop appropriate robustness criteria. The term "robustness" has not been defined by any official quality group, but is considered to be a critical characteristic. It is reported that many investigators have already discussed and defined robustness in their own fields, and the definition in the same field can be varied with the proposers.

Robustness is conventionally defined as follows:

a) Robustness is resistance to minor variations in test conditions, which only occurs during the transition of operators or equipment.

b) The robustness of an analysis process probably occurs along with the parametric conversion and variation.

c) The robustness of an analysis process is a measure of the ability to remain unaffected by variations in parameters. It points out that the reliability, i.e., robustness, evaluates the ability of a method to resist variation under normal application conditions.

d) The robustness of a process refers to the ability to produce consistent and qualified products through a process, and make the process least affected by variations under uncontrollable manufacturing conditions.

e) The robustness of a method reflects the observed level of being affected to minor intentional variations under given experimental conditions. Therefore, the robustness should be regarded as a characteristic of experimental optimization applied in the analysis program.

f) In multivariate situations, robustness is regarded as the sensitivity and prediction ability of models to changes on external factors (environment, equipment and sampling conditions).

g) Robustness is the product stability gained with time.

h) Robustness is the information feature on the response surface near the investigated optimization domain.

i) The concept of robustness refers to the ability of models to maintain stability under small disturbances.

j) Box statistically defined robustness as a process through which good results can be given even based on the assumed violations. Robustness of statistical analysis refers to the sensitivity of optimization design to models out of specification. It is regarded as a sensitivity measurement for outlier estimation. Therefore, the application of robustness in statistics improves the resistance to outlier estimation. Robustness of models refers to the non-sensitivity of nonconformance to statistical hypotheses (linearity, normality or independence).

8.2 Reliability-Based Robust Design of Mechanical Products

Reliability-based robust design of mechanical products is carried out based on reliability design, optimization design, sensitivity design, aiming to integrate reliability sensitivity into the optimization design model. The reliability-based robust design is summed up as a problem of multi-objective optimization meeting design reliability requirements. The appropriate application of reliability-based robust design method in the design of mechanical products can secure reliability of these products in various disturbances, so as to make the reliability of products insusceptible to changes in design parameters and improve safety, reliability and robustness of the products. Throughout the years of development, the idea of robustness design has been developed to satisfy the optimization of system performance and the minimization of performance deviation, as well as the optimization of performance in optimal design and the robust design problem in constraints. That means the objective function should meet the constraints and the product performance should be insusceptible or slightly susceptible to the disturbance of design variables.

Main methods are described as follows:

a) Ternary designs

In the 1970s, a group of investigators headed by Dr. Genichi Taguchi (JPN) brought testing techniques developed by British scholar R.A.Fisher et al. into Japan, which were developed for multi-factor field trials. As a result, he developed the Orthogonal Table and established the ternary designs method for reasonably analyzing relevant test results.

Thee ternary designs are composed of system design (the first design), parameter design (the second design) and tolerance design (the third design). The design parameters and preset tolerances are tested according to arrangement in the orthogonal table. The interferences of the design parameters and noise parameters are simulated on the product quality, and the nominal-the-best loss function is used as a stability index for measuring the product quality characteristics to determine the reasonable combination of the design variables and their tolerances, and ensure that products pass the constancy testing.

The method is featured as follows:

(i) As the method is carried out based on orthogonal tests, the number of necessary tests increases with the influencing factors. Considering that factor combination used in the parameter design is selected from combinations at determined significant levels, the approximate range or level of the optimal solution should be known in advance (which is sometimes difficult). As a result, the number of tests increases and additional expenses are possibly required;

(ii) factors processed with this method are hypothesized as normally distributed and independent discrete variables with relatively small quantity; and

(iii) the method has complicated steps and relatively low efficiency.

b) Tolerance polyhedron method

Tolerance polyhedron method was proposed by Mihcael & Siddall in 1981. They set all variables to theoretical values (except the design variables with tolerance) according to guiding ideology that the higher the machining tolerance of the given variables, the lower the product cost. That is in the method, only the tolerances of the design variables are considered, while the noise factor variation is not considered. The method is featured as follows:

(i) the method can be used to solve constrained optimization problems;

(ii) the method is suitable for solving tolerance design problems, especially the worst-case tolerance design; and

(iii) the above analysis revealed that the method only considers the variations of design variables instead of the variations of noise variables.

c) Tolerance model method

Tolerance model method is also known as variation transfer method, and was proposed by Pakrisnon et al. in 1993. The design values of structural parameters, physical parameters or mechanical parameters of products are inevitably different from actual values after manufacturing or in service. These differences are called variations of design variables and noise factors. These variations are transferred to design functions (criterion function and constraint function) to derive variations of quality indexes and constraints. The method is featured as follows:

(i) the method is more realistic than the tolerance polyhedron method and is a suitable mathematical expression for Taguchi method; and

(ii) the method does not overcome a constraint of Taguchi method that variables must be subject to normal distribution.

d) Dual-response surface methodology

Myers and Carer proposed the dual-response surface methodology in 1973. The method does not adopt the concepts of signal-to-noise ratio and two-step optimization of Taguchi method. It achieves the objective of Taguchi method with two surfaces, i.e., one surface fits the mean value of quality characteristic, and the other fits its variance. Through appropriate test design, the mean model and variance model of the quality eigenvalue (i.e., response) to be investigated are fitted based on test result data.

e) Stochastic model method

The method is used to solve engineering problems with stochastic factors using the combination of optimization technology, probability theory, mathematical statistics and computer technology. The stochastics of controllable and uncontrollable factors is main considerations in the method. The method is featured as follows:

(i) with stochastics of controllable and uncontrollable factors, the method is significant for practical use;

(ii) the stochastic model of the method is complicated in terms of establishment and computation. Therefore, approximate data or algorithms are unavoidable in practical use of the method, which reduces the accuracy of computing results.

8.3 Taguchi Robustness Design Method

Taguchi Robustness design (TRD, hereinafter referred to as Taguchi method) is a low-cost and efficient quality engineering method developed by Dr. Genichi Taguchi of Japan in the 1970s. Taguchi method advocates the utilization of inexpensive components in designing and manufacturing high-quality products, and the usage of advanced test technology for lowering the cost of design and tests. Taguchi method initiates a revolutionary change in the traditional ideas and provides a new direction for increasing business benefits.

Dr. Taguchi divided the product design into three stages: system design, parameter design and tolerance design, also known as three-stage design. Taguchi method has no relation to system design. It focuses on parameter design and tolerance design, especially the parameter design:

The system design stage, also known as concept design phase, mainly aims to find various designs or techniques to possibly realize the expected system functions.

At the parameter design stage, a system design scheme is optimized actively and positively, and a combination of control factor levels is determined through tests to minimize the sensitivity of the system to noise factors and improve the system robustness.

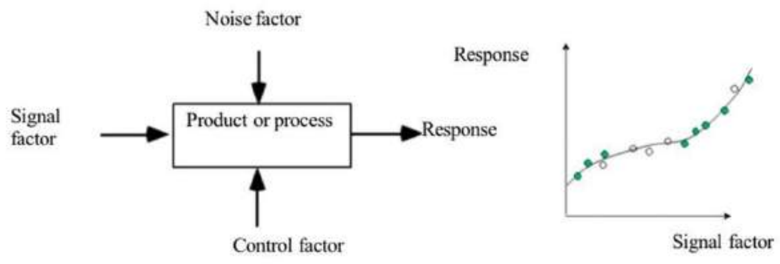
At the tolerance design stage, appropriate tolerance ranges of parameters are determined on the basis of the optimum conditions confirmed at the parameter design stage. Tolerance design is relatively passive and is related to manufacturing cost. High tolerance often means low cost.

Taguchi method reduces the variation of the target value (i.e., the effect of noise factors on the target value) by selecting design parameters, determining orthogonal table test design and taking the SN ratio as an analysis index. In this way, the robustness of the product is strengthened to guarantee the robustness and reproducibility of product performance.

Taguchi method has the following characteristics:
Evaluation of quality characteristic based on quality loss function;
Measurement of robustness by SN ratio;
Arrangement of test designs by means of Taguchi Orthogonal Table.

8.3.1 Signal Factor, Control Factor and Noise Factor

Figure 8.1 P-diagram system



P-diagram system can be used to show the parameters affecting the quality characteristic, which are divided into signal factors, control factors and noise factors. According to characteristics of signal factor values, the system can be classified into:

A static problem when the signal factor is a constant value; or

A dynamic problem when the signal factor is inconstant. For dynamic problems, designers expect that system response changes with the signal factor level according to predefined rules.

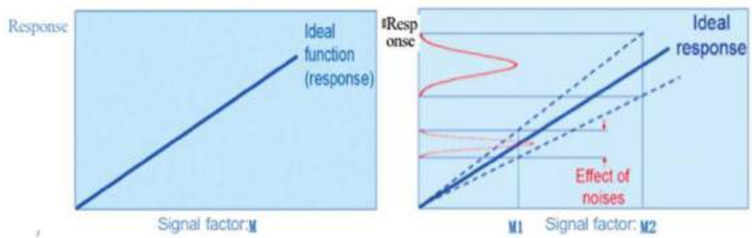
For dynamic systems, signal factors are set by product users or operators to express the ideal response values. When the target response value changes, the signal factor can be changed to align the average response value with the target ideal value. Taking the automobile steering system as an example, in the dynamic system, the signal factor is the steering angle set for the driver, and the system response is the actual steering angle.

Control factors are parameters at levels mastered and determined by designers. In robustness design, designers must search for different combinations of control factor levels to find the most insensitive design scheme allowing response least susceptible to changes caused by noise factors. In general, manufacturing cost does not increase with the control factor level.

Noise factors are parameters beyond the control of designers. Any parameters uneasy or to be controlled at a certain level or requiring material expense in control can be regarded as noise factors. The noise factors can be divided into three categories:

Ambient noise: ambient temperature, humidity, user usage, etc.
Manufacturing noise: variation between products, manufacturing error, fluctuation between parts, etc.
Internal noise: material aging, component aging, etc.

Figure 8.2 Ideal response vs actual response



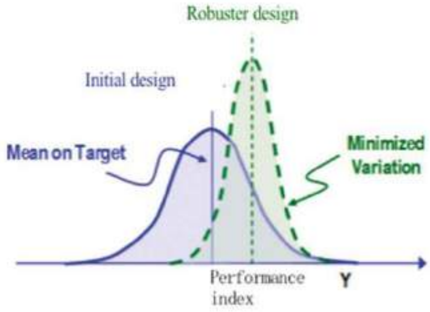
System response is jointly determined by noise factors and control factors. For dynamic systems, the ideal response equals actual system response when the noise factor is zero, and it has a linear relationship with the signal factor.

8.3.2 Robustness Design

There is a deviation between the actual response and the ideal response of the system because of the disturbance of noise factors. Robustness refers to the property that a product can maintain its design performance under disturbance. To improve product robustness, product capability of resistance to these noise factors should be improved to allow the product to be stable in different application environments and conditions. The robustness design aims to align the actual response with the ideal response as far as possible.

In robustness design, the noise factors are introduced into the design process. "Robust control factor level" is obtained by minimizing the influence of noise factors (i.e., "Minimize Variation"), and the system performance (response) is kept approach to the ideal response (i.e., "Mean-on-Target") to improve quality.

Figure 8.3 Robustness design concept



8.3.3 Quality Loss Function

Unlike the conventional definition of quality, Dr. Genichi Taguchi defined the product quality as a characteristic of avoiding losses to the society after the product delivery. Consumers are the final deciders of quality, and they will express their satisfaction with quality on the market. In this way, inferior products or brands will gradually lose the market. When the quality characteristic is consistent with consumers' expectations (targets), consumers express the lowest dissatisfaction, and quality loss is minimized. The dissatisfaction grows when the quality characteristic deviates from the target, and the quality loss also increases. Therefore, the following descriptions of product quality can be regarded as equivalents:

a) Good quality;

b) Minor social cost;

c) Minor quality loss;

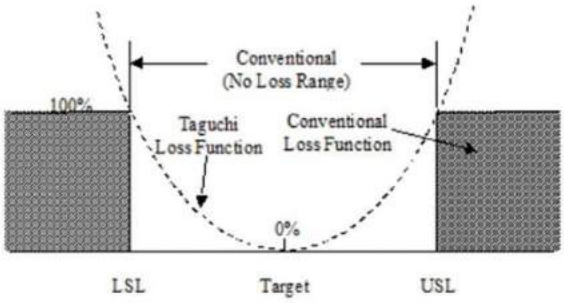
d) High consumer satisfaction; and

e) Low consumer dissatisfaction

To quantitatively describe the product quality loss, Taguchi proposed the notion of "quality loss function". It assumes that when the quality characteristic y deviates from the target m, the quality loss increases at the rate of a quadratic curve:

$$L(y)=k(y-m)^2$$

Figure 8.4 Quality loss function



Signal-to-Noise ratio (SN ratio for short) is an indicator for measuring the product robustness in Taguchi method. It indicates the level of derivation from system response to ideal response. High SN ratio corresponds to low loss and high robustness of the system.

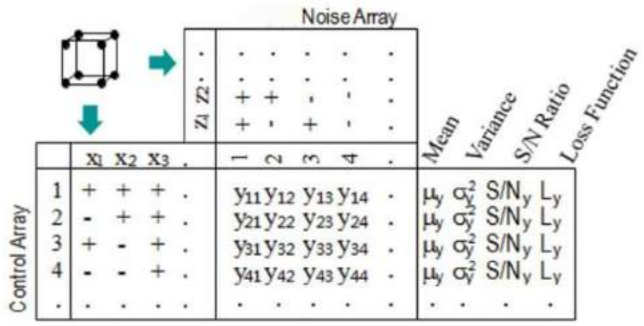
After determining the optimal conditions and corresponding predicted values, Dr. Taguchi proposed carrying out a confirmation experiment with the optimal parameters, and then comparing the observed SN ratio with the predicted SN ratio. If both ratios are very similar, the interaction effect between factors can be ignored and the factor effects can be superimposed. Therefore, the estimation of the factor effect is reliable, and the conclusion has good reproducibility. Otherwise, the estimation of the factor effect is unreliable due to the strong interaction effect between factors.

8.4 Introduction to Robustness Design Algorithms

8.4.1 Construction of Orthogonal Table

The parameter design of Taguchi method is established based on orthogonal tests. The controllable factors and uncontrollable factors are listed in the inner and outer arrays to control the optimal combination of factor levels. The sensitivity of quality to stochastic volatility is evaluated by maximizing the SN ratio (as shown in Figure 8-5).

Figure 8.5 Orthogonal test table of Taguchi method



Main procedures are described as follows:

Define the intention and objective of the test plan and select the quality characteristic;
Establish a system model and define input factors, signal factors and output response; and define the ideal function/response of the quality characteristic;
Define all control factors and select key control factors and levels. Select an Orthogonal Table and assign control factors to the table;
Define all noise factors and select key noise factors and levels;
For dynamic problems, define the signal factor level and range;
Implement the test plan and collect data. For dynamic problems, a noise factor test plan should be conducted for each combination of control factors at each signal factor level.

Data analysis:
For static systems, compute SN ratio;
For dynamic systems, compute dynamic SN ratio and sensitivity (b);
Find the response table/graph;
Perform two-step optimization to determine the optimal combination of control factor levels and maximize (dynamic) SN ratio;
Perform confirmation tests; and
Summarize the results in the design report.

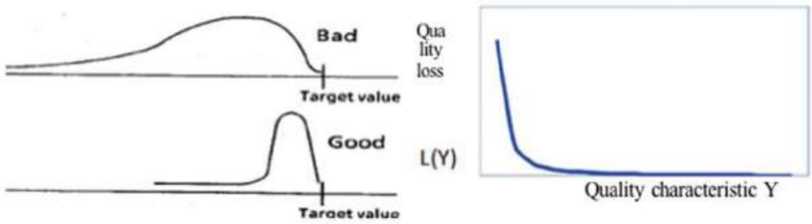
8.4.2 Static Characteristic Evaluation Indexes

Larger-the-better (LTB) means that a larger quality characteristic Y is better.

Equation for SN ratio of the LTB is: $SN = \eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$

Equation for quality loss of LTB is: $L(y) = k\left(\frac{1}{y^2}\right), \quad y \geq 0$

Figure 8.6 Larger-the-better

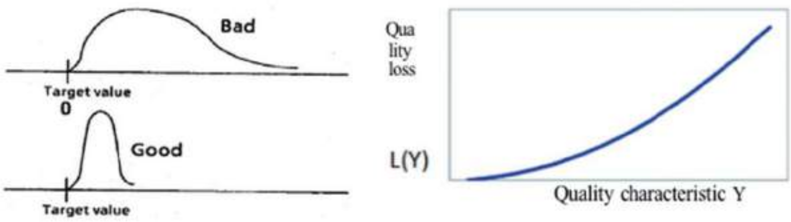


Smaller-the-better (STB) means that a smaller non-negative quality characteristic y is better, and the ideal value of y is 0.

Equation for SN ratio of STB is: $SN_{STB} = \eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$

Equation for quality loss of LTB is: $L(Y) = ky^2, \quad y \geq 0$

Figure 8.7 Smaller-the-better

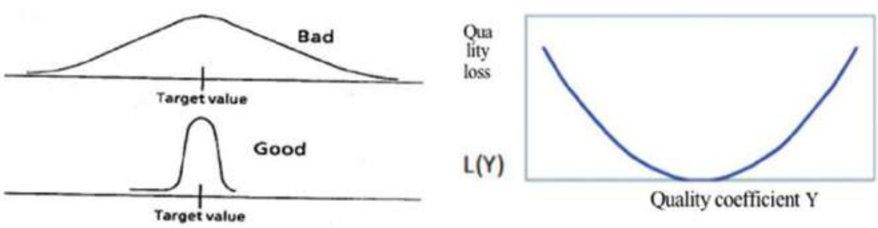


Nominal-the-best (NTB) means that the quality characteristic y has a target value. With the two-step optimization method, the first step is to obtain "robust control factor level" based on SN response table to minimize the influence of noise factor (i.e., "Minimize Variation"); and the second step is to find the key control factor, adjust the mean value, and make the system performance (response) approach to the ideal response (i.e., "Mean-on-Target") to improve quality.

Equation for SN ratio of NTB is: $SN_{NTB} = \eta = 10\log_{10}\left(\frac{\mu^2}{\sigma^2}\right)$

Equation for loss of NTB is: $L(y)=k(y-m)^2$

Figure 8.8 Nominal-the-best

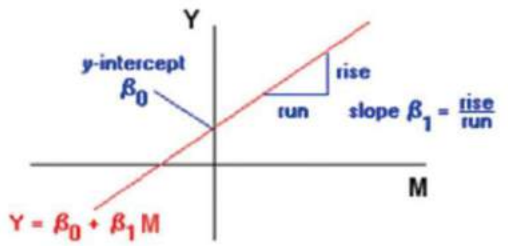


8.4.3 Dynamic Characteristic Evaluation Indexes

Dynamic SN ratio is used to measure the linear relationship between signal factors and response of a dynamic system, as well as the degree of variation deviating from the linear fitting. The dynamic SN ratio can be obtained by introducing the variation effect of noise factors into each test design scheme (depending on control factor) and computing through relationship between the signal factor and system response.

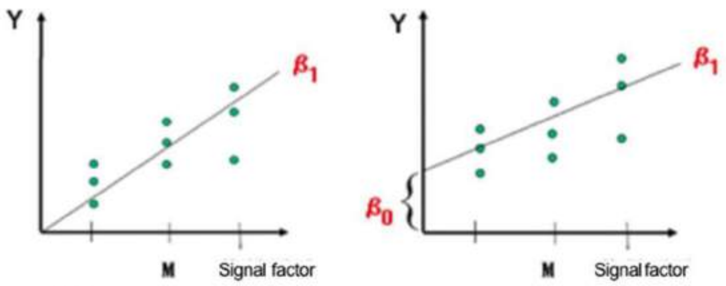
For dynamic systems, the linear relationship between the signal factor and system response can be expressed by a linear regression: $Y_i=b_0+b_1M+e_i$, where b_0 is intercept, b_1 is slope of the line (i.e., sensitivity), M is signal factor, Y is response, and e_i is error.

Figure 8.9 Linear regression of dynamic characteristics



When the intercept b_0 is 0, the signal factor and response is in a Zero Point Proportional relationship, and the signal response line passes through the zero point. For example, the initial point of a weighing scale must be output as 0. When the intercept b_0 is not 0, the signal factor and the response is in a Reference Point Proportional relationship, as shown in Figure 8-10, and the signal response line passes through a known reference point. For instance, the initial temperature of an oven must not beset to 0.

Figure 8.10 Zero Point Proportional (left) Reference Point Proportional (right)



Equation for sensitivity is: $b=\frac{\sum_{i=1}\sum_{j=1} y_{ij}M_i}{\sum_{i=1}\sum_{j=1} M_i^2}$

Equation for error mean square is: $s_e^2=\frac{1}{mn-1}\sum_{i=1}\sum_{j=1}(y_{ij}-bM_i)^2$

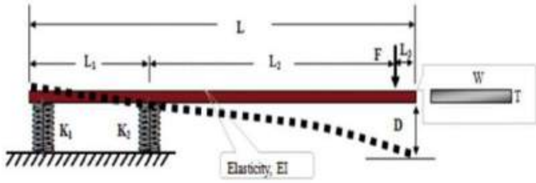
Equation for dynamic SN ratio is: $SN=h=10\log_{10}\frac{b^2}{s_e^2}$

8.5 Demonstration of Cases

8.5.1 Problem Description

Considerations for a springboard composed of springs and cantilever beams:

Figure 8.11 Springboard



Control factors:

Cantilever beam length (BoardLength)

Cantilever beam width (BoardWidth)

Cantilever beam thickness (BoardThickness)

Linear spring stiffnesses (SpingConstantK1, SpringConstantK2)

Modulus of elasticity (ModulusOfElasticity)

Applied force (Force)

Noise factors:

Position of applied force (ForcePosition)

Material property uncertainty (MaterialVariation)

Effect of applied force (ImpactForceAffect)

Signal factor:

Support point position (SupportPosition)

System response:

Deflection amount (Deflection), larger-the-better (Higher is Better)

8.5.2 Robustness Design

Control factors are set as follows:

For BoardLength, Levels = 114.0, 126.0.

For BoardWidth, Levels =18.0, 24.0.

For BoardThickness, Levels = 1.5, 2.0.

For linear spring stiffnesses SpingConstantK1, SpringConstantK2, Levels = 1200.0, 1800.0.

For ModulusOfElasticity, Levels =750000.0, 1250000.0.

For Force, Levels =150.0, 200.0.

Noise factors are set as follows:

For ForcePosition, Levels = 0.0, 10.0.

For MaterialVariation, Levels= -15.0, 15.0.

For ImpactForceAffect, Levels = 50.0, 100.0.

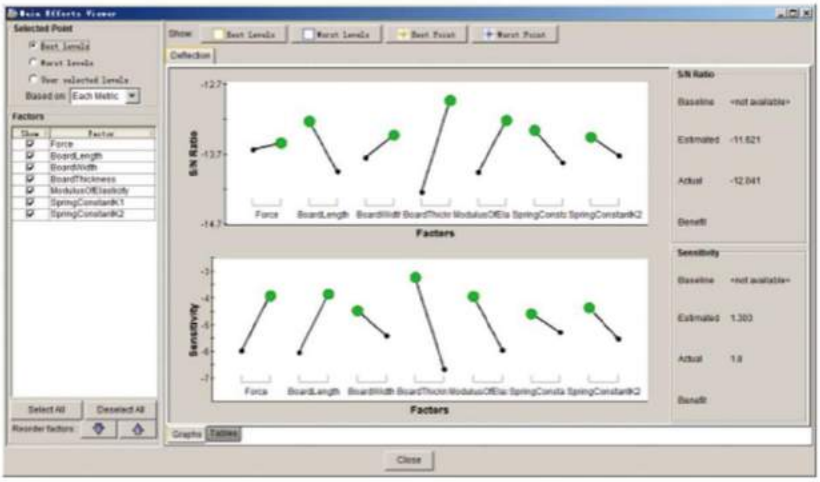
Signal factor is set as follows:

For SupportPosition, Level = 24.0, 30.0, 40.0.

System response is set as follows:

Deflection is set to be response, [Type] is set to Higher is Better, and dynamic system characteristic is set to General Linear Equation.

Figure 8.12 Main effects viewer



a) Main effects of all control factors on Deflection are displayed in the areas of S/N ratio and Sensitivity, which are located in the center of the main effects viewer. Users can directly view the key control factors and sensitivity through the interface.

b) The best robustness design scheme can be estimated by selecting [Best Levels] from the check box of [Selection Points] at the top left.

c) To perform a checking computation, the estimated robustness design scheme can be verified by clicking [Execute] from the [S/N Ratio] and [Sensitivity] boxes on the right.

After decades of rapid development, the reliability-based robust technology has entered into a new stage and been widely spread in electronic, mechanical, chemical, automatic and aerospace fields. The reliability-based robust technology is applied to products from the most complex space crafts through to daily used washers, refrigerators, duplicators and cars, and tiny implants including cardiac pacemakers. The reliability-based robustness of products has become one of the important indicators used to measure product quality. With the development of reliability-based robust technology, new methods and means are constantly developed which attracts great attention of scholars from various countries.

References:

[a] Qiu Jiwei, Zhang Ruijun, Cong Dongsheng and Guo Nan. Study on Reliability Design Theory and Method of Mechanical Components [J]. Chinese Journal of Engineering Design, 2011, 18 (06): 401-406+411.

[b] Zhang Yimin. Connotation and Development of Mechanical Reliability Design [J]. Journal of Mechanical Engineering, 2010, 46 (14): 167-188.

[c] Zhou Feng. Mechanical Robust Reliability-based Optimization Design [D]. Taiyuan University of Science and Technology, 2011.

CHAPTER 9

Simulation of Material Processing Technology

CHAPTER 7

Simulation of Material Processing Technology

Product design shall meet requirements for service performance and have manufacturability. The product with excellent manufacturability can guarantee its quality at a reduced cost. The simulation of material processing technology can effectively verify and optimize the manufacturability of products.

9.1 Overview

Considering that products are made of various materials, there are multiple technologies for processing and manufacturing products with these materials. Manufacturing processes can be divided into machining and non-traditional machining according to energies for manufacturing. Non-traditional machining is a general term describing all machining methods except those only using mechanical energy. The available energies include electric energy, heat energy, fluid energy, luminous energy, sound energy, chemical energy and mechanical energy.

Machining includes cutting and shaping. Non-traditional machining includes electrospark machining, electrochemical machining and high-energy beam machining. 3D printing of additive machining belongs to the non-traditional machining. Non-traditional machining is essentially different from traditional cutting and shaping in terms of machining mechanism and mode.

The current simulation of material processing technology is mainly based on theories of mechanics and heat transfer for simulation computing of deformation, stress and temperature of materials during processing. This chapter focuses on the process simulation of machining.

9.2 Process Simulation Modeling

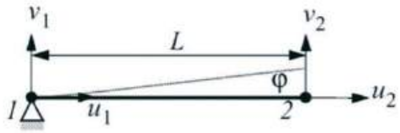
Material processing is a process of obtaining the materials in required geometry and dimension based on interaction between tools or molds and materials. Therefore, the process simulation model shall be able to precisely express materials, tools and their interactions, correctly describe the mechanical behaviors of materials and tools in the process, and accurately predict the processing quality of products.

For mechanical analysis, the phenomenon that deformation displacement and strain of materials and tools involved in the machining is called geometric nonlinearity rather than a linear relationship. The phenomenon that stress is not proportional to strain for materials (or tools under special conditions) is called material nonlinearity. The contact relationship between materials and tools interacted is called boundary nonlinearity. Therefore, the simulation of material processing technology is a complicated nonlinear mechanical problem.

9.2.1 Geometric Nonlinearity

Geometrical nonlinearity includes large deformation and large displacement. The small deformation with large displacement shall also be treated as a geometric nonlinear problem. The commonly used engineering (infinitesimal) strain is suitable for the case of small deformation and displacement, as shown in Figure 9-1. The geometric nonlinearity requires logarithmic (natural) strain (also known as true strain).

Figure 9-1 Engineering (infinitesimal) strain



$$\varepsilon = \frac{\partial u}{\partial x} = \begin{bmatrix} \frac{-1}{L} & 0 & \frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \end{bmatrix} = \frac{u_2}{L}$$

Engineering (infinitesimal) strain is defined as follows:

ex = du/dx

For minor rigid body rotation,

u2 0, v2ˆϕL

Since ϕ value is small (tan (ϕ)ϕ),

εx = u2 / Lˆ0

ε y = v2 / L = ϕL / L = ϕˆ0

For arbitrary rigid body rotation,

u2ˆL (cosϕ – 1), v2ˆL sinϕ

So,

εx = cosϕ – 1 ﬃ0

εy = sinϕ ﬃ0

According to calculation of engineering (infinitesimal) strain, the rigid body in rotation produces non-zero strain.

Engineering (infinitesimal) strain = εE = (L – L0)/L0

- Engineering (infinitesimal) strain corresponds to engineering stress.
- Engineering (infinitesimal) strain is only applicable to small deformation and strain.

Logarithmic (natural) strain = εL = dL/L = ln(L/L0)

- Logarithmic (natural) strain corresponds to Cauchy stress.
- It is suitable for large deformation and strain.

The relationship between engineering (infinitesimal) strain and logarithmic (natural) strain is as follows:

εL = ln(1+ εE)

In case of small strain (e.g. <3-4%), identical results will be obtained by different strain/stress measurement methods.

Engineering (nominal, conventional) stress= σE = F/Ao

- Computation depending on area and geometric dimensions before deformation

Cauchy (true) stress = σC = F/A

- Computation depending on area and geometric dimensions after deformation

9.2.2 Material Nonlinearity

Material nonlinearity means stress is in nonlinear relation with strain. For example, rubber is a nonlinear elastic material, as shown in Figure 9-2, and metal is a nonlinear elastoplastic material, as shown in Figure 9-3.

Figure 9-2 Hyper-elastic material

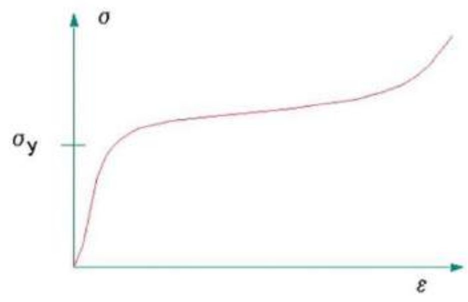
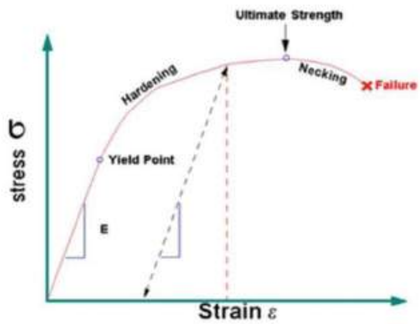


Figure 9-3 Elastoplastic material



9.2.3 Contact

During machining, materials and tools interact with each other by means of contact. The contact is defined as inequality constraint in a simulation model, which is called boundary nonlinearity.

Contact is defined as point-to-point contact and body-to-body contact. For point-to-point contact, gap unit (GAP) is defined as a contact element with the assumption that small tangential displacement happens at the contact points and the contact exists between two selected points.

Contact element is not necessary for body-to-body contact, and arbitrary motions between contact bodies are allowed, including two-body contact and multi-body contact. These contact bodies include elastic bodies and rigid bodies. Rigid bodies are assumed to be non-deformable. That is, these bodies have no stress and they can transfer heat and have temperature.

Friction will be produced due to interaction among these contact bodies. Coulomb friction and shearing friction are frequently used in friction models. If static friction is involved, a "stick-slip" model can be used.

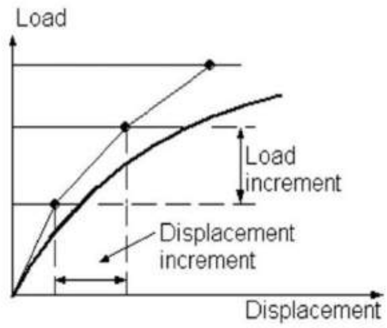
9.3 Process Simulation Computing Method

9.3.1 Iterative Computation

Simulation of material processing technology is a non-linear problem. The computing results of a non-linear problem are related to the loading path. The non-linear problem is normally loaded by incremental method, and the iterative computation is conducted in each incremental loading step.

For computation of a simple increment loading, as shown in Figure 9-4, the final computing results will deviate from the true equilibrium position.

Figure 9-4 Increment loading



Algorithm of simple increment:

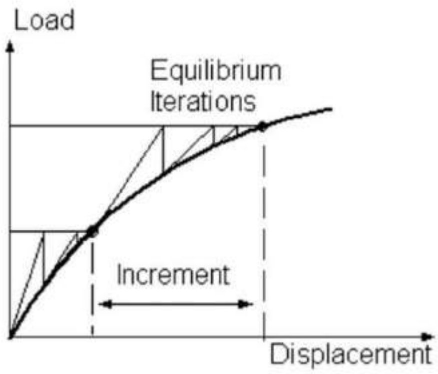
- Increment loading
- No iterative correction
- Residual amount estimation based on increment step
- Following path
- Stiffness update for each increment step
- Excursion from true equilibrium position

To allow the computing results to be consistent with the true equilibrium position, it is necessary to implement iterative computation in each incremental loading step to converge to a true value, as shown in Figure 9-5.

Incremental iterative algorithm:

- Increment loading
- Iterative correction until convergence to equilibrium position of increment step
- Following path
- Stiffness matrix update for each increment step or iterative step
- Newton-Raphson method

Figure 9-5 Iterative computation



9.3.2 Newton-Raphson Iteration Method

The following equation shall be solved during computation:

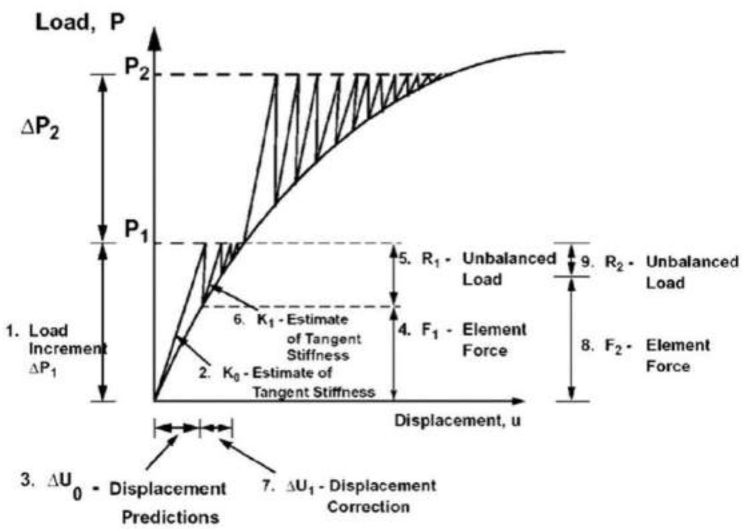
$$[K]\{a\} - \{F\} = 0 \text{ or } \{I\} - \{F\} = 0$$

The equation aims to balance the internal force {I} and the external force {F}.

In linear analysis, the equilibrium equation can be solved in one step through Gaussian elimination method. However, in nonlinear analysis, both stiffness and external force may be displacement functions. Newton-Raphson method can be used to solve such a nonlinear equation, which is an incremental iteration method.

$$I(a) - F(a) = 0$$

Figure 9-6 Newton-Raphson iteration method



Algorithm:

a) Determine an increment (external force, displacement or arc length) in the equilibrium path.

b) Compute tangential stiffness matrix.

c) Compute displacement increment by solving the equilibrium equation.

d) Compute element force according to displacement.

e) Compute the unbalance between element force and external force, and check whether the unbalance converges. If convergence occurs, follow the first step; otherwise, continue to the next step.

f) Compute tangential stiffness matrix.

g) Compute the displacement increment caused by unbalanced force.

h) Compute element force

i) Compute the unbalanced force and check whether the force converges. If convergence occurs, follow the first step; otherwise, continue to the sixth step.

Steps 1 to 5 refer to the loading stage or the prediction stage.

Steps 6 to 9 refer to the correction stage or iteration stage.

ΔP1 do not have to be equal to ΔP2.

K0 and K1 do not have to be equal.

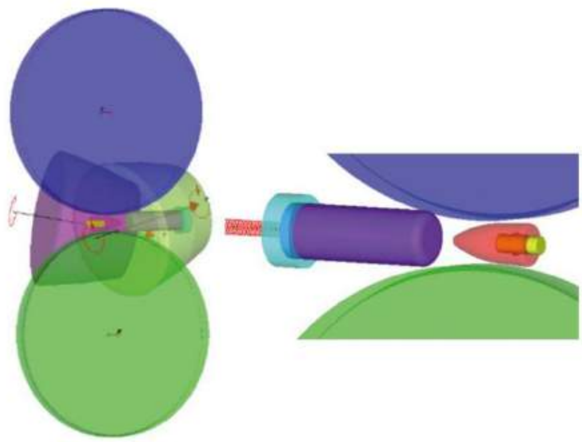
9.4 Simulation of Cross Piercing of Seamless Steel Tube

Steel tube piercing is a process that a solid round billet is subject to two-roll skew rolling at high temperature and is pierced to form a hollow billet under the action of a piercing plug and a guide disc. It can be seen that the steel tube piercing process involves flow deformation of metal materials, interaction between tube blank and tools, and thermal coupling. Therefore, from the perspective of simulation computing, the steel tube piercing process is a highly complicated nonlinear thermo-mechanical coupling problem, including material nonlinearity of metal plastic deformation, geometric nonlinearity of large material flow deformation and contact nonlinearity of interaction between the tube blank and tools.

9.4.1 Finite Element Simulation Modeling of Cross Piercing

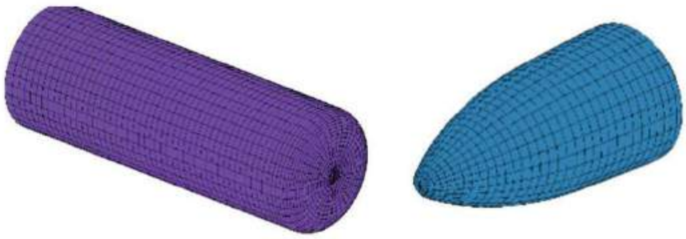
Figure 9-7 is a diagram of 3D geometric model of the simulation. The geometric model is mainly composed of a roll, a guide disc, a piercing plug, a tube blank, a push trolley and a plug fixed bearing (supporting the plug). The push trolley is only used for auxiliary computation and has no effect on piercing process of the tube blank.

Figure 9-7 Diagram of geometric model of cross piercing



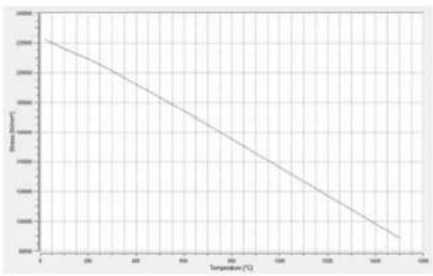
In the simulation computing, the tube blank and plug are set to elastic bodies, and their finite element meshes are shown in Figure 9-8. The roll, guide disc and other parts are set as rigid bodies. The roll and guide disc actively rotate at a preset rotating speed, the plug is driven by friction force generated by the tube blank to rotate freely, and the fixed bearing supports the plug. The push trolley defines a fixing force to assist the tube blank in biting into required zone.

Figure 9-8 Finite element meshes of tube blank and plug

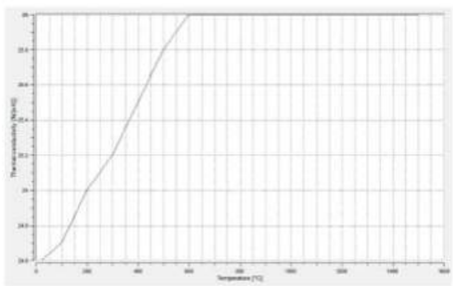


The material designation of the tube blank is X20Cr13, and material properties used in the computation are shown in Figure 9-9. The material designation of the plug is X54NiCrMoW4, and material properties used in the computation are shown in Figure 9-10. The effects of temperature and strain rate on parameters of material are taken into consideration. The thermophysical characteristics (coefficient of heat conduction, heat capacity and thermal expansion coefficient) of the tube blank and plug materials vary with temperature. The resistance to deformation is a function of thermodynamic parameters (deformation extent, velocity and temperature).

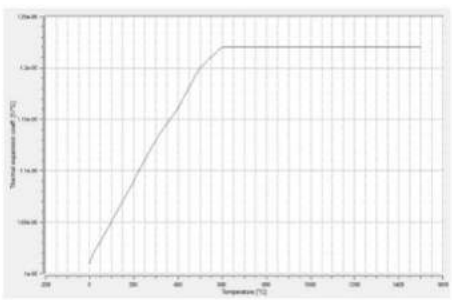
Figure 9-9 Parameters of tube blank material model



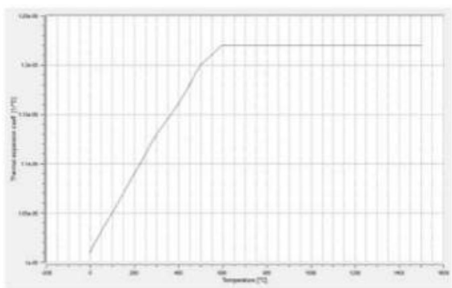
Young modulus



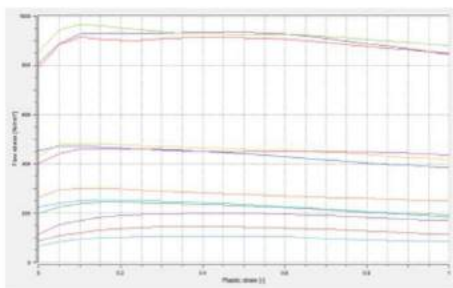
Coefficient of heat conduction



Specific heat capacity

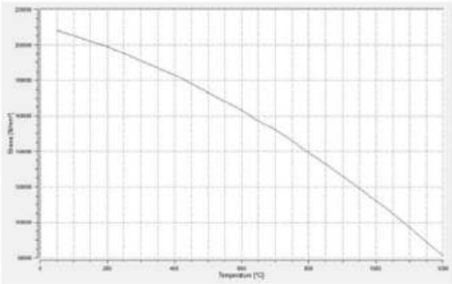


Thermal expansion coefficient

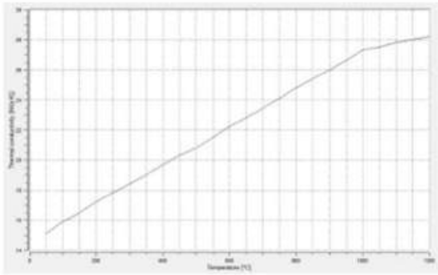


Flow stress curve

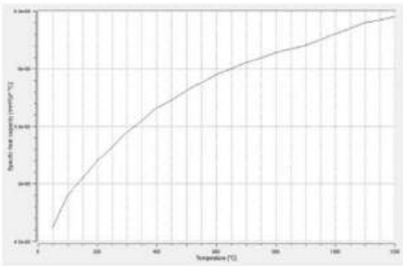
Figure 9-9 Parameters of tube blank material model



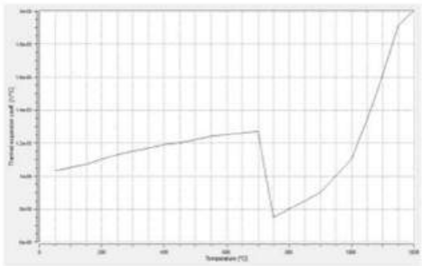
Young modulus



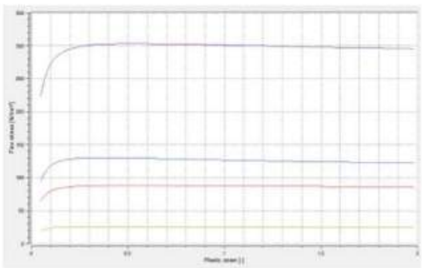
Coefficient of heat conduction



Specific heat capacity



Thermal expansion coefficient



Flow stress curve

It is assumed that the contact surfaces of the roll, the guide disc, the plug and the tube blank are subject to Coulomb law of friction. The coefficient of friction between the roll and the tube blank is 0.45, between the guide disc and the tube blank is 0.3, and between the plug and the tube blank is 0.3.

Temperature rise occurs in the plug and tube blank due to heat generated by plastic deformation and friction. It is assumed that 90% of the plastic work and friction work are converted into heat.

The roll and guide disc are regarded as thermostatically rigid bodies with surface temperature of 150°C. The initial temperature of the plug is set to 20°C, and the initial rolling temperature of the tube blank is set to 1200°C.

There are convection and radiation heat transfer between the free surface of the rolled piece and surrounding. Considering such radiation and convection heat transfer, the heat exchange coefficient is 0.2kW/(m2°C), and the ambient temperature is 50°C.

When the tube blank contacts with the roll, the guide disc and the plug, there is contact heat transfer between the tube blank and these parts. The coefficients of contact heat transfer between the work piece and the roll, the guide disc and the plug are set to 20kW/(m2·°C), respectively.

9.4.2 Finite Element Simulation Results of Cross Piercing

The simulation results of the two skew-roll piercing are shown in Figure 9-11. In the figure, a roll is hidden for the purpose of display.

Figure 9-11 Simulation of piercing process

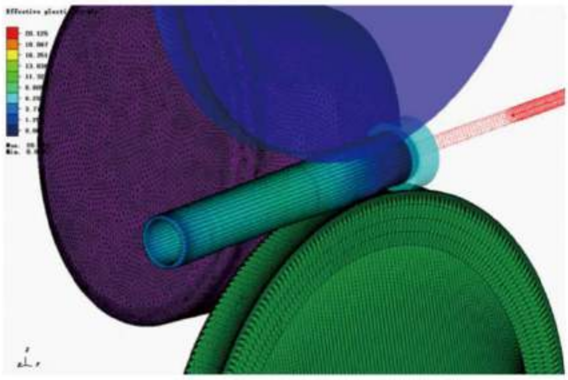


Figure 9-12 Material flow during piercing

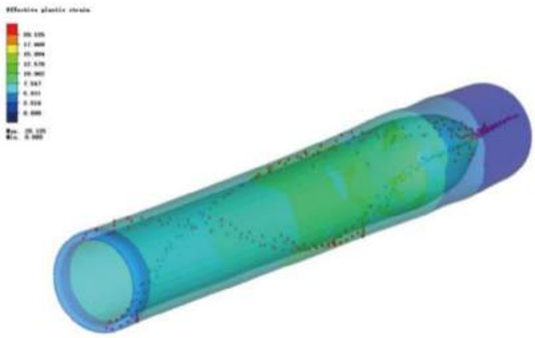


Figure 9-13 Profile of the rolled piece on the plane of the roll

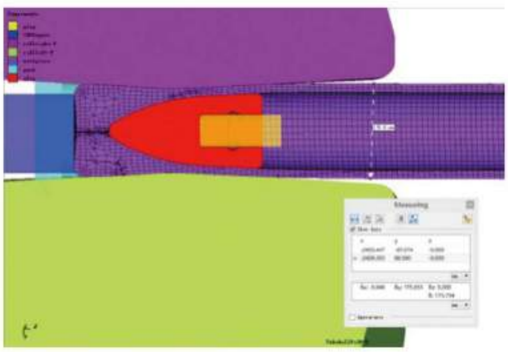


Figure 9-14 Profile of the rolled piece on the plane of the guide disc

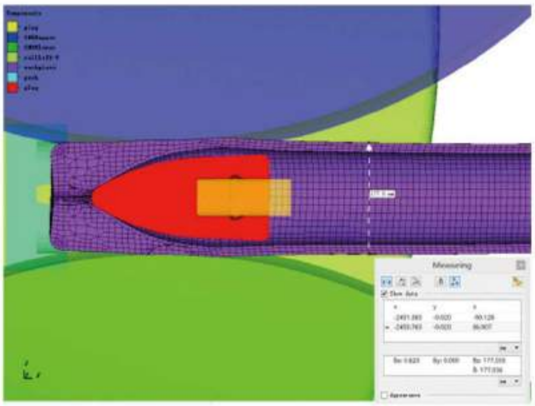


Figure 9-15 Cross-sectional views of the rolled piece at different longitudinal positions during piercing

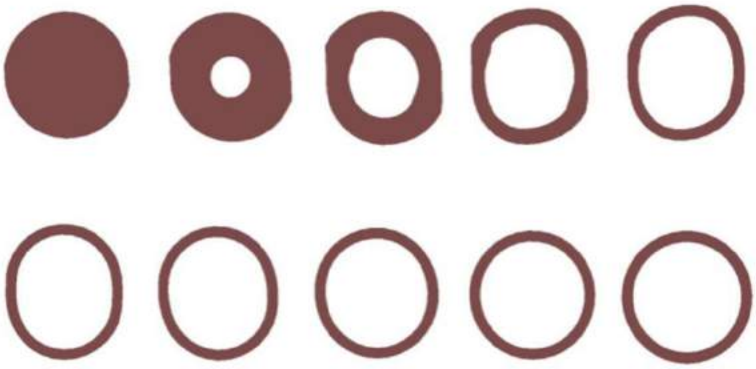


Figure 9-16 Temperature distribution of the plug

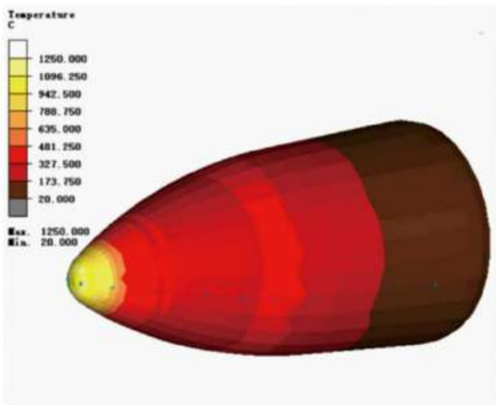


Figure 9-17 Profile of temperature distribution of the plug

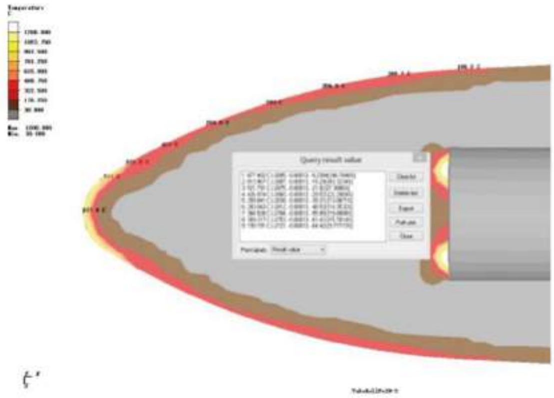


Figure 9-18 Contact stress of the plug

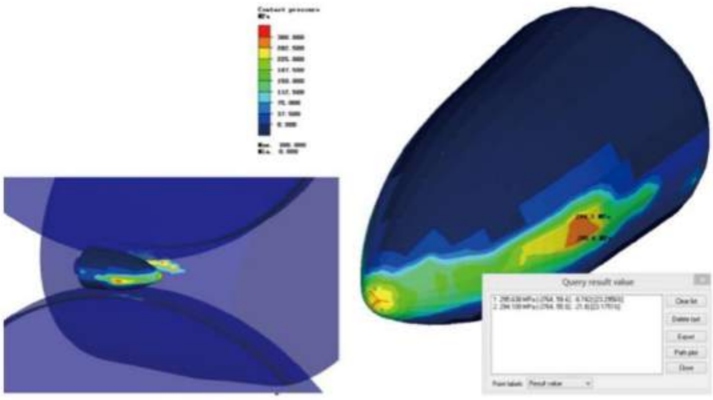
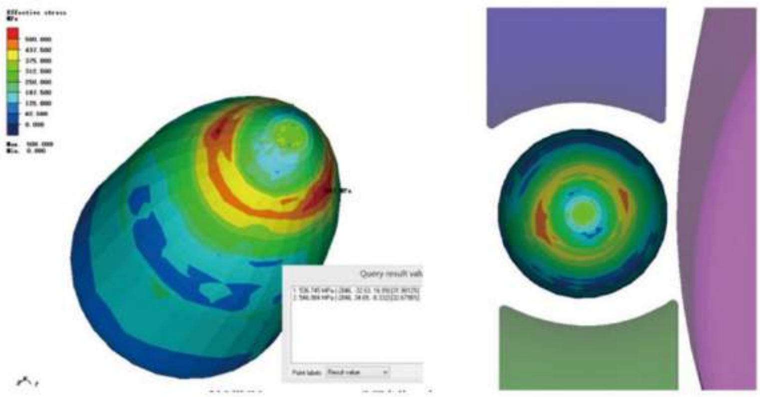


Figure 9-19 Equivalent stress of the plug



CHAPTER 10

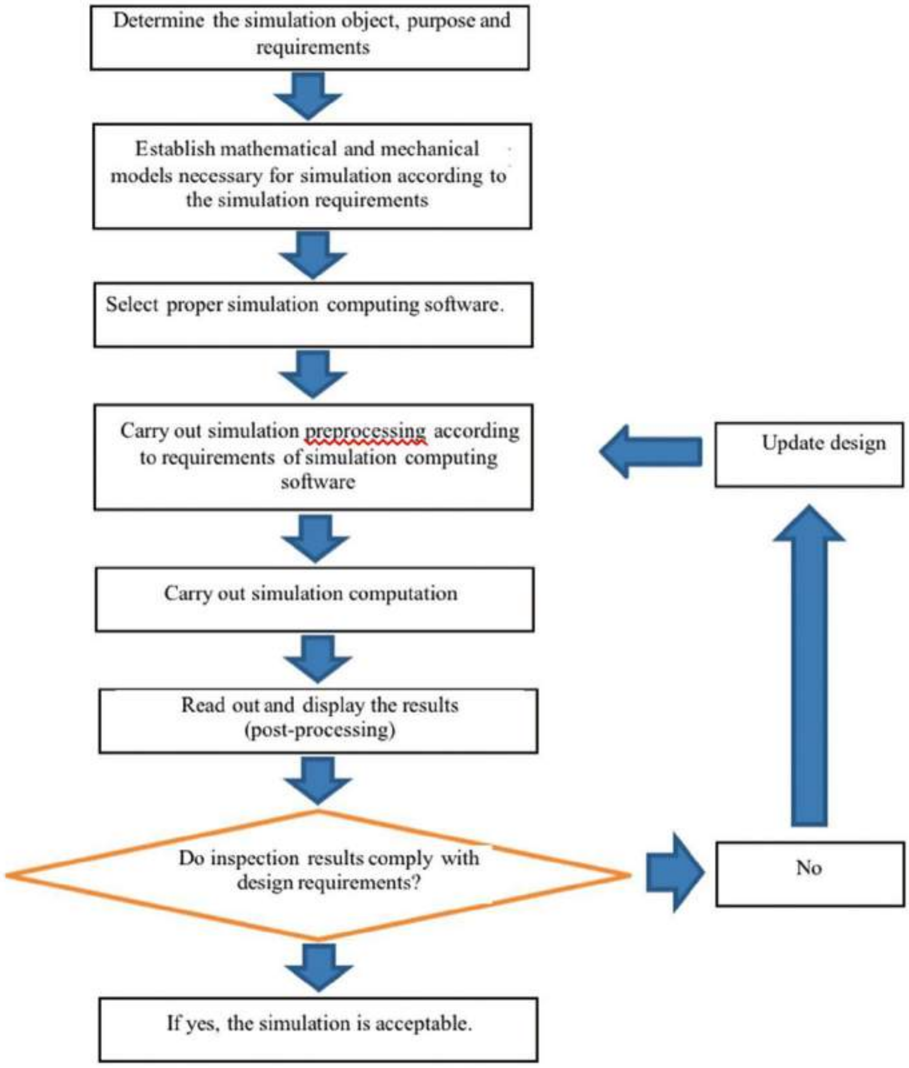
Establishment of Digital Virtual Test Standard for Enterprise Products

CHAPTER 10

Establishment of Digital Virtual Test Standard for Enterprise Products

10.1 Overview of Simulation Process

Based on knowledge above, we could conclude that a virtual simulation can be completed through the following steps:



10.2 Verification of Simulation Results

Simulation preprocessing includes the following steps:

a) Import of product CAD model

b) Simplification and fixing of CAD model

c) CAE meshing

d) Assignment of material parameters

e) Settings of constraints, boundary conditions and connection relations

f) Setting of loading conditions

A model capable of simulation computing can be generated by the mentioned preprocessing steps. After the simulation computing, the simulation software is used to post-process to read out the required results.

How can we judge the correctness and reliability of these results? Firstly, we need to check the simulation results against benchmarks of the test.

We need to check the relative errors between test results and results computed based on the simplified model and steps. We should confirm that these simulation simplifications are correct and relevant results are also credible.

10.3 Basic Concept of VV&A

The important function of simulation is to implement the virtual verification of products after design through digital modeling without an actual prototype, so as to greatly reduce the manufacturing cost of the prototype. Through multiple digital simulation verifications, it is conducive to modify the design and seek the optimal design schemes before the prototype is manufactured.

Therefore, the key is that whether the digital model could authentically represent the model we need after mathematical and mechanical simplification, and the computation is reliable. This is also a problem encountered by everyone. To guarantee and verify the correctness of the model, the concept of Verification, Validation and Accreditation of modeling and simulation has been defined internationally, which is short for VV&A concept.

VV&A concept was originally proposed in system simulation modeling. The system simulation modeling is only presented in a 0-dimensional or a 1-dimensional way rather than a 3-dimensional way. Therefore, a verification system and method should be established to confirm that relevant modeling simulation can accurately reflect the function and performance of products in 3-dimensional designs. Similarly, there are multiple simplifications and hypotheses during modeling for 3D design and simulation. Thus, VV&A process shall also be conducted to prove the correctness and credibility of modeling and simulation.

The verification, validation and accreditation are literally similar, but they have different meanings in simulation systems.

Verification is used to determine whether the simulation system accurately represents the conceptual description and design process of the product designer. Verification is concerned with the issue of "building model and simulation system in correct way (building the model right)", i.e., designers shall convert the problem statement into model description and correctly design model of the simulation system according to applications and functional requirements of the simulation system, and simulation software developers shall correctly implement the simulation model provided by the designers. For our three-dimensional design and digital simulation, verification focuses on reasonable model simplification, which involves the following problems: How to select computing software? (static, dynamic, non-linearity, heat and electromagnetic field problems) What kind of element shall be used? (solid element, plate & shell element, beam element and element size) How to load? What are the constraints required? All of these problems shall be solved before simplification to ensure correctness of models.

Validation is the process of determining the consistency between the simulation system and the actual system according to applications of the simulation system. Validation is concerned with " building the right model", i.e., "to what extent the simulation system reflects the real world in the concrete application ". That is, if we set material parameters and load size in the model to calculate displacement, deformation, stress and strain, we need to validate whether that computing results are consistent with test results. Whether the simulation has reference value and whether we can use this modeling method safely in the future can only be determined after validation.

Accreditation is a process of "officially accepting a simulation system for a specific application purpose (the official certification)". Accreditation is an official certification of acceptability and effectiveness of the simulation system, which is implemented by an acceptance group consisting of personnel of the competent department, users and experts of the simulation system, after verification and validation. Only in this way can modeling method be solidified and written into a specification manual for simulation modeling, just as a standard operating manual to be followed in a real physical test. The specification manual prepared and established for simulation modeling is the precious knowledge of enterprises in digital design and simulation. With such specifications, we can relievedly obtain the same results with credibility from the same simulation, regardless of staff turnover or different engineers for simulation.

Verification, validation and accreditation are closely linked. Verification provides basis for accreditation of the system, validation provides basis for assessment of system effectiveness, and both verification and verification are associated with the system performance.

Significances of VV&A:

a) VV&A provides objective basis for credibility evaluation of application purpose of the modeling and simulation system, and improves the confidence of the system sponsors and users in solving specific problems by applying the simulation system.

b) Verification and validation work can early detect the problems and defects in the modeling and simulation design and development, and assist designers and developers in taking measures to modify the model design and software development, so as to avoid the losses and risks to the simulation system due to defects and errors in the design and development process.

c) Verification and validation work provides a good foundation for application of modeling and simulation in the future, and can increase the confidence in applying modeling and simulation for specific application purposes.

d) Verification and validation work can detect errors in design and development as early as possible, reduce losses caused by errors of model and simulation strategies, and provide important data for developing simulation systems.

e) Verification, validation and accreditation provide potential power for improved analysis of prototypes.

Common concepts in VV&A:

a) Model testing

Model is checked for errors or imprecise and inaccurate properties or conditions. Normally, certain data and cases are given to judge consistency between results of the model and the actual system.

b) Simulation accuracy

It indicates error or permissible error between static and dynamic technical indexes receivable in the simulation system and specified or expected static and dynamic performance indicators. Factors affecting the simulation accuracy include material parameters, mesh parameters and model simplification methods.

c) Simulation fidelity

It indicates the proximity of model to prototype for specific modeling purpose, i.e., the strong and weak similarity between the model and the prototype.

10.4 General Principles of VV&A

There are 12 universally applicable principles summarized in the internationally recommended guidelines for VV&A methods, as shown below:

a) Principle of relative correctness

The credibility of model has restricted range and specific conditions.

The correctness of modeling and simulation is only available for the application purpose and experimental environment. A complete and integrated simulation model testing is impossible.

There is no definitely correct model.

b) Full lifecycle principle

VV&A shall be followed throughout the lifecycle of modeling and simulation development.

VV&A activities shall be arranged at every stage in the lifecycle of a simulation system according to study contents and application purposes to detect possible problems.

c) Principle of limited purposes

The purpose of VV&A shall focus on application purpose and functional requirements of the simulation system.

Before accepting and confirming the modeling and simulation results, problems shall be systematically described to define the problem scope in modeling and simulation correctly.

d) Principle of being "necessary but insufficient"

VV&A cannot guarantee correctness and acceptability of application results in the simulation system.

VV&A is necessary but insufficient. The following three types of errors shall be avoided if possible:

"The simulation system is correct but rejected";

"The simulation system is incorrect but accepted";

"The simulation system solved a wrong problem".

e) Global principle

Verification and validation of individual components of the simulation system cannot guarantee the correctness of the overall simulation system. The correctness of the whole simulation system must be verified and validated throughout the system.

f) Locality principle

If a simulation model only focuses on a component of modeling and simulation, the evaluation shall also be limited to the component.

Acceptance of all sub-models does not mean that the overall model passes the test.

Credibility of the overall simulation model cannot be inferred by verification and validation of sub-models, and vice versa.

g) Extent principle

Acceptance of modeling and simulation is not an either-acceptance-or-rejection issue.

The results of VV&A cannot be used to arbitrarily judge whether the simulation model is absolutely correct or incorrect, but to judge the acceptable level against application purpose of the simulation system.

h) Creativity principle

Simulation is a highly creative technology. The VV&A of simulation system shall be carried out by personnel with sufficient insight and creativity.

VV&A is both a science and an art.

i) Principles of good planning and recording

VV&A of a simulation system must be implemented according to plan and recorded in detail to provide necessary information for follow-up work and acceptance.

A good plan shall cover the activities that contribute the most to the correctness of the simulation system and the credibility of the simulation results, and optimize the implementation process to maximize the chance of finding problems and improve the simulation system.

j) Analyticity principle

VV&A of simulation systems not only involves the data obtained from system testing, but also makes full use of the knowledge and experience of system analysts to carry out detailed and in-depth analysis on relevant problems.

k) Principle of relative independence

VV&A requires "independence without preference" to ensure the independence of evaluation and prevent judgment against developer's preference.

VV&A shall be conducted in cooperation with designers to sharpen their understanding of the system.

l) Principle of data correctness

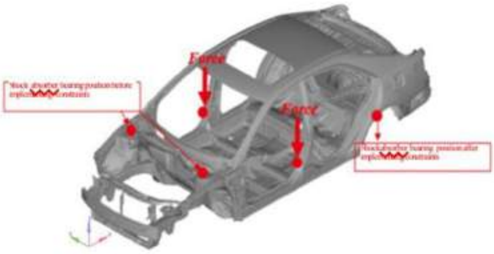
Successful VV&A requires that data must be verified, validated and accredited before use.

The data and database required by VV&A must be verified, validated and accredited to prove their correctness and sufficiency.

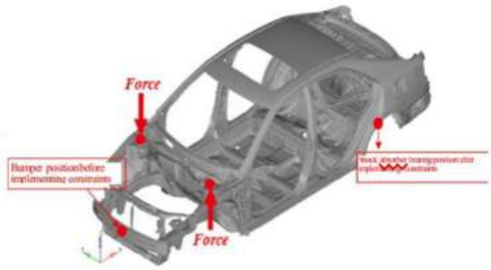
10.5 Demonstration of Cases

The figure below is a specification diagram of simulated bending stiffness and torsional stiffness of body in white of an automobile enterprise:

10.5.1 Specification diagram of loads and constraint positions in simulation computing of bending stiffness;



10.5.2 Specification diagram of loads and constraint positions in simulation computing of torsional stiffness;



In addition to simulation specifications for constraints and load conditions, the actual simulation specifications should cover other details, including:

a) Simulation software of developing company required for the type of simulation computing, i.e., software name and software version number, including computing software name as well as pre-and post-processing software names;

b) Standards for simulation meshing for every component, elaboration of elements for corresponding components, size of every mesh, and quality inspection requirements for meshing;

c) Material card of the computing software, which is used for setting material parameters of components;

d) When defining the component assembly joint relationship, the link units of the software to be applied;

e) Various loading positions, and ensure that there are nodes at these positions;

f) The designation of various constraint positions and types.

In conclusion, a detailed specification will be developed for the same type of simulations, and a simulation specification manual will be prepared to ensure that different engineers can obtain the same results depending on simulation of the same model. Even though there is a change in simulation engineers, specification requirements generated based on simulation experience will be passed on within the enterprise through the manual.

10.6 Solidification of Experience in Setting Up Simulation Analysis

The environment setting parameters of simulation analysis applied to actual situations and analysis processes are precious knowledge wealth of enterprises. The parameter settings and processes have been tested and corrected through numerous tests and are pretty close to practical engineering conditions. These valuable experiences are solidified through the mentioned simulation analysis process template to ensure that the engineering analysis results are also accurate after designing new products.

Enterprises can standardize CAE simulation analysis work by developing and applying the CAE simulation analysis specification, so as to effectively reduce the time required for CAE analysis and improve the CAE analysis quality. Enterprises can further accumulate experience and knowledge involving engineering analysis by establishing an accumulation-update mechanism according to the specification, with the purpose of improving the enterprise-wide R&D and design/analysis capability for products, and promoting enterprise analysis knowledge sharing and innovation.

CHAPTER 11

Establishment of Automatic Enterprise Digital Virtual Test Process

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Establishment of Automatic Enterprise Digital Virtual Test Process

This chapter introduces the introduction of general simulation software, enterprise-specific interfaces and computing technologies, to form dedicated digital simulation tools for enterprises' own products.

11.1 Characteristics of Enterprise Digital Virtual Process

Complex products with multiple functions produced by manufacturing enterprises are usually composed of multiple materials and components with varying loads borne. Two important indexes of these products are economic efficiency and safety, and safety needs to be guaranteed through a variety of tests. Taking automobile manufacturing as an example, automobile fatigue strength is all tested after the prototype is manufactured, thus the internal structure of the car is unchangeable. The automobile structure design will be affected if special circumstances are encountered, which will prolong the automobile development cycle. As computer hardware and software refine, new automobile test methods have changed greatly. For example, tests can be completed on the virtual proving ground. Enterprises can use digital virtual test, an important technical means in modern manufacturing, to repetitively test products at relatively small costs without consuming any physical resource. As for the automobile industry, large Original Equipment Manufacturers can already perform various operating conditions tests without a prototype, greatly shortening the product development time. In addition, the product can be re-designed against the problem detected. Therefore, it is very necessary for enterprises to build the digital virtual test process.

At present, VPG, a virtual test technology based on the secondary development of large simulation analysis software (e.g. MSC Adams/ANSYS/LS-DYNA), can realize the virtual tests for parts and even the whole product. Again, taking the virtual test of the entire vehicle as an example, we can use a vehicle as a study object, enter required speed and simulated road data and consider various nonlinear factors to obtain a relatively high analytical precision. Although there are errors between the virtual and prototype tests, the engineering error can be controlled within an acceptable range by improving the virtual model. Therefore, the enterprise digital virtual test can partially replace actual product testing.

The obvious technical features of enterprise digital virtual test include:

a) The product to be tested and fully digitized test conditions. This means test objects (enterprise products such as automobiles), test instruments, test environmental conditions (temperature, humidity, wind speed and the like), test tools and fixtures, test processes and loading processes must have been digitally modeled and loaded into computer memory. In other words, digitization underlies the virtual test.

b) The virtual test satisfies the loop of the real test process. The physical logic from the input end to the output end during the real test must be reconstructed in the virtual test. In a word, the consistency between the virtual circuit and the physical circuit is the prerequisite for ensuring that the virtual test results are correct. In the fatigue test of the entire vehicle for example, all important links and their connections need to be reconstructed in the virtual test.

c) Virtual tests need to coordinate with physical tests. Although the virtual test can restore the real test situation with high fidelity, it is not suitable for basic parameters of some materials, long-term performance of components, and test items with great randomness. For example, basic mechanical tests should be performed for structural and material parameters of elastic components (e.g. springs and rubber) to obtain reliable real performance parameters, and then the reliable real performance parameters are modeled in virtual test models to obtain accurate virtual test results. For another example, for highly dispersed fatigue performance parameters, fatigue tests of large complex structures still need real tests instead of virtual test methods.

In conclusion, the virtual proving ground can be constructed by using multiple digital modeling and simulation tools, applying virtual prototype technologies, establishing accurate digital models for an integrated system, simulating the dynamic analysis under various working conditions, and finally extracting the test results of interest. Virtual tests provide a technical alternative to the physical product tests which are costly and time-consuming. Ideas for constructing a vehicle's virtual proving ground are shown in Figure 11-1. The composition of NASA's intelligent virtual flight control test is shown in Figure 11-2. Combined with this case, the following describes the characteristics and process of the virtual test.

Figure 11-1 Technical analysis of virtual vehicle test field

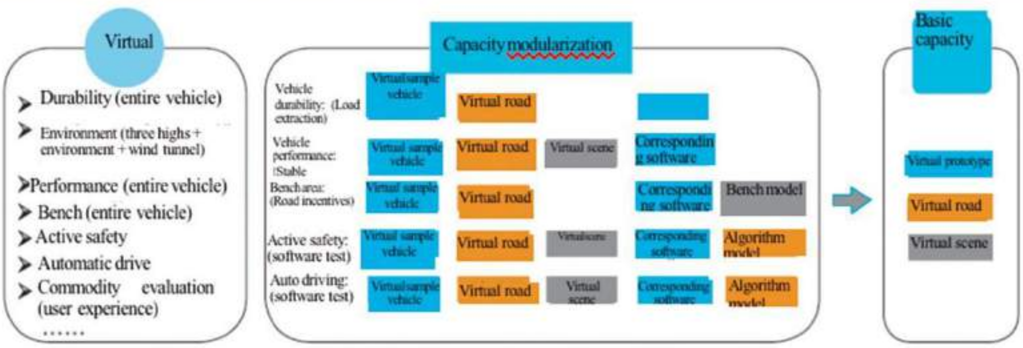
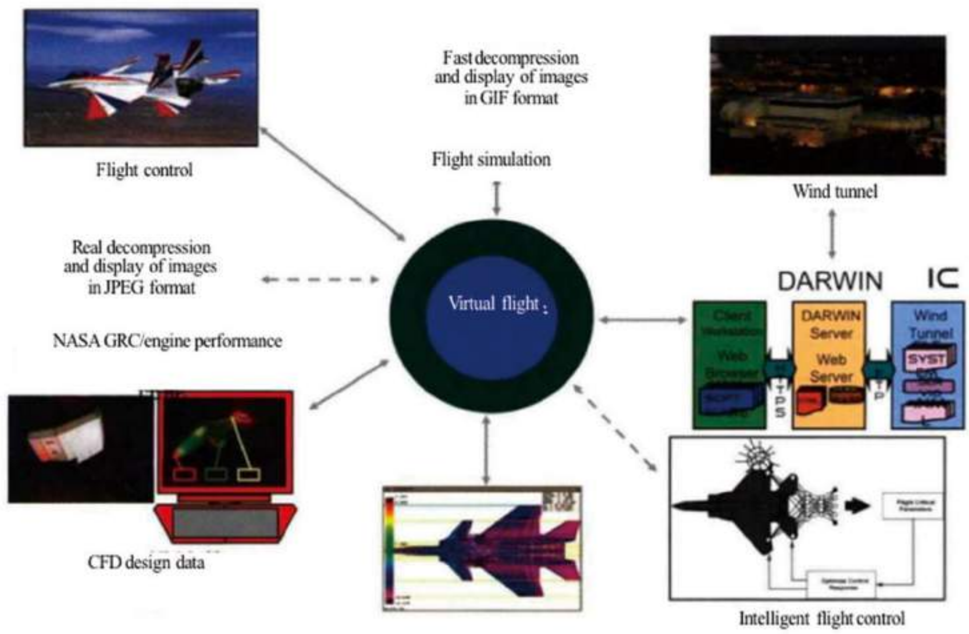
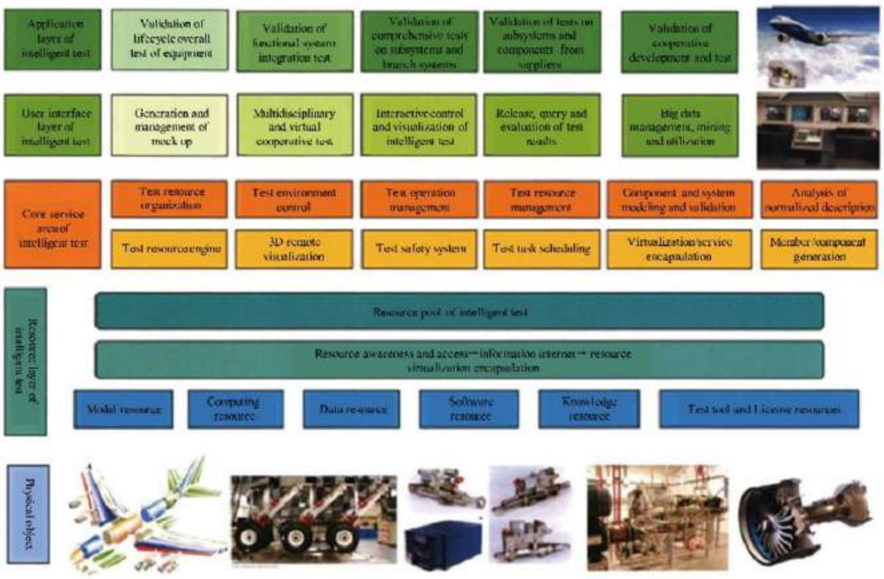


Figure 11-2 Virtual flight control system of NASA



The virtual test not only supports the component and subsystem verification during the product development, but also supports the comprehensive verification and system integration verification of the subsystems and branch systems, as well as the whole-cycle overall test of products. To better explain the hierarchical structure of the virtual test system, a layered architecture is used including (from bottom to top) a virtual test physical object, a virtual test resource layer, a virtual test core service layer, a virtual test interface layer, and a virtual test application layer, in which the virtual test core service layer and the virtual test interface layer are further specified, and the virtual test core services are detailed from the logical view. The hierarchical structure of the virtual test system is shown in Figure 11-3.

Figure 11-3 Hierarchical structure of a virtual test system



The entire vehicle virtual test can be divided into entire vehicle durability, vehicle performance, vehicle bench, active safety, and active driving according to function areas. The above functional modules are subject to capability decomposition according to Figure 11-1, and the basic capabilities required for the construction of the virtual proving ground include virtual prototypes, virtual roads, virtual scenes, and virtual vehicle tests, as well as extraction of test data.

(1) Virtual prototype

In the entire vehicle virtual proving ground experiment, a virtual prototype needs to be established first. The overall modeling of the prototype uses a finite element model. In addition to the stress and deformation of the car body structure, the dynamic performance of the vehicle and the vehicle-road interaction model are key technologies. Available computing software includes Adams of the MSC series, Nastran and meshing tool Hypermesh.

(2) Virtual road

3D road modeling is mainly derived from digital reconstruction for 3D scanning data of the test field. To obtain comprehensive data, the types of test roads should be diversified, including various strengthened test roads, high-speed ring roads, durability test sections, ABS brake test sections and other types of roads.

Figure 11-4 Virtual vehicle test field

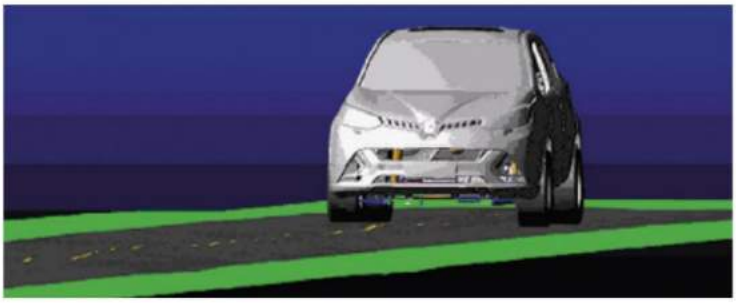
(3) Virtual scene

Next, virtual test conditions (virtual scenes) need to be constructed. Virtual scenes include roads, sky, cars, grass, trees and other elements. The near view shall be painted in a fine and realistic way, while the distant view is painted with relatively coarse grids to make the software more practical. Environmental changes should be quantitatively described with models and parameters, such as sunny, overcast, rainy, and snowy days. At the same time, the trees, grass and signs in the scene are painted to integrate the road and the scene into a field that meets the requirements, as shown in Figure 11-4.

(4) Virtual test for entire vehicle

The virtual prototype, virtual road and virtual scene are integrated through a model to form the virtual proving ground. The power parameters are entered and comprehensive tests of the virtual prototype are carried out according to the specified test driving conditions, as shown in Figure 11-5.

Figure 11-5 Virtual test for entire vehicle



(5) Extraction of test data

With the help of numerical computation software, required virtual test results and data can be obtained. For example, the finite element software is used to obtain the distribution map of dynamic loads between the vehicle chassis and the body's connection hard points, and the dynamic loads on each component are loaded in the finite element software, while corresponding constraints are applied to analyze fatigue durability of the vehicle parts. In this way, effective ideas to solve the problem can be obtained for guiding designers to conduct rational design and layout. For another example, valuable aircraft load data can be obtained from virtual flight tests, including overload (which significantly affects the pilot's physical conditions), load spectrum (stress/strain-time curve of each takeoff and landing of the aircraft), and so on.

11.2 Cooperative Computing Technology for Virtual Simulation

With the rapid development of computer network and IT-related technologies, computer supported cooperative work (CSCW) has sprung up. CSCW uses Internet to overcome the constraint of geographic distance, and uses high-speed transmission of network data to establish virtual cooperative work environment (e.g. remote guidance of surgery has been realized through networked VR), thereby it effectively supports large-group cooperative work across time and space, and makes a qualitative change in the way of work. CSCW has been widely used. In the field of digital design and manufacturing, one of CSCW's applications focuses on cooperative computing, especially for difficult engineering CAE work, such as structural finite element analysis, system dynamic analysis and other knotty problems.

CSCW focuses on solving the relationship problems among group members, between members and organizations as well as among knowledge areas, which means to timely find and resolve contradictions by computers, thus reducing unnecessary repetitions, improving work efficiency and minimizing losses. Some people hold different views on regarding computers as the connotation of CSCW system to identify and solve contradictions. For example, it seems that document transfer within or between organizations does not help to identify and solve contradiction. Is it a kind of cooperative work? The answer is yes. Because the documents are transmitted in an orderly manner among a certain group of people, and there are certain processes to conduct automatic management and ensure the correct transmission for circulation and correction.

The cooperative computing for virtual simulation is mainly characterized by:

a) Groupment

When using the CSCW system, we should first make clear the members who we should cooperate with and their permissions. The CSCW system supports multiple groups, and a member is allowed to participate in multiple groups' work, but non-member cannot participate in the activities of the group. Group members can be people, organizations, and even domain knowledge, so the groupment is clear and definite.

b) Interactivity of groups

The CSCW system is different from software that supports individual work. In this system, the groupware cannot be used by any individual, which is impractical and meaningless. It must interact with members of the group. This is similar to traditional telephones, which require two persons to make a call. Therefore, a group, which consists of more than two members, must be identified, and the group members must participate in interaction.

c) Dynamic

Members of working groups, task scheduling, equipment and environment are changing dynamically throughout the working process, from steps to stages. Therefore, the cooperative process shall be adjusted from time to time according to changes in members, equipment, task requirements, implementation and other influencing factors to meet the requirements of dynamic changes.

d) Concurrency

Traditional design methodology is implemented by individual designers who cannot share information in a timely manner. Therefore, possible contradictions and conflicts cannot be discovered until at the manufacturing stage. As a result, massive losses are inevitable in most cases. The concurrent engineering is developed to correct shortcomings in current design method by exploring new concurrent design methodology. CSCW needs supports in terms of concurrent design method, implements and develops new methods. Concurrency has two meanings. Attention shall be paid to ensure highly-concurrent tasks based on general concurrent task scheduling. The efficiency of parallel computing depends on specific cooperative computing.

e) Remoteness

Group members are generally located in different regions and shall communicate through LAN, enterprise network or Internet.

f) Metachronism

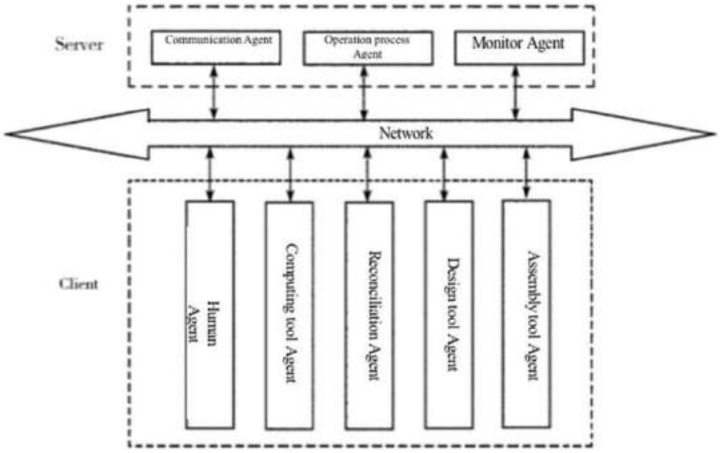
Metachronism is another important characteristic of CSCW. Software-based man-machine interaction is the only available form in the individual working mode. However, in the cooperative work mode, there is a tripartite relationship among the group, individual and software system, so communication among them is a critical task. According to the temporal relation of interaction among members, there are real-time interaction and time-lapse interaction. For cooperative interaction, CSCW system often provides two working modes: synchronous mode and asynchronous mode. Synchronous mode refers to a real-time interaction in the presence of all members involved at the same time. The asynchronous mode allows an interaction between these members without the presence at the same time. That is, they can interact at different times within a specified time. Both of these working modes have strengths and shortcomings:

a) generally speaking, synchronous mode shall be enabled in case of highly-demanded instantaneity. For example, the synchronous mode and the most reliable communication method must be used to complete a surgical operation of a patient in another place. Further, in the actual test stage of a major project (e.g., space launch), the synchronous mode is also enabled for cooperation; and

b) on the other hand, for occasions where instantaneity is not required, the asynchronous cooperative design and computing are adopted to improve efficiency, flexibility and adaptability at a lower cost than that in the synchronous mode.

It should be noted that a few years ago, world-wide group coordination was still difficult to support the transmission of large-capacity multimedia data due to time difference and limitation of communication capability. The real-time transmission was expensive and difficult to realize. Therefore, international cooperation was basically implemented in the asynchronous mode. However, with the popularization and promotion of 5G technology, after 2020, it will be feasible for the transregional or even international group coordination in the synchronous mode and also for small and medium enterprises, the economic cost will be affordable. The organization of a typically cooperative working system is shown in Figure 11-6.

Figure 11-6 Diagram of cooperative working system

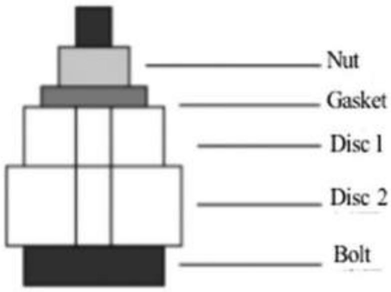


An engineering example of cooperative design is outlined briefly below.

Example: Cooperative design of a mechanical part

The design object is a bolt assembly, as shown in Figure 11-7. The example is really simple, small but complete. The example presents the meaning and characteristics of cooperative design.

Figure 11-7 Bolt assembly



The mechanical assembly comprises five subcomponents: a bolt, a disc 1, a disc 2, a gasket and a nut, as shown in the figure above. The "parameter modification" in the example refers to the modification of three parameters: total tension borne by the bolt, stress and safety factor. When these three parameters change, it is possible to change bolt diameter (d) in the original design depending on calculation with updated parameters. With the change of bolt diameter, the disc, gasket and nut shall be changed accordingly to maintain the matching relation. Meanwhile, the length of the bolt shall be coordinated with the total thickness of the disc, gasket and nut to avoid excessive or insufficient bolt length and provide a practical and pleasant appearance.

The cooperative design scheme is to:

- assemble the design task of the client at the server side or a "management" side, control the architecture of the overall system and integrate the bolt assembly;
- take charge of the detection and coordination of conflicts during the cooperative design. The task can be completed by a special person through a terminal supporting management function or by a program with AI function; and

• set Agent units for corresponding components in the bolt diagram.

The design process is realized by a plurality of cooperative Agents, including software agents and human agents. These Agents are characterized in that:

• they can be added or removed dynamically;

• they strongly support concurrent design and operation processes;

• they allow working in synchronous and asynchronous modes;

• reconciliation Agent can automatically detect and coordinate conflicts throughout the working process;

• they support human-human interaction to detect and coordinate conflicts; and

• they preserve all cooperation histories.

As Agents have outstanding characteristics in terms of autonomy and cooperation, the multi-agent system architecture attracts much attention. The cooperative design system adopts a system architecture combining multiple Agents and Client/Server. Normally, Agents can be structured in two ways: active architecture and reactive architecture. The Agents in active architecture have cognitive intelligence, and the rapidly developed artificial intelligence (AI) can play a significant role in the field. On the other hand, reactive Agents are incapable of ratiocinating and require manual intervention. In the example, the cooperative design system is designed as several relatively independent design tasks. The system consists of 13 Agents, with functions shown as follows:

a) Communication Agent is responsible for communication and management among the agents.

b) Monitor Agent is used for visually monitoring the running state of every Agent.

c) Operation process Agent is used to control and coordinate operation processes of the system.

d) Chairman Agent0 is a group member Agent that initiates the discussion of parameter modification; and it is also a discussion member Agent participating in the discussion of parameter modification.

e) Discussion member Agent1 is another member participating in the parameter modification discussion. It is a computing tool Agent that can compute according to input parameters as the CAE in the system, and coordinate the conflicting Agents as well as dimensional conflicts of components.

f) Nut design tool Agent2 selects a nut from a part repository according to constraints and makes design drawings.

g) Gasket design tool Agent3 selects a gasket from a part repository according to constraints and makes design drawings.

h) Disc design tool Agent4 selects a disc from a part repository according to constraints and makes design drawings.

i) Bolt design tool Agent5 selects a bolt from a part repository according to constraints and makes design drawings.

j) Assembly tool Agent6 assembles these parts and makes drawings.

The system has been realized as a scientific research achievement and incorporated in teaching in the Sun workstation /Intranet system of domestic universities.

11.3 Automatic Computing Technologies for Virtual Simulation

The automatic computing technologies for virtual simulation herein refer to (automatic) parametric modeling, automatic establishment of digital model (including automatic mesh generation), automatic computing and software system (combination) integration technologies, which are introduced one by one according to four aspects hereinafter.

11.3.1 Parametric Modeling

Popular CAD software basically supports parametric modeling which has become a leading CAD technology and serves as an important basis for subsequent parametric design. In the parametric modeling environment, parts are composed of feature sets. Features may be composed of positive or negative spaces. A positive spatial feature refers to a real block (e.g., a protruding boss), while a negative spatial feature refers to an excised or subtracted portion (e.g., a hole). Parametric modeling mainly focuses on the set of geometric elements required for design. The key issue during modeling lies in the way to create a parametric model that meets the design requirements. To this end, it is necessary to consider the following factors during parametric modeling:

a) Analyze the basic elements that make up the part's geometry, and the relations among the elements.

b) Analyze which elements are related to free parameters, and how to ensure free changes of parameters.

c) Determine the primary features of the model and all secondary features.

d) Use expression editor to analyze parts of expressions according to free parameters.

e) Determine the creation order of features and create the model.

f) Change the values of free parameters and verify that the changed model is acceptable.

The parametric modeling is fundamentally different from the conventional modeling. It mainly applies features and parameters, with more abstract geometric objects. Specifically, parametric modeling boils down to a modeling approach based on geometrical features. It determines the primary and secondary features, and then correlates them through logical Boolean operation, which can achieve the system modeling. These features can be classified into:

a) Base features (base point & line & curve)
Base features include datum plane, datum axis and reference coordinate system. These features, which serve as the positioning datum for the primary and secondary features, are digitized and determined by special parameters during modeling.

b) Curve-related features (operation)
Curve-related features include extrude, rotate, sweep, map and mirror. These features operate on curves by manipulating edges of solids or performing parametric modeling in combination with drafts.

c) Boolean operation
Boolean operation is a spatial operation that defines geometric features relative to each other. For example, A-B (remove B) means to remove and subtract B from A, while A-B can also retain B. For another example, A*B can be defined as an interface or boundary line between A and B.

d) Curved surface-related features (operation 2)

Similar with the curve-related features, curved surface-related features include extrude, rotate, sweep, map and mirror. The result of these features usually is parametric modeling of 3D solids.

e) Additional features (appendix)

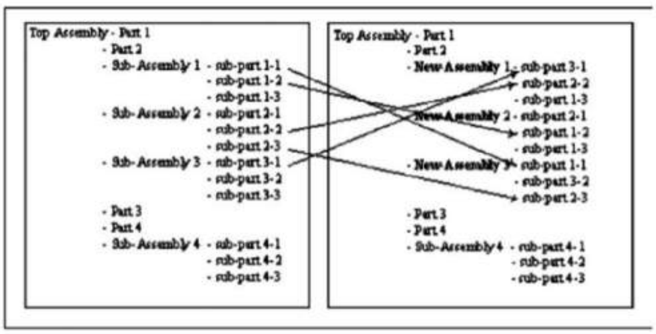
These features include engineering features such as holes, slots and bosses which can be generated indirectly through basic geometric element features. Because they often appear in modeling, however, they are usually standardized to simplify the modeling process and reduce error rate. That said, these features can only operate based on primary features instead of being self-operated.

f) Modeling by using draft

A draft is a two-dimensional graphic related to a solid model. Thanks to the dimension-driven draft plan, design parameters can be altered by adding constraint to draft objects or modifying constraint value, thus easily changing the features of objects. A Parametric solid model is generated by extruding, rotating and sweeping the sectional curve on the draft to extract the parameters of the sectional curve in the model and extrude the parameters to make the entire model driven by dimension.

It should be specially noted that there can only be one primary feature in parameter modeling, with other features depending on the primary feature, positioned by the datum point of the primary feature and maintaining a fixed positional relation with the primary feature. From the perspective of computer data and software, parametric modeling forms a dataset of assembly, component or hierarchy, among which some part data can be shared and generally present as an assembly tree, as shown in Figure 11-8.

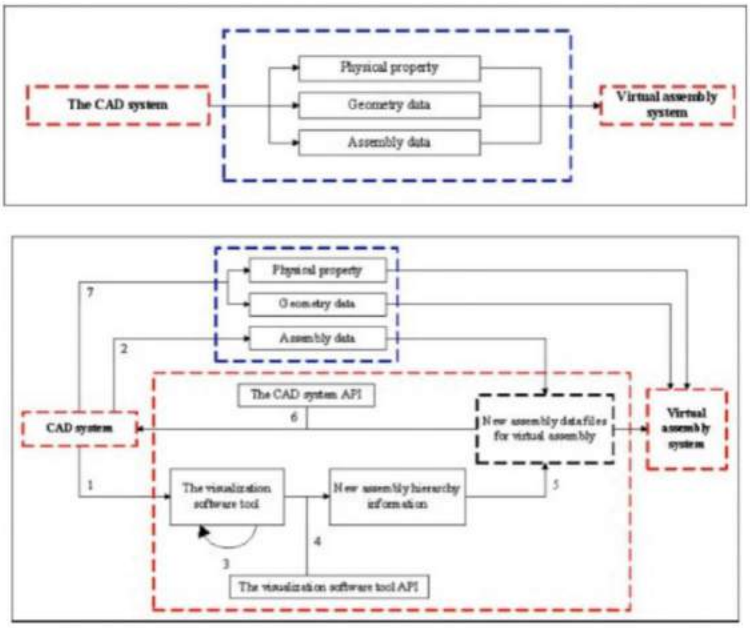
Figure 11-8 Assembly tree



Among many advantages of parametric modeling, the greatest one is to facilitate the subsequent parametric design and analysis, because parametric modeling generates fewer design variables. It is impossible to design all geometric dimension details on every part by manual way or by computer. In other words, parametric modeling lays the foundation for subsequent digital design and manufacturing.

In addition, parametric modeling realizes unified CAD data format and access, greatly facilitating the subsequent digital simulation computation and analysis. Figure 11-9 shows the data processing flow to extract data from the abovementioned assembly tree and build a virtual assembly system (i.e., virtual design). After the virtual assembly system is rebuilt, it can be displayed in the graphic display terminal or imported into a virtual reality device to reconstruct a virtualized actual object through appropriate technological processing.

Figure 11-9 Relation between CAD and establishment of virtual assembly system



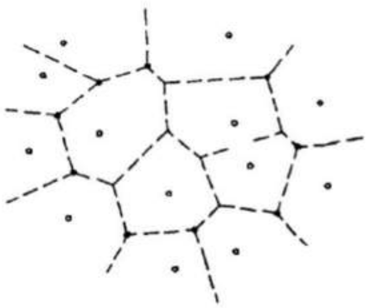
Currently, popular CAD software products are very powerful in parametric modeling. In addition to the abovementioned commonalities, they each have their own technical features. To establish a globally uniform technical standard for CAD, ISO issued an international standard in 1997, namely ISO DIS 13367 - The Proposed International Standard for Structuring Layers in Computer Aided Building Design. With the continuous technology development, the CAD software companies have developed different graphic file formats, and this urges the International Organization for Standardization (ISO) to unify these file formats.. Therefore, ISO introduced STEP (Standard for the Exchange of Product Model Data) in 2013, which considers all digital information required for digital designs of products, and provides the file transfer format used by a majority of current CAD technologies. STEP is currently undergoing a review process for its improvement. It is formulated by the Fourth Subcommittee (SC4) of the ISO Industrial Automation and Integration Technical Committee (TC184), with ISO designation of ISO-10303. By providing a neutral mechanism independent of any specific system, the standard aims to realize exchange and sharing of product data. Thanks to its descriptive nature, it is suitable for exchanging files and serving as a basis for executing and sharing product databases and archives. Developed countries have applied the STEP standard to industrial applications. By significantly reducing the cost of information exchange throughout the product life cycle and improving the product R&D efficiency, it becomes a key basic standard for international cooperation and competition in the manufacturing industry and an important tool to maintain enterprise competitiveness.

11.3.2 Automatic Mesh Generation

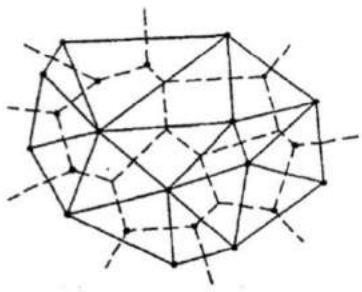
As the finite element method develops, the automatic mesh generation technology for FEM has also thrived. Up to now, the automatic generation for finite element meshes has already become a mature technology to solve 2D plane problems and has been applied to many types of commercial finite element software. However, there is still much to be improved in automatic partition of 3D finite elements.

Typically, 2D meshes are automatically generated through Delaunay triangulation, which is a popular and universal method for generating automatic unstructured finite element meshes. Beyond that, it also has important applications in mathematics, geography, engineering and other fields. Delaunay triangulation is evolved from Dirichlet and Voronoi graphics. A selected area is first split into interconnected convex polygons, in which a point set is defined. This graph is called a Dirichlet graph, as shown in Figure 11-10a. Each region (the area enclosed by the dotted line in the figure) is called Voronoi which grows in all directions at the same pace as a cell, with the middle point regarded as a cell nucleus. The boundary of one cell stops growing when it meets the boundary of another cell. Finally, the area formed by the points at the boundary will continue to grow, while other points will divide the given area into a series of convex polygons. These polygons do not overlap, and each polygon corresponds to a cell nucleus, (i.e., node). The resulting pattern is called Dirichlet, as shown in Figure 11-10b. If a node with a common edge is connected, a convex triangle is shaped, namely the Delaunay triangulation.

Figure 11-10 Delaunay triangulation



a) Dirichlet graph



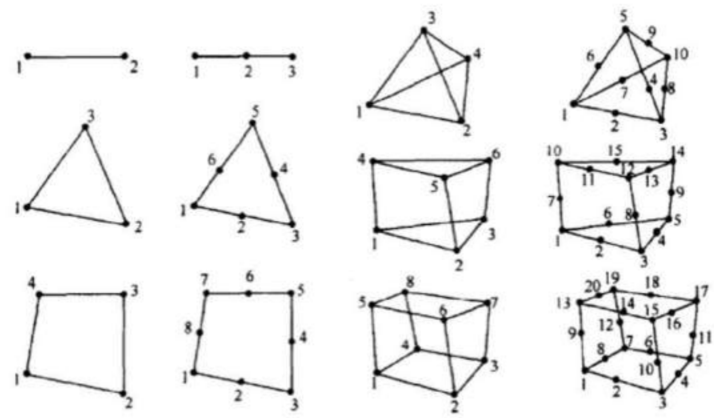
b) Delaunay triangulation

The classical Delaunay triangulation technology has been quite mature. In recent years, researches focus on constraining the boundary restoration algorithm of Delaunay triangulation, and solving the sliver elements generated by the Bowyer-Watson algorithm degradation. Until now, Delaunay triangulation-based algorithm can solve the automatic generation of finite element meshes for 2D problems in most engineering practices.

In contrast, the automatic generation of 3D finite element meshes is much more difficult. At present, for certain structure type, the automatic generation of 3D finite element meshes can be realized through thorough research on geometric characteristics, especially the topological structure. In general, the 3D mesh for special structure can be automatically generated in a “skillful manner”.. For example, a "columnar" solid can use "sweep-mesh" method, which essentially copies the 2D meshes along a certain aspect. Copy can be made by scaling algorithm, etc., to make this method suitable for many 3D “columnar” models. Another method is called "map-mesh" which is a regular meshing method for a regular model. Map-mesh has restrictions on shape of the contained elements, and follows special mandatory rules. The mapped face mesh contains only quadrilateral or triangular elements, while the mapped body mesh contains only hexahedral elements. In addition, map-mesh typically has regularly shaped elements that are apparently lined up. To get this type of meshes, the model must be divided into a series of fairly regular body or face to accept mapped meshing. It can be seen that both "sweep" and "map" methods have certain requirements for the topological shape and the scheme type of the 3D solids to be split. For an irregular 3D body, only by using a 4-node tetrahedron element, which is also known as a "free-mesh", can make the 3D finite element mesh generate automatically. It shall be mentioned here that a large number of theoretical and practical examples show that the computational accuracy of 4-node tetrahedron elements is lower than that of 8-node hexahedron elements, resulting in that the computational accuracy of was suspected by the engineering community and their application was limited over a past long time. tetrahedron elements was suspected by the engineering community and their application was limited over a past long time. With the development of finite elements and computing hardware & software technologies, however, the computational accuracy obtained by quality tetrahedron elements with encrypted meshes can fully meet engineering requirements. More importantly, the 4-node tetrahedron elements can be easily converted into 2-order 10-node tetrahedron elements by adding intermediate nodes, as shown in the two quadrihedrons in Figure 11-11. Similarly, theoretical analyses and numerical computations demonstrate that the computational accuracy of 2-order tetrahedron elements can be equivalent to that of hexahedral elements. In other words, computational accuracy of finite elements required by engineering can be achieved by using the elements in Figure 11-11 to automatically divide the 3D meshes. Of course, using 10-node hexahedral elements means more nodes, higher degree of freedom, and greater computational scale and cost. Having said that, it is not difficult to increase the memory and computing speed of a computer today.

In summary, most of the problems in engineering practices can be solved by the full-automatic finite element mesh generation technology.

Figure 11-11 Topological property of element



11.3.3 Automatic Simulation Computation

Automatic computation is a broad concept associated with Numerical Algorithms, Intelligent Computation, Evolutionary Computation, Machine Learning, and even Cloud Computing. Herein, automatic simulation computation refers to the software technologies that are seamlessly connected to CAE from CAD, including automatic construction of numerical models, model checking, CAD import into CAE technology, and automatic conversion and storage of digital design and analytical data. These technologies can realize automatic modeling and automatic computation from CAD to CAE in three directions, namely,(1) downward from CAD to CAE or finite element analysis; (2) upward from CAE to CAD software; and (3) realize automatic simulation and computation through independent secondary development of CAD or CAE. Here are brief introductions of a few typical cases.

Introduction 1. Solid Works Simulation

SolidWorks has great capacity in modeling and designing 3d solids. It fully supports parametric modeling as described in Chapter 2, which is not repeated here. In addition, SolidWorks Simulation is a CAE tool that every design engineer and analysis engineer can quickly and easily use. By embedding FEM in CAD software, the FEM computation capability of SolidWorks Simulation covers linear stress analysis, nonlinear analysis, computational fluid dynamics (CFD), kinetic analysis, frequency analysis, and even metal fatigue, with analytical and computing capacity rivaling the traditional FEM programs (e.g. ABAQUS). Throughout the development cycle of a product, design tends to be at the core of the product's early lifecycle when compared with analysis, which means that CAE is subordinate to CAD. For this reason, downward connection from CAD to CAE or finite element analysis has leading advantages in engineering products, which promotes the SolidWorks to increase in installation. It is fair to say that SolidWorks has achieved a seamless connection from CAD to CAE at the working platform level.

Introduction 2. Hyperworks series products

Altair Hyperworks evolves from a software product dedicated to finite element meshes parting. As technology upgrading and software development for several years, the core module Altair HyperMesh remains powerful and advantageous. At the same time, the latest edition has grown into an innovative and open enterprise-level CAE platform. It integrates a variety of design and analysis tools, and is characterized by unparalleled performance and a high degree of openness & flexibility with a user-friendly interface. The following computing modules are contained: Altair HyperForm one-step solver that integrates the powerful functions of HyperMesh and metal-forming function (this solver is metal plate forming simulation finite element software using reverse approximation method); Altair HyperOpt nonlinear optimization tools for parametric study and model adjustments with various analysis software; Altair OptiStruct world-leading finite element-based optimization tool which uses topological optimization methods for concept design; and Altair OptiStruct/FEA which includes basic linear static mechanical analysis and eigenvalue (natural frequency) analysis modules. In particular, Hyperworks provides leading CAD interface and geometric model sorting technology among CAE software. (1) Almost all CAD software can be imported and exported; (2) it has the most reliable geometric model sorting technology which basically eliminates all the possible gaps, overlaps and defects in the input geometric model; (3) the overall speed and effectiveness of meshing are superior to other software systems; and (4) it provides the most comprehensive model checking techniques, such as nephogram showing mesh quality and element quality tracking inspection tools and other convenient tools which can timely examine and improve the mesh quality.

Introduction 3. Secondary development of ANSYS APDL/ABAQUS Python

ANSYS APDL and ABAQUS Python-based secondary development is most and widely studied in China. APDL, namely ANSYS Parametric Design Language, is not only a basis for the ANSYS classic characteristics such as optimization design and adaptive meshing. The ABAQUS Python language interfaces with Abaqus scripting and provides scripting for various functions, including rapid modeling, access to the output database, additional post-processing of external data, and some advanced processing functions. These interfaces facilitate the seamless connection from CAD to CAE. APDL mainly aims to enable users to organize ANSYS commands with programming language and write parametric user programs, thus realizing the whole process of finite element analysis, that is, establishment of a parametric CAD model, parametric meshing and control, parametric material definition, parametric load and boundary condition definition, parametric analysis control and solution, and parametric post-processing. For brevity, a Monte Carlo stochastic finite element analysis project containing corrosion pit plate of distribution point, which is developed by ATLAB\APDL\Python, is introduced. The main modules of the program are main program module, parametric modeling module, database module, automatic mesh generation module, computation module and computation extraction module. The main computation processes include:

a) Modeling corrosion pit

In the automatic computation, the corrosion rate is computed as the sum of the corrosion pit volumes divided by the total volume. The corrosion pits are randomly distributed in the middle of the steel plate and measures are taken to avoid overlap of the pits. The sample plates are divided into several small pieces in advance, in which each corrosion pit is distributed. Taking the center of the small piece as an origin, a random number generator is used to generate three sets of random numbers (radius of the corrosion pit, the distance between the pit's center point and the origin, and the angle between the pit's center point and the origin) as the location parameters of the corrosion pit to establish 2D model.

b) Establishing a 3D model containing corrosion pits

The above 2D corrosion plate model generated is swept through meshes to form a 3D hexahedral mesh element model, and a rectangular steel plate with a predetermined corrosion rate is established, as shown in Figure 11-12. As shown in the figure, a solid model similar to the actual corrosion complexity can be simulated.

c) Automatically generating APDL/INP files and ANSYS/ABAQUS computation

This step generates executable finite element model analysis code, including checking the model, extracting elastic and plastic material parameters in the database and setting computation options. In this study, either ANSYS or ABAQUS can be used for elastic-plastic finite element computation.

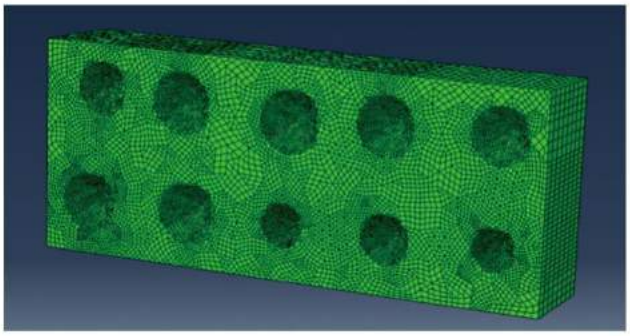
d) Python postprocessing of ABAQUS/ANSYS APDL postprocessing

The result extraction, in addition to FEA computation, also needs to be automated. Here we apply python postprocessing of ABAQUS/ANSYS APDL postprocessing to extract the computing results of interest.

The program is characterized by completely automatic finite element pre-processing, computation and post-processing of finite elements, with many finite element analyses and computations per execution. In the engineering practices, we can perform 1,000 finite element computations under one carriage return if we select a total of 1000 valid samples.

In summary, the popular large CAD or CAE programs can perform automatic computation and analysis to some extent. That said, due to the complexity of engineering practices, we can use CAE or CAD software secondary development for certain products to realize the whole process from digital design to finite element computation and simulation through a programmatic rather than manual way.

Figure 11-12. Automatically generated 3D steel plate model



11.4 Basic Database for Virtual Simulation

It is quite necessary to establish a basic database for virtual simulation to echo the requirements of digital design and manufacturing. The combination of intelligent design and expert system based on knowledge base system mentioned in Chapter 2 has become the trend of digital design and manufacturing. By using digital design database, designers can timely and accurately obtain the information and assistance required for product development. In addition, information sharing and exchange can be realized through Web mechanism to solve the knowledge demands during product design. Processing of design data through big data and artificial intelligence covers from database to data warehouse and knowledge base, from simple dataset to data knowledge mining by following certain rules, as well as making the data self-learned and self-accumulated. If this intelligent process is synchronized with practical engineering applications, a crucial leap-forward advance may be achieved for manufacturing technologies. As can be seen from the above, both virtual manufacturing (VM) and virtual test (VT) rely on information can be expressed in a normalized manner, efficiently stored and effectively utilized. Based on the requirements of virtual simulation, the basic database can be divided into basic material library, basic element library, basic product data, basic (software) component library, etc.

11.4.1 Basic Material Library

It is truly a massive database that refers to all the performances, indexes or parameters of any material used in all industrial products. It is divided into three types according to the source of database. The first type is public network database, and usually refers to the databases that are publicly accessible and can be shared and used freely on the internet, such as globally available MatWeb database. The second one is public official database. Such databases are usually owned by certain organizations and can be shared and used within limits. There are many such databases, such as the physical property database of National Institute of Standards and Technology (NIST), the ASM-International of American Metals Association, the material database (mits.nims.go.jp) of National Institute for Material Science, the physical properties and thermochemistry database of Chinese Academy of Sciences, and material resources of Cambridge University. The third type is enterprise material database, such databases are usually not publicly accessible, such as NASA's internal database and material database established by a large domestic steelmaker. Given the data authority, detail level and reliability, the third type is undoubtedly the best data source compared to the first two types which often need to be verified before they can be used with confidence. By establishing their own basic material libraries, enterprises can obtain material data from public databases, verify the data through a systematic and comprehensive way, and then import the data into the enterprise servers to form their own material libraries, which becomes a part of basic work for digital virtual design and manufacturing simulation.

11.4.2 Basic Element Library/Basic Product Data

Establishing a basic element library is essential to digital design and manufacturing for private sectors. The basic element library stores the basic standard parts, reusable parts and CAD files of old products that are repeatedly used according to certain formats and rules, so that the enterprises do not have to start with a single "screw cap" when designing a new product with CAD. In addition, the database involves broad areas, with 3D model data of various industrial products as the main dataformat. Similar to the material library, it can also be divided into public network database, public official database and enterprise in-house database. However, a huge gap remains between the material library and the 3D model database of industrial products in data quantity and quality. For example, 3D CAD model data for tens of thousands of industrial products are available on the 3dcontentcentral.com website, and 5481 results are listed under the search results of keyword "bolt".All the complete CAD model files can be downloaded in around 30 file formats, which almost support all CAD software to reuse. These models are usually provided by the suppliers free of charge, thus playing a role of advertising and omitting some important product information. Therefore, other manufacturers can only use these models as a reference rather than direct use in new product design. In other words, there is no public database to which small and medium-sized enterprises (SME) have direct access in basic element library. This is because the models available on public network databases are basically impossible to meet enterprises' design requirements of their own products. Therefore, the basic element libraries need to be built by the enterprises. Relatively speaking, almost all the enterprises have their own basic product database which includes descriptions, characteristics, parameters, data, indexes and other elements of all products produced by the enterprises. This database reflects the technical reserve and strength of an enterprise in the era of digital manufacturing. Sooner or later, all the enterprises will establish this product database, but the size, quality and utilization efficiency may vary greatly. Given the requirements of digital design and manufacturing, enterprises shall use normalized and unified data in their basic product databases, while applying and improving intelligent and scientific management throughout new product design and manufacturing, thus better utilizing their basic product databases for digital design.

11.4.3 Basic Component Library

Component, a term of modern software technology, refers to the simple packaging of data and method, which means a software module containing certain kinetic energy. According to object-oriented programming language, a component is a specific object derived from a class root. Components may have their own attributes and methods. Attributes are component data, and methods are some simple and visible functions of components. Drag-and-drop programming, fast attribute handling and true object-oriented design can be realized through the component technologies which refer to relatively independent software programs capable of fulfilling expected functions herein. For example, Flash, which we are familiar with, is a component. Flash is a movie clip with parameters which can be used to modify the component's appearance and behaviors. Each component has predefined and configurable parameters. In addition, each component has a set of its own methods, attributes and events collectively known as application programming interfaces (APIs). Programming can be separated from software interface design by using components, thus improving reusability of codes. Components can be developed by and applied in C++ or a variety of other programs. Component technologies can be very effective for enterprises to establish digital design and manufacturing software platforms. The so-called basic component library aims to classify and store components and some basic functions (e.g. matrix operation and display of CAD animation) in the network integration software platform according to functions, and specify a unified access method and software interface technology. Establishing a basic component library lays important foundation for digital design and manufacturing. For example, by using the component technologies, there is no need to rely on specific CAD and CAE software to obtain CAD, CAE, CAM, CAPP and other basic functions, thus forming an enterprise-owned digital design and manufacturing software platform. A large amount of tedious CAD/CAE works can be avoided by virtue of the high reusability of component technologies. Component technologies also facilitate the promotion and use of modern manufacturing technologies such as network sharing mechanisms and cooperative design and manufacturing. With the development of software system engineering and technology, China lately introduced the V+ industrial parts technology, with a view to making full use of component technologies to better serve the digital system engineering of enterprises. Readers can refer to relevant websites and technical materials if interested.

11.5 Establishment of Enterprise Digital Virtual Test Automation Process

Enterprise digital virtual test platform refers to the workpiece or product test stand built-in a software environment. Virtual simulation models of test platforms and members to be tested are built in software environment to perform the test missions that are identical or similar to the actual tests. Through virtual tests, we can fully understand and timely discover problems before physical tests, thus minimizing repetitive work. On the other hand, virtual tests enable us to fully prepare for and reduce the dependence on physical tests, so as to accelerate product development.

Typical virtual test platforms can be divided into the following types according to functions of virtual tests:

a) Test platform for simulating the strength and safety (including structural stiffness, stability, fracture and fatigue) of a structure;

b) Test platform for simulating vibration and dynamic characteristics of a mechanical system;

c) Virtual environment test system;

d) Virtual factory building or workshop for simulating the manufacturing assembly process;

e) Simulator and virtual training machine for simulating the use of virtual products;

f) Demonstration platform for simulating product functions.

According to their work contents, these systems are classified as virtual products (objects to be tested), virtual excitation system, virtual sensing system, virtual environment, virtual control system, and man-machine interaction control, etc. The modeling of the above parts is completed in a computer with simulation models of such parts being assembled, to complete the main construction goals of the virtual test system under different working conditions.

An enterprise's virtual vibration test stand is taken as an example to explain the major steps to establish a virtual test platform according to the requirements of the enterprise for product test.

11.5.1 Establishment and Verification of Simulation Model of Test Platform

The first is to demonstrate the modeling scheme and choose a reasonable numerical computation tool. For example, member deformation is computed through ANSYS or ABAQUS, mechanical motion is simulated by MSC.Admas, the hydraulic system is simulated with AMESim, the simulation system of test instruments is established through Virtual.Lab, and a control module is set through MATLAB/Simulink. Usually, a simulation model uses one certain physical model, but more than one computation tools are available for the simulation model. For example, a majority of structural stress and strength computations can use finite element methods through many optional popular finite element software systems, such as MSC.Nastran, ABAQUS and ANSYS. In addition to the finite element method, computation tools focused on PDE solution, such as Cosmos, meshfree computing method and MATLAB\FEM, can also be used in some cases. Generally, a single computation tool cannot meet the high demands of virtual tests.

Taking the virtual vibration test platform as an example, the finite element method and the nonlinear multi-body dynamics method (built-in control unit and finite element) can be used to simulate vibration. However, since the finite element method is an open-loop simulation, finite element models are built in various parts of the vibration test platform and assembled by appropriate connection units. When designing a vibration test platform, this method can be used to verify its structural characteristics, including strength, modality, transfer function and coupling with the test piece model. While by combining the control and electromagnetic actuator system models, the multi-body dynamic model can realize the complete closed-loop simulation. The mechanical part of the vibration test platform is modeled by multi-body dynamics software, while the controller and electromagnetic actuator parts are modeled by system simulation software. The two parts can be integrated to achieve closed loop analysis. The controllers, excitation, machinery and their coupling may be considered for this method to facilitate the scheme selection and verification of the complete scheme during the design of vibration test. The multi-body dynamics model of the vibration test platform is ultimately integrated with the finite element model of the test piece, usually by means of the rigid-flexible coupling analysis of multi-body dynamics software.

11.5.2 Creation of the Model of Test Piece

As for a car to be tested, a model of the entire car needs to be built. Similarly, as for an aircraft to be tested, an aircraft simulation model consistent with the real one needs to be built. Despite the enormous workload, modeling and computation of the overall system simulation are completely achievable under the current computation level and conditions. Besides, many manpower and material resources are required. As previously mentioned, such a large platform for virtual simulation tests of overall systems may only be obtained by those advanced and large multinational manufacturing companies. Small and medium-sized manufacturing companies usually conduct digital virtual test platform research on a certain component or intermediate product. The modeling of simulation model for a test piece is required to be true and accurate, with product characteristics consistent with the actual physical test pieces. Before virtual test, certain technical means shall be used to ensure the accuracy of the simulation model of test pieces.

11.5.3 Assembly of the Test Piece Simulation Model and Virtual Test Platform

The model assembly shall focus on the true reflection of connection characteristics of the test platform and the test piece, including the physical and mechanical properties (stiffness, damping) of the system, in order to ensure the accurate coupling between the test platform and the test piece. This is also a key step in the establishment of the entire virtual test system.

11.5.4 Building A Software Platform for the Virtual Test Platform

Based on the construction goals of the virtual test platform, the virtual test system involves CAD modeling, finite element modeling, multi-body dynamics modeling, control and electromagnetic system simulation, rigid-flexible coupling analysis, mechanical-electrical analysis, test correlation analysis and model updating, as well as multidisciplinary optimization, which need to be combined to form a closed-loop simulation software system.

11.5.5 Operation and Debugging of Virtual Test Platform

This step aims to execute the main program of the virtual test platform, track the specific model data in the system (subsystem), verify that the model and the data meet the design requirements of the virtual test, and extract the virtual (dynamic) response under the virtual excitation. Where possible, the error between the virtual and the actual test results shall be compared to update the model or parameters, and achieve the expected test purpose.

11.5.6 Applying Virtual Test to Testing and Inspection of New Products

This is the ultimate goal of enterprises to establish virtual test platforms. Before a new product is put into production, by obtaining reliable test data about the new product from the virtual test platform, the enterprise can know fairly well about its developed product, and make the new product more competitive with the support of test data. This is very important for enterprises to ensure the core competitiveness of products.

In summary, the enterprise digital virtual test platform plays an important role in digital design and manufacturing, and can partially or completely replace the traditional physical field test. Establishing virtual test platforms is of great significance for enterprises. First, virtual tests can speed up the development of new products, saving a lot of time, manpower and resources required for product testing. Second, virtual tests are essential to keep the products advanced and ensure enterprises' core competitiveness. Because only by conducting virtual tests can the new product's performance data be obtained before the production of new products, thus knowing products in advance and avoiding the "blind production" and "major investment failure". Finally, the virtual test can completely eliminate various personal and property safety risks that may occur in some new products on field tests, because some product tests are destructive (e.g. vehicle durability test, connector failure test, rotating machinery vibration and dynamic tests), and need to test the products until they are completely destroyed. This process is inevitably risky. For modern manufacturing enterprises, establishing their own digital virtual test platforms has become an inevitable choice to enter the era of digital economy.

CHAPTER 12

Enterprise Digital Design and Simulation Data Management

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Enterprise Digital Design and Simulation Data Management

12.1 Necessity of Establishing Simulation Data Management Platform

As product development applies simulation technologies continuously, a product needs to be simulated several times before final design to verify that the design meets the performance and function requirements, and to confirm that the designed product meets static strength, dynamic performance, fatigue life and other requirements. Virtual simulation computation has replaced a large number of physical tests of actual prototypes. Taking the automobile industry as an example, from the year 1980 to 2000, the number of collision tests applied in car model development was reduced from 240 to 80 with the collision simulation technology, greatly shortening the automobile development cycle. At the same time, the number of analysis engineers engaged in collision simulation has increased dramatically. Today, each of the three major US auto companies conducts dozens of or even nearly a hundred collision simulation computations per working day, involving hundreds of analysis engineers. Such a large team can generate 100 files and reports during a simulation, and each simulation can generate 1GB data. If one team conducts simulation once per day, more than 20,000 simulation files and over 200 GB data will be generated per year, let alone the hundred times of collision simulations carried out by these three companies. Without effective management, how can we search and use such a large amount of simulation files and data? And how can we compare them with test results and make the correction?

These data hold the key to assessing design performance and functions. If engineers store the data in their own computers, or fail to hand over the data in case of employee turnover, it is difficult for us to look out the necessary data. Therefore, it is very important for enterprises to establish their own data management platforms for simulation. This is exactly what we are talking about in this chapter: establishing enterprise simulation management platform for digital design.

12.2 Framework of Simulation Data Management System

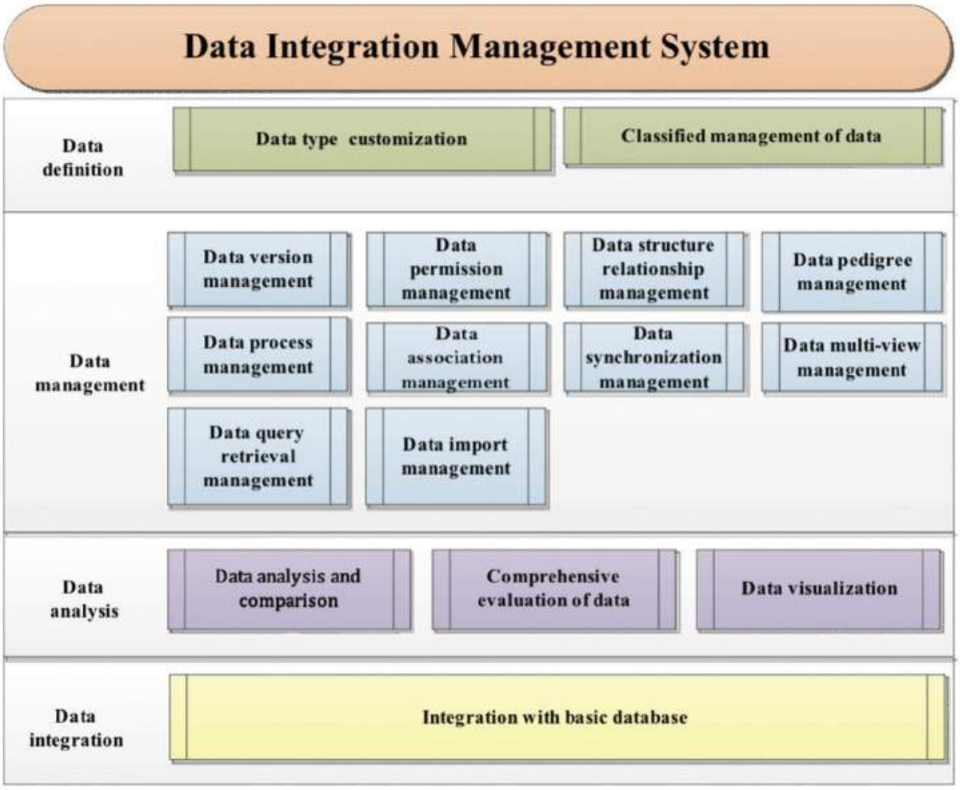
As process data, the simulation data management system can lock, share, compare, batch process, track, and audit simulation data. Data management tools have interfaces to databases and enterprise-level data management systems which can be quickly integrated with existing data management systems. Simulation data management can also mine, extract and process simulation data, and establish simulation knowledge-based management, such as simulation model library, simulation analysis process template library, report template library, material library, and CAE-related specification library.

In addition, simulation data management can also perform multi-keyword combination query, multi-level query, and multi-condition fuzzy query on simulation projects, data, files and other resources. Users with permissions can perform online browsing and download through query function. In addition, the CAE supervisor or project manager can query the progress of the corresponding simulation task, as well as staffing of the entire simulation project and CAE room.

12.3 Simulation Data Organization

An important goal of enterprise simulation data management is to make enterprise simulation data and knowledge resources flow properly and smoothly in business processes, thus enabling every employee to easily access business-related data and knowledge, and contribute their knowledge, experiences and skills for the enterprises. Only by combining the specific business process with the precipitation, sharing, learning, application and innovation of data and knowledge can enterprises improve their professional proficiency and create values.

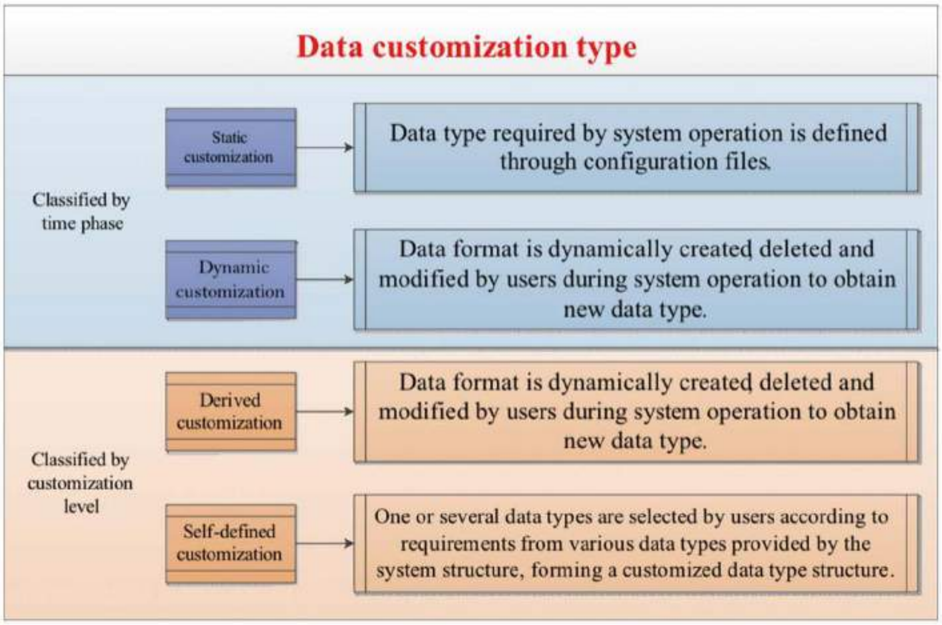
Based on normal design work, independent services are needed to collect all types of data generated during the design of all levels of a product to form a complete design data management and knowledge management system. This knowledge system will provide data support for important functions including design process optimization and reuse of design knowledge.



12.3.1 Data definition

a) Data type customization

The system provides multiple data type customizations which can be classified according to the following methods: According to the time phase of customization, it can be classified as static customization and dynamic customization. As for static customization, the data type required by system operation is defined by the system administrator through configuration files before system operation. Dynamic customization allows users to dynamically create, delete and modify data format during system operation to get new data type. From the level of customization, it can be divided into derived customization and self-defined customization. Derived customization entails establishing a basic data model, then performing derived design based on the existing model according to the actual demands of the enterprises, and finally generating the method for designing the custom data type. For this type of customization, the basic data of the system are relatively fixed, so that the universality of the system is guaranteed. The derived design is mainly driven by the actual demands of the enterprise. For example, the enterprise needs to add a certain feature to the product definition, and this feature is expected to be reflected in the final report. As for self-defined customization, the user selects one or more options that currently meet their needs from many data type options provided by the system structure, and combines them into a customized data type structure. During data type customization, the above several customization methods, such as the dynamic and static customizations, the derived and self-defined customizations, can be combined to meet the user's customization requirements in a flexible and diverse manner.



b) Data classification management

Data can be classified into different categories and as self-defined category according to data type customization method, data display mode and data function.

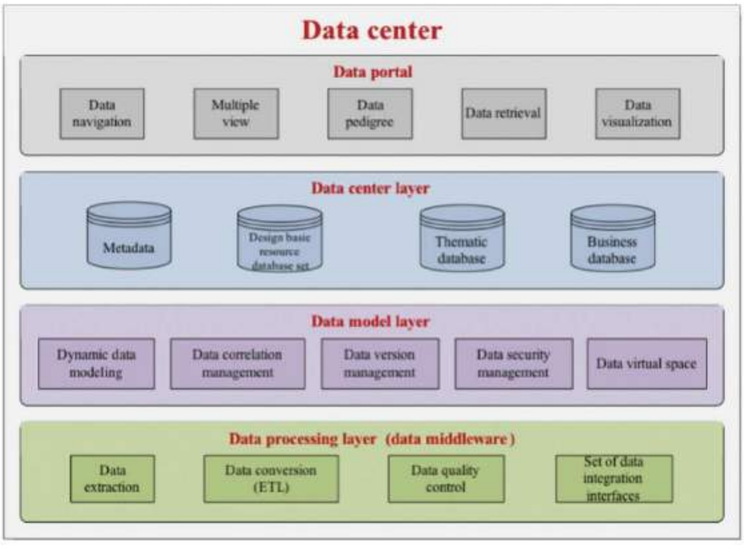
According to customization methods, data can be classified as multiple categories such as static data, dynamic data, derived data and custom data, and classified management can be realized.

According to display modes, data can be classified as a variety of categories such as 2D image, 3D image and curve, and classified management can be realized.

According to functions, data can be classified as design scheme data, index data, model data, process data and log data.

12.3.2 Data Management

The data exchange system of the simulation data management system aims to conduct unified management and exchange for simulation system data during the primary implementation of application systems through data bus technology. Technical requirements include the database framework system of the data center, data extraction from heterogeneous data sources, data sharing push mechanism among data centers, and data analysis and display.



a) Data version management

Data version is a snapshot that records the optional states of a specific object. Version management aims to record and maintain the evolution of the object, and select the appropriate topological structure between versions according to the actual application background. Version management includes the following functions: generating new versions, unifying and coordinating all versions, recording evolution of different versions and managing these versions effectively to minimize redundant recording of versions.

Besides, different versions shall be consistent in logic and independent from each other to ensure that no other version will be affected if a version is generated or deleted. In case of version switching, after the new version is specified, the mapping of the object remains the same as the specified version.

b) Data permission management

The system's responsibility system is dynamic, which is determined by the business characteristics and prevents the business information system from being flexible. This is because dynamic responsibilities require business process independent of certain personnel assignment, abstract rather than real business logic operator, and user and organization information in application systems dynamically acquired from contexts. These requirements directly affect the way through which the overall system is implemented.

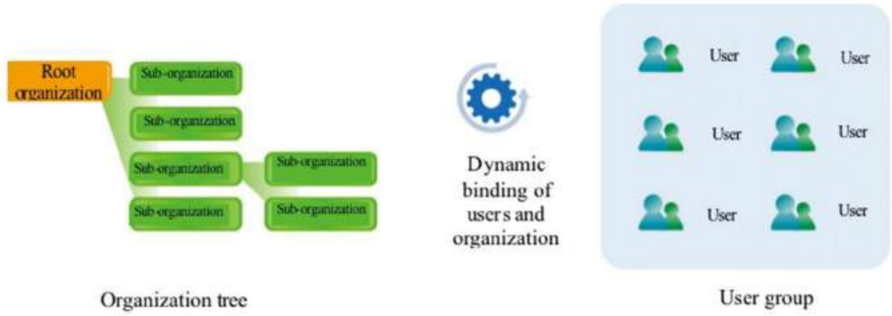
To realize dynamic responsibility system for specific technology means to dynamically bind the organization, user group and resource. That is, technical implementation includes three layers of independent management systems:

i) Organization tree that manages the organization.

ii) User information management that manages user groups

iii) Resource management that manages application subsystem, module and data.

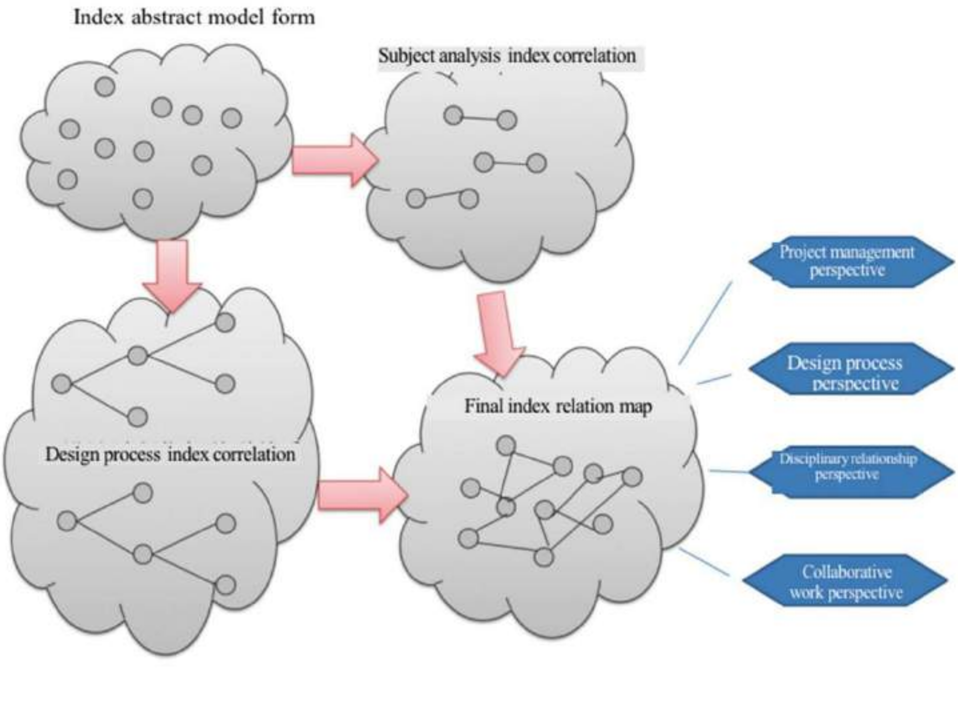
The following figure is a dynamic binding view of the organization and users. At runtime, association between the organization tree and specific users can be established dynamically. There is only one organization tree in the figure, but there may be more than one in practice.



c) Data structure relation management

Organizing design data from design process model is based on the design model to organize the relation of design data from the macro perspective of product design. This provides a complete data utilization chain for the rapid design of products to maximize the use of existing design resources, and fundamentally eliminates isolation of design data, forming a clear data organization structure and data distribution map. Users can define, edit, view, query and delete data and data structure relations.

Based on the centralized management of the simulation process, the product data packet decomposition model and the general decomposition structure model tree are established. The main purpose is to form a data packet directory, with result data generated by engineers at different positions stored on the data packet directory nodes. The data in these data packet nodes correlate with each other in a subordinated, decomposition and convergent manner, forming the decomposition, inheritance, and expansion relations among data sets. There are two forms in these relations, one is a tree-like relation structure generated by decomposition from top to bottom; and the other is the transversal relations of non-subordinated indexes or data that are manually established for computation and analysis. These two types of relations constitute a network relation between index data, which is actually a data map and an internal relation index for monitoring and managing multi-view design. The following figure shows the process for establishing index data relation.



d) Data process management

In data process management, design type data are managed in a relatively simple manner or process data are managed according to simulation environment, and the design database organized by the simulation design process model can record data, corresponding logic relationships and time information generated by the task at every moment, and clearly expresses the changes and processes of design data generation, evolution, transmission and regression, which is important for design data backtracking, and lays a foundation for backtracking of design data in reuse. It provides basis during design of process model frame and meets design and multidisciplinary comprehensive requirements.

e) Data correlation management

Data generated during product design, including demand characteristics, design objectives, design parameters, technical indexes and verification result, correlates with each other in a breakdown manner from the overall system to sub-system. In addition, due to the objective constraint by multidisciplinary verification, there are internal correlations among parallel data, and also copy/reference and index relations during data transmission. This kind of correlation may depend on objective discipline determinant or subjective cognizance. User management can be realized for mutual correlation.

f) Data synchronization management

The system provides data synchronization, sharing and exchange. In heterogeneous subsystems where data are not concentrated, effective technical means must be taken to ensure heterogeneous data to share and exchange.

g) Multi-view management of data

A multi-view management data module exports views from one or several tables or views, with its structure and data based on the table query. Like the real table, a view also contains several defined data columns and multiple data rows. These data columns and rows are derived from the referenced table. Users can choose different rows and columns as required to create different views in various professional and organizational presentation forms. Multi-view management can centralize data in views, simplify and customize different demands of different users on database. It can mask data complexity, enabling users to easily use and manage data without understanding the database structure, while simplifying the data management permission and reorganizing the data to export to other applications. Through the multi-view management, users can only concern certain data of interest and certain tasks that they are responsible for, without any needless or non-relevant data display in views.

h) Data query/ retrieval management

Data query/retrieval is available, and there are two methods for querying data:

The first one is to click the links of relevant documents in document list according to product and relevant data documents to access all the knowledge documents of the models queried during design.

The other one is to search based on keywords which can be data name, ID, creator and descriptive conditions. Fuzzy keyword query is supported to query related data documents. By clicking the links of these documents, the specific data information can be accessed. Multiple keywords can be selected for one search to make the search results more suitable.

i) Data import management

The data integration management system allows users to import information from other applications, such as word processing (Txt, XML), spreadsheets (Excel) and database programs (ORACLE, SQL Server). The data integration management system integrates the interfaces of this type of data. It can import & export, open, edit and display these data, facilitating users to use and operate different types of data.

12.4 Simulation Material Data and Standard Part Data Management

Based on unified standards and specifications, we can create a simulation material library that can be directly invoked and computed by other system programs, in order to greatly improve modeling efficiency and quality. At the same time, simulation results are guaranteed to be consistent and traceable.

Material management

As the original input for simulation analysis, material data directly affects the accuracy and consistency of simulation results. Therefore, establishing a unified material library is essential for simulation. Furthermore, to improve efficiency, various material models (or material cards) are defined for certain application tool software based on the specific needs of various simulation analyses, and stored for directly being invoked by related computing program.

In product structure analysis, according to the composition of materials, different types of simulation analyses need varying material parameters. For example, as for static simulation analysis, the material parameters provided by the material library include elastic modulus, tensile strength and yield strength. As for fatigue simulation analysis, the material library can provide the fatigue strength of the material. In addition, a unique material model ID is assigned for each material model in the database to facilitate recognition and program invocation.

The material model data card in the material library is shown below. The material library is scalable, which means that users can add and delete material categories, designations and properties (database fields) as needed. In addition, during different simulations, users can also directly invoke the data in the material library, or use these data to directly generate material cards for invocation.

Material model ID	Category	Designation	Density [g/(mm^3)]	Modulus of elasticity (GPa)	Tensile strength (Mpa)	Tensile yield strength (Mpa)	Compressive yield strength (Mpa)	Fatigue strength (Mpa)	Elongation
10001	Aluminum alloy	2024	2.8	68	470	325		105	20%
10002	Aluminum alloy	2A70	2.8		355				12%
20001	Titanium alloy	TC4	4.5		895	825			10%
20002	Titanium alloy	TC10	4.5	108	1150	1060			
30001	Magnesium alloy	AZ31	1.74	44.6	260	195	100		14%

Standard part management

The system can also establish suitable simulation model databases of standard parts and common parts based on the characteristics of enterprise products for direct invocation during simulation. In addition, these simulation model databases can be parameterized to quickly generate CAE mesh model required by simulation.

12.5 Multi-Scheme Data Comparison

Product design involves multi-scheme selection and comparison, requiring comprehensive performance evaluation for rapid multi-scheme and multi-case data comparison. Based on analysis target, data comparison can provide automatic data mining and combination for multiple analysis schemes and analysis data of different cases. Through data comparison, numerical curves of key analysis results can be interpolated, assisting engineers in analyzing the evolutionary trend of design schemes and realizing 6-Sigma design.

Engineers can select assembly components and analysis type according to requirements. They can either perform only one type or several types of simulation analysis at a time. Through definition of simulation analysis and interface of application software, driver software operates in an interactive or batch processing manner. Integrating configuration with the analysis process makes it possible to form a comparison report on the comparison results of multiple schemes, models and their key results, and the report can be conveniently released to other enterprise information systems, such as PDM system.

With optimization design tools, designers can update CAD models by directly changing design variables, while observing new design models through fast and lightweight browsing tools. After the CAE analysis button is clicked by the simulation personnel, the multi-scheme optimization system automatically outputs the model to the simulation analysis module for analysis, and displays the analysis results to designers in a quick and lightweight manner. The schemes are compared by providing designers with analysis results in forms of graphs or table. In addition to analyzing and comparing the final result data, the system can also analyze and compare the data generated by different application systems at different stages.

12.6 Result Visualization

Through visualization of simulation result data, one or several data can be displayed graphically, operated and processed. Visualization of simulation result data provides basis for engineering technicians to refine the model. At the present stage, it is difficult to realize the unified visualization of CAE models. We can convert CAE models into one particular data format and then view the models through visualization tool, provided that CAE models support this data format.

Display tools based on lightweight display technologies are important auxiliary tools for cooperative R&D platforms of performance digital mock-ups. Their main functional requirements are to solve the following problems in multi-disciplinary simulation analysis:

Increasingly diversified CAD/CAE/CAM tools with wide range and high frequency of application.

As application of computer and related information technologies deepens, CAD/CAE/CAM tools used by R&D enterprises are becoming more diverse as indispensable tools on which these enterprises rely. Designers, in particular, deal with the design software every day.

A large number of data that is difficult to manage or share.

The popularity of CAD/CAE/CAM inevitably produces a large amount of file data, such as 3D model data and computing results. Over time, a large amount of data have been accumulated, among which a majority of large-volume files may reach gigabyte. How to effectively manage and share these data poses challenge to R&D enterprises. Frequent data exchange between large files in large amount will undoubtedly waste time and lower effectiveness.

Multiple data formats that are difficult to process uniformly.

Various CAD/CAE/CAM tools produce a variety of data files. Generally, different data formats require corresponding professional software tools for view and processing, which greatly increases the difficulty and cost of computer management, presenting enterprises with a problem in their computer working environment.

Demands of related departments for viewing shared data through collaboration.

With more detailed division of responsibilities and close collaboration in modern design work, the demand for multi-department cooperative design and data sharing is becoming more and more urgent. It is necessary to provide effective data sharing and viewing solutions in cross-department collaboration, so that relevant departments can understand and view related design data in a timely, fast and convenient manner.

With 3D visualization based on Web and Web- browser, result visualization module is characterized by unified management, easy maintenance, and independence of client, greatly enhancing the efficiency of R&D enterprises in sharing and viewing mass data and facilitating management and maintenance.

12.7 Automatic Report Generation

The product simulation data management system can automatically generate reports. Based on the existing simulation results, the automatic report generation system generates virtual simulation result reports according to the enterprise's design verification requirements. By using a WORD file as a template, in which the keywords and relevant expressions are added, a WORD report is generated by external characters, data and charts.

Defining this WORD template file and controlling its input data is the customization of simulation reports. Definition functions of simulation reports mainly include:

a) Definition of WORD simulation report template;

b) WORD simulation report template controls parsing of keywords and expressions;

c) WORD simulation report template is managed in the report template library.

d) Keyword entry applied by simulation report in simulation results.

e) Generation of specific WORD simulation report.

The entire simulation data management system can retrieve and query these standard report files. They serve as knowledge base files for reference and use in new design schemes.

12.8 Benefits Brought by Simulation Data Management Platform for Enterprises

Innovation. Innovation holds the key to obtaining different products with excellent performances in virtual simulation process. By enabling simulation processes to run more simulation-based researches quickly and easily in early development, high-efficiency virtual simulation can reduce costs, time and risks. This is a breakthrough of traditional design but also an arduous challenge.

Exploratory research of design space. In addition to accessing the current design, it is also important to access all cases encountered in designs and products in design space during exploratory study. This makes it possible to explore all design possibilities at an early stage, in order to optimize the product performance under all possible service conditions. An efficient exploratory research environment can accelerate the virtual prototyping and enable evaluation of all design and load case variables. Therefore, a method to obtain and reuse the simulation process shall be provided in this environment.

Management. Nowadays, analysts have spent a lot of time on routine data management and searching previous models and results data. The immature data management has become a major barrier to make full use of simulation technologies. As a necessary link in simulation promotion, the simulation data management system organizes and indexes all data, relieving users of onerous data management. In addition, tracking data pedigree is essential to understand and interpret simulation data.

Aided design. Improving the product development process is a basic approach to enhance product performance, in which timely feedback is very important. Unfortunately, many enterprises still perform simulation after design, which causes the simulation data to be submitted too late to improve the design. If virtual simulation and design can be seamlessly integrated, feedback will be timely provided to designers, so as to ensure better design. To ensure that the simulation works during the design phase, the model needs to be updated in real time according to current design, and the results and conclusions shall be fed back to the designers in a fast and consistent manner. Under the product lifecycle management framework of enterprises, this needs to connect different PLM components such as PDM systems and simulation management data systems with notification and signature mechanisms. The simulation data management system can be designed as a component under the PLM framework, and such component is capable of interactively communicating the data flow between enterprise systems within the PLM framework, thus participating in enterprise-wide workflow.

Efficiency improvement. Usually, during early stage, the immediate benefit of using a simulation data management system is to reduce the routine and administrative workload of analysts. Customer performance shows that the efficiency has improved by over 50%.

Sharing of model and accumulation of knowledge base. The simulation data management system provides consistent access to data, models and results of different development projects, thus generating long-term, substantial benefits. This includes enabling analysts to access previous knowledge and work, thus accelerating current project. Analysts can also determine the correlation and trend by data mining, and make new conclusions. Among the factors reflecting product development capabilities, two are of vital importance. One is the enterprise' own development process and specifications, and the other is the database of its own knowledge. By integrating simulation experiences, knowledge, and specifications into the simulation platform, the simulation data management system enables enterprises to establish their own specialized product design analysis knowledge base. This is very important for enterprises to be responsive and competitive in the future market competition.

CHAPTER 13

Co-Simulation Cloud Platform for SMEs

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Co-Simulation Cloud Platform for SMEs

13.1 Status of Simulation of SMEs

CAE has been widely applied in large and super large enterprises in automobile, transportation, civil ship, rail transportation, motorcycles, engineering machinery, heavy equipment, molds, motors and other industries, and achieved great economic benefits. However, CAE is barely used by SMEs for the reason that the adoption of CAE technology requires not only large capital investment, but also professional technicians. The lack of professional technicians is the biggest challenge for SMEs to adopt CAE.

Compared to the advanced manufacturing countries, China is still at the initial stage in simulation application. This can be seen from the obvious disparity of simulation application across China: There are huge gaps between SMEs and large enterprises in simulation application; Enterprises lack the talent team for simulation application; Application of simulation is barely mature without process specification and material database and thus simulation technology in each discipline can only be applied independently; The simulation application fails to align with the product design and test departments, thus only serving as a means of verification.

In SMEs, senior and middle management as well as design R&D departments tend to emphasize design, software and use rather than simulation, talent and specification. To change the simulation status of SMEs, the following aspects shall be considered:

a) Simulation strategy. The top priority is to determine the product simulation as the core capability of product R&D and select a simulation strategy that meets the corporate product strategy and status quo. We should establish the product simulation capability at the enterprise's strategic level. A good strategy shall be based on status quo with continuous improvement to cater the future demands.

b) Organizational system and cultural environment. To build the simulation capability, as a design R&D soft power of SMEs, it is important to build a team around the simulation strategy and conduct personnel training, while creating organizational system and cultural environment conducive to the cultivation, evaluation and motivation of simulation talents.

c) Simulation standards and specifications. Without standards, enterprises don't know when and what software and simulations are applied during design and development; and without specifications, enterprises don't know how and what to do. In this case, the simulation results fail to keep constant as a design reference. Establishing simulation standards and specifications, which represents an enterprise's core simulation capability, must be always taken into account when constructing simulation capability.

d) Co-simulation ecology. Constricted by financial, manpower and material resources, it is impossible for SMEs to establish well-developed simulation analysis capability. So we shall make use of our advantages and avoid the disadvantages. We shall take advantage of technical resources provided by external simulation experts, and build a reliable co-simulation service supply chain via Internet and informatization collaboration platform to quickly obtain the product R&D simulation technologies and capabilities.

13.2 Analysis of Simulation Requirements of SMEs

In terms of relevant discipline, the simulation requirements of SME involve all aspects of simulation technology. However, given the needs of an individual enterprise, the disciplines involved are limited. As application of simulation technology deepens, the simulation technology has evolved from single-disciplinary simulation to multi-disciplinary and multi-field co-simulation, with workflow constantly simplified. Some enterprises have begun to conduct secondary development for simulation software according to needs and established their own material library and standard parts library. Simulation technology has gradually taken the lead in product R&D process to drive the innovative design of products.

Generally speaking, the simulation requirements of SMEs are in line with the general law of CAE simulation technology capacity building: It evolves, progressively and incrementally, from point to plane and from single-disciplinary analysis to multi-disciplinary coordinated optimization and simulation. However, given the constraint of financial and manpower resources, it is impractical for SMEs to be self-reliance in building the simulation capability step by step. At the initial stage of CAE capacity building, enterprises confront large investment in hardware and software, shortage of talents, inefficient product simulation capability, slow returns and low input-output ratio, making them reluctant to build simulation capability, so that the product R&D core capacity is difficult to improve.

Given the characteristics of SMEs, when building simulation capability, they should first address their simulation requirements, and then conduct personnel training and gradually equip with simulation devices, and finally refine their simulation standards and specifications.

First of all, enterprises should consult their simulation strategies which need to be foresighted and practical to achieve long-term and tangible benefits. The simulation strategy should be based on the industry's CAE application level and status quo of the enterprise, and specifies the enterprise's goals and plans for building simulation capability as well as the talent development program.

Next, key issues to be solved in real products should be identified, and appropriate simulation technology service providers should be found to establish stable supply chain partnership, thus quickly obtaining CAE analysis capability by purchasing simulation technology services. Integrating external resources brings less cost and quick returns, making enterprises more confident in building simulation capability and encouraging them to implement the simulation strategies.

During the simulation cooperation with external parties, enterprises can gradually cultivate simulation project management and technical personnel, develop product simulation methods with the assistance of external talent resources, and allow the internal staff to reuse the resulting fruits and methods to build their simulation capability step by step.

Finally, by summarizing the process methods that are tested or verified by products, enterprises can develop their simulation standards and specifications to be applied in product R&D and manufacturing.

13.3 Simulation Technology Solutions for SMEs

Simulation technology solutions for SMEs should include software tools and technical services. CAD/CAE manufacturers mainly provide general solutions in terms of software tools and software support service. Since they only provide limited technical support and reference cases, the specific technical details of product simulation need to be explored and mastered by users themselves.

Different manufacturers provide solutions from different perspectives. Professional CAE manufacturers provide entry-level CAE simulation tools that are cost-effective and easy to learn with basic analysis functions, such as kinematic analysis of mechanism, structural strength and stiffness analysis, modality and the like. As simulation technologies popularize, professional CAE manufacturers no longer overemphasize this concept currently. Basic analysis functions are not sufficient to address key problems to be solved by simulation for products of SMEs. Professional CAE manufacturers provide one-stop multidisciplinary solutions through acquisitions and mergers to meet the simulation requirements of different industrial fields. The solutions focus more on specialty than on distinguishing enterprise sizes.

Simulation technologies have become more suitable for non-professional users and small-sized enterprises. At the same time, Simulation technologies are also becoming more affordable by embedding the simulation functions in CAD environment or embedding CAD functions in CAE software or simulation environment, enhancing the automation of simulation process, importing industry simulation template into R&D processes, and improving management of simulation data and processes.

With CAD/CAE integrated solutions that integrate or enhance CAE simulation capability, products of mainstream CAD manufacturers become more and more popular in SMEs. To echo the increasing popularization of CAE technologies, traditional CAS manufacturers with large user groups rush to acquire CAE manufacturers' software and integrate such software into CAD software. For example, AUTODESK acquired ALGOR, CFDESIGN and MOLDFLOW, and Dassault Systèmes acquired abaqus, Isight, SIMPOE and SimPack. Siemens has a relatively good CAE foundation among traditional CAD companies, and its product line includes the famous I-DEAS simulation software. After acquiring Nastran solver technologies in the antitrust competition in the United States, Siemens has significantly enhanced its competitiveness of CAE simulation products by acquiring a series of CAE manufacturers such as LMS.

The CAD/CAE integration solutions lower the threshold to introduce CAE technologies for SMEs, so that designers can quickly master the CAE simulation technologies in familiar CAD environment. These CAD/CAE integration software systems are desirable choice as the entry-level solution for SMEs.

Most domestic simulation technology companies do not develop CAE products by themselves but provide combined solutions consisting of one or several agent products. Such solutions are limited by the products of the manufacturers and suitable for industries in which the agent products have comparative advantages.

Since SMEs are generally short of CAE technical personnel, the acquisition of technical capability for product simulation is more important than CAE simulation tool and software. Since the CAE software products available on the market are abundant, enterprises can select proper products according to their needs and budgets. By contrast, it is difficult to obtain sustained product simulation technical capability. CAE technologies have been fully utilized by foreign SMEs (especially those in developed world) to enhance their own innovation ability, most of which are professional service firms supported by social forces, in particular the CAE technologies. This is exactly what we can learn from them. Therefore, simulation technology solutions for SMEs should focus on provision of sustained and affordable product simulation technology services.

13.4 Co-Simulation Cloud Platform of SMEs

Simulation capability and capacity building of SMEs involves great investment in manpower, financial and material resources. They need to firstly carry out the strategic planning of simulation business and then gradually obtain proper hardware & software resources and human resources, which is unreachable for most SMEs.

With the popularization of cloud computing, public cloud has become a good choice for SMEs. By relying on software& hardware resources of public cloud organizations, especially extensive human resources, co-simulation cloud platform can be established to provide SMEs with rich, quality and affordable simulation technology services. Enterprises can determine their simulation strategic plans through consultation with cloud platform experts, forge close tie with simulation technology service providers via cloud platform, and establish virtual CAE service departments.

Similar to the cooperative work platform applied within the enterprise, the simulation cloud platform uses information-based means to establish close cooperation between enterprises and simulation technology service providers, thus normalizing communication, improving communication efficiency and lowering cooperation cost of both parties. Secondly, the simulation cloud platform must be configured with highly scalable, highly available, large-scale and low-cost software & hardware resources to provide flexible and cost-effective simulation equipment resource services for SMEs. Based on the development of product simulation business, enterprises have gradually built their own basic simulation capability system. For complex, frontier and exploratory simulation business, they still rely on external professional simulation technology services.

Many companies have already explored the way to build co-simulation cloud platform with public cloud computing resources. These platforms, however, focus on provision of simulation software & hardware resources, which are not align with the actual needs of SMEs. Co-simulation cloud platforms built by SMEs should focus on provision of information-based services in co-simulation ecology, thus effectively aligning enterprise simulation requirements and socialized simulation technology services resources, hardware & software resources, and providing professional, and efficient co-simulation platform. The co-simulation cloud platforms of SMEs focus on the following issues:

13.4.1 Normalized Description of Simulation Requirements

During simulation analysis, complete and accurate description of simulation requirements is the basis for modeling simulation and checking verification. By defining requirements, simulation analysts can understand in detail the user's problems to be solved by simulation analysis. Proper simulation analysis is built on accurate description of simulation requirements.. Sometimes properly putting forward questions is even more critical than solving such questions. Due to different professional backgrounds, descriptions of simulation requirements vary greatly, sometimes such variations may lead to significant differences in understanding of physical models. Normalizing the description of simulation requirements aims to avoid differences in understanding of the analysis problem as possible.

The disciplinary analysis of simulation analysis design involves broad fields. Besides description of commonality, simulation requirements specification should also include disciplinary analysis requirement description. The simulation requirements description shall include at least the following contents:

Description of simulation problem

The simulation problem can be described according to simulation object, operating state, running process and problem phenomenon (damage, failure or to be improved).

Simulation object: It can be a single structure or a complex system, highlighting the parts to be simulated. If the simulation objects cannot be accurately defined, simulation experts can properly enlarge and accept or reject objects during modeling.

Operating state: It describes the constraints, motion and loads of a structure or system.

Running process: The simulation object is in different operating states at different time, such as processing simulation.

Problem phenomenon: It is the main problem to be solved by simulation analysis. Simple problems include strength and stiffness check. Complex problems involve vibration and noise reduction, performance optimization, and confirmation of processing parameters. In some cases, if users cannot determine the disciplinary attributes of simulation problems, detailed phenomenal description should be provided, such as the "structure rupture after xx working hours" or "the vibration noise increases obviously during high-speed operation". Detailed description of problem phenomenon facilitates simulation experts to build physical models and clarify modeling ideas and methods.

Description of simulation target

Description of simulation target describes the problems to be resolved by simulation analysis according to described problem phenomenon, such as increasing strength, reducing vibration, lightening product and refining process parameters.

An example of requirements of a simulation project is given below:

In a shafting transmission system, a marine cross-shaft universal joint transmits heavy-load torque, and cylindrical rollers distributed on the bearing convert the torque into distributed contact force and transmit to the bearing. After 10,000h operation, significant contact wear in certain percentage is detected in a universal joint during maintenance, shortening the service life of the universal joint.

In this project, by establishing a reasonable simulation model and method, the contact stress distribution of the rollers is obtained to find the main cause of bearing wear within the design life. In addition, the simulation analysis method is used to improve product design, thus increasing the service life of the joint by 20%.

To better normalize the simulation requirements description, standardized forms are used to facilitate the description and communication of requirements. Targeted simulation requirements form can be formulated for specific problems, with above description converted into the following table: Table of simulation analysis requirements for preventing contact wear of marine cross-shaft universal joint.

Description of simulation problem	
Simulation object	Marine cross-shaft universal joint
Operating state	Both ends are supported and fixed by the bearing support, large load torque is transmitted at a rated speed of 1000RPM, with working torque up to 100kNm. The cross shaft and rollers are lubricated with grease.
Running state	Low-speed rotary motion at speed ranging from 0 to 2000RPM.
Problem phenomenon	After 10,000h operation, the contact wear of a certain proportion is detected on the cross shaft, affecting the service life of the product.
Description of simulation target	
Contact stress distribution	Establish a proper simulation model and method to obtain contact stress distribution of the rollers, thus seeking out the main cause of bearing wear within the design life.
Service life improvement	Apply this simulation analysis method to improve the product design, prolonging the service life of the joint by 20%.

13.4.2 Abstraction of Mechanical Model Based on Simulation Requirements

Abstracting a proper mechanical model based on simulation requirement description is an important step for effective simulation analysis, which tests the professional skills of simulation engineers. Since the importance of this process may not be highlighted in simple simulation, people tend to ignore this process and directly conduct simulation modeling analysis. But for complex simulation, properly abstracting a mechanical model holds the key to successful modeling analysis. It is easily perceive the essence of a problem through phenomenon if the thinking mode to abstract the mechanical model from simulation requirements is developed.

The abstract mechanical model expresses the essence of a problem by establishing a description, through which the problem is studied. The model is not a replica of the real matter, and it is only designed to meet a specific goal. The description of some characteristics of a real matter may not and cannot be exhaustive. From this we can conclude an important principle of mechanical model abstraction: it should only focus on certain simulation target without abstraction or description of redundant and irrelevant factors. Besides the consideration of cost, efficiency and hardware & software computing capacity, this is also to prevent the simulation engineers from being inundated with excessive details in real matters. This principle must be followed throughout the process from simulation requirements to mechanical model abstraction.

Mechanical model abstraction expresses the essence of a problem, helping us clearly and thoroughly understand the final modeling target and avoiding deviation from the target during modeling. During such modeling process, modelers tend to keep the mechanical model abstraction in their mind, which cannot facilitate the establishment of simulation models. As the modeling analysis deepens, the abstract mechanical model will gradually change to reasonably express the essence of the simulation problem. The mechanical model summarized after iterative analysis can be more accurate in representing the simulation system, thus serving as a basis for subsequent normalized modeling after verification.

According to the aforementioned description of the cross-shaft joint simulation requirements, a mechanical model is abstracted by only taking out the cross bearing, the rollers and the outer ring, applying rated torque to the center of the cross shaft intersection and computing the contact stress distribution of the roller on the bearing. Considering the structural and stress symmetry, only a quarter of a single bearing is considered for computation. According to the stress characteristics of the bearing, half the number of contact rollers are used, greatly simplifying the mechanical model.

Without abstraction of the mechanical model against simulation requirements, the simulation model that represents all the details will be extremely complicated, resulting in huge solution cost and even no solution due to limitations of hardware resources.

13.4.3 Normalization of Simulation Modeling Analysis Process

Despite modeling for abstract mechanical models, the normalization of simulation modeling process is needed to gradually accumulate simulation experience and consolidate the existing simulation analysis results. The simulation modeling analysis should be normalized step by step. Attention shall be paid to summarization and accumulation of experiences from simulation practice. To this end, whether the current modeling method can be normalized should be put into consideration throughout the modeling. Especially for important products or repetitive simulation analysis, it is very meaningful to summarize the simulation specifications. Many foreign enterprises set great store by normalizing simulation process. For large and complicated product R&D, all stages in simulation from overall design, detailed design to experimental verification have been normalized, and disciplines involve strength, heat transfer, vibration noise and aerodynamic analysis. China leads the world in establishing simulation specifications in the aerospace and automobile industries, with desirable application results achieved, setting a good example for SMEs to promote and apply simulation specifications.

What exactly is simulation analysis specification, why should an enterprise establish a simulation specification and how to establish it?

Concept of simulation analysis specification

The simulation analysis specifications are a set of theoretically guided normalized operation procedures developed based on characteristics of the products by summarizing previous simulation analysis experiences, referring to test data, and drawing on relevant standards from other industries. CAE simulation specifications mainly include the basic general CAE simulation specifications and the analysis specifications involved in the main CAE simulation businesses.

The basic general CAE simulation specifications refer to the overall work specifications of enterprises for CAE simulation, in which the ways to conduct CAE simulation analysis and management are pointed out and can be classified and sorted according to the specific businesses of customers.

Specific business analysis specification is formulated by an enterprise to conduct a certain type of simulation analysis for a particular type of its self-developed products. For example, the strength analysis specification for a certain type of casing includes model import, geometric cleaning and simplification, mesh generation, assignment of materials and other attributes, boundary load setting, analysis submission, result processing, evaluation and report preparation. At the same time, a set of working instructions are developed based on which analysis engineers to conduct strength analysis of the casing, thus promising work efficiency and accuracy. Therefore, it is necessary to sort and plan the specifications according to the enterprise's own product classification.

Usually, the main products developed by the enterprise are taken as the research objects to establish corresponding simulation analysis specifications, with a view to regulating the enterprise's simulation analysis.

Why should enterprises establish simulation analysis specifications?

Many engineers participate in CAE simulation analyses conducted by enterprises. However, due to their different professional knowledge, software mastery and understanding of products, they may have different methods for model simplification, meshing, and processing of boundary condition, thus causing great randomness. As a result, different analysts may provide different analysis results for the same problem, arousing suspicion of the analysis results from product designers and wasting a lot of manpower and material resources to verify the analysis results.

Much repetitive work in CAE simulation analysis is extremely time-consuming, such as modeling, meshing, loading and report generation. Due to the repetitive, non-value added yet unavoidable work, senior analysts and experts falling far short of need are swamped with basic analysis and have no time to carry out advanced analysis and technical innovation. This is a great obstacle for enterprises to enhance their competitiveness. Besides, since the simulation analysis involves CAD/CAE modeling, different performance simulation analysis solutions, result evaluation and report preparation in which different tool software systems are used, the analysts need to frequently convert, transfer and modify data, thus resulting in human error and wasting time.

To this end, enterprises attaching importance to new product development are in dire need of establishing their own CAE simulation specifications to solve various problems in CAE simulation. The establishment of the CAE simulation specifications can be used to guide and normalize finite element analysis, and facilitate accumulation of own knowledge, so that other analysts can follow the normative working processes quickly. In this way, enterprises can perform CAE simulation in an effective, time-saving and precise way, providing strong guarantee for product R&D.

How to establish simulation analysis specifications?

Establishing CAE specifications is closely related to CAD and tests, with general steps as follows:

Clarify performance requirements of products. Because a product has different types of performance requirements, we have to determine which performance indexes need to be verified by simulation analysis.

Determine evaluation criteria for performance indexes. The evaluation criteria shall be built on a large number of experiments and tests, computational analyses and quality accident statistics of similar products with references to relevant standards.

Formulate finite element modeling standards, with focuses on mesh quality standards, boundary conditions and load standards, material data, and connection simulation standards (e.g. bolts, spot welding, and seam welding). Such standard shall be built on checking a wealth of test and experiment results with computing results.

Determine the processing methods of the computing results. The final computing results may need to be further processed in existing computing output, so that the processed results are checked against the experimental and test results and evaluation indexes.

The main technical routes for establishing CAE simulation analysis specifications include:

a) Formulating normative CAE preparation methods;

b) Formulating general CAE specifications;

c) Normalizing CAE specific business analysis process;

d) Formulating normative CAE business operation instructions; and

e) Customizing secondary development template of applied CAE software.

CAE simulation specification shall be established and improved continuously. First, we should start with the most basic and certain performance which typically have abundant experimental and test data, computing analysis data and quality accident statistics, and relatively mature product design. Therefore, these performance indexes can be better mastered. On this basis, we can formulate CAE specifications, and analyses can be credible under guidance of the specifications.

By establishing and applying CAE simulation analysis specifications, CAE simulation analysis can be standardized and normalized, shortening the time and improving quality of CAE analysis. In addition, accumulation-update mechanism can be established according to the specification, thusconstantly accumulating engineering analysis experiences and knowledge, enhancing the capability to design/analyze R&D products, facilitating sharing and innovation of enterprises' analysis knowledge.

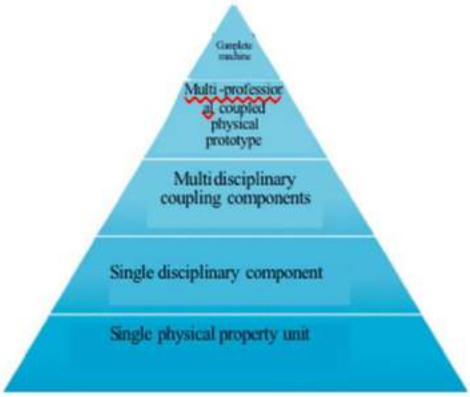
13.4.4 Simulation Analysis Quality Control and Evaluation

The traditional and typical product R&D process is design-simulation (virtual test) -real physical test. With the development of CAE technologies, simulation gradually replaces physical test and becomes virtual test after verification. In advanced manufacturing states, virtual tests supersede more than 70% of physical tests on average, and even completely replace the real tests in certain industries. The US Jaguar Principal CAE/CFD Division completely replaces the aerodynamic drag calculation and nacelle heat management tests with the fluid CAE tools. Austrian Virtual Vehicle Research Center carries out virtual crash tests with dummies on the virtual proving ground, superseding over 90% of crash tests and saving a large amount of costs.

It is the high credibility and verifiability that makes CAE simulation an alternative to physical prototype tests. Simulation analysis quality control and evaluation follow the verification & validation (VV) concept of CAE, and the concept was introduced nearly ten years ago abroad. It refers to the verification and validation of CAE model, a key to make CAE simulation become virtual test. For example, in the simulation department of an advanced enterprise, time spent on simulation modeling & analysis is less than 50%, while time spent on CAE simulation V&V and test is more than 50% on average, highlighting the significance of CAE verification and validation (VV). The core thought of V&V is to verify and validate CAE models with physical test results, analytic solutions and other data, promising the consistency between CAE simulation results and test results. American Society of Mechanical Engineers (ASME) and National Agency for Finite Element Methods and Standards (NAFEMS) convene special worldwide V&V conferences annually for exchanging V&V technologies.

CAE simulation model needs to be established at each level, from complete machine to a single physical characteristic unit of a product. Each level also requires physical tests to verify the model.

Figure 13-1 Model verification from single physical characteristic unit to complete machine



13.4.5 Cooperative Management of Simulation Business

There are intricate sequence relationships, cooperative relationships, and data exchange and information sharing requirements among the co-simulation processes. How to effectively manage, control and coordinate the entire simulation process is essential for co-simulation. In response to the characteristics and requirements of asynchronous co-simulation, a hierarchical management mode and a process management and control mechanism integrating task flow and workflow are proposed. By developing and expanding the functions of project and process management, and the function and data integration of the task flow and workflow, the hierarchical and integrated management and control of the co-simulation process are realized.

Implementing simulation tasks based on normative simulation process management allows simulation workers to obtain correct data and clearly understand their job objectives, thus making the simulation more efficient. In addition, the simulation process management has a flexible extension mechanism which solidifies specific simulation processes, simplifies the simulation process, and can be integrated with the enterprise's existing application systems.

Through the integration of simulation technologies, tool software systems are integrated into a unified environment, in which engineers no longer need to switch various tool interface environments and data can be transmitted automatically among the software systems, which relieves simulation engineers of burdensome unskilled work, thus improving their work efficiency. Some specific and processed analysis processes can be packed to provide guidance and template throughout simulation.

As for parameterization and parameter management, parametric modeling and analysis are achieved by defining model parameters and managing parameters, thus making simulation analysis more efficient. The parameterization and parameter management module can define parameters and manage the parameters based on the parameter manager in a centralized manner. After confirming that the analysis process can be entirely completed, users can adjust the parameters and re-execute the solution to drive the simulation process based on parameters.

Optimization design modules are combined with parameter managers to realize design optimization by adjusting design parameters. By running the design exploration-driven parameters, optimization design can retrieve the maximum and minimum values, and perform response surface analysis and other optimization analysis.

13.4.6 Simulation Expert Studio

Simulation experts are important resources and their management constitutes a key part of the simulation cloud platform. The simulation cloud platform connects simulation requirements and expert resources through simulation project management to coordinate the simulation analyses between customers and simulation experts.

A networked environment for product R&D and manufacturing is built through off-site deployment. Co-simulation off-site deployment provides a "face-to-face" cooperative work environment for temporally and spatially dispersed simulation workers, thus realizing sharing and access control of simulation data for all parties. In this way, simulation workers can better exchange information through a shorter information transfer way without temporal and spatial barriers, thus saving time and efforts and improving work quality and efficiency.

Simulation expert studio provides the following functions:

•Introduction of team resources of expert studio: Introduce team and core team resources, including professional background, skills and expertise of simulation experts, and team business orientation.

•Studio project experience: Provide existing project experiences for customers' reference.

•Business Scope: The expert studio can define the business scope based on their resources.

Expert teams can be hierarchical and mutually complementary based on division of labor, with a view to establishing co-simulation ecology. Senior simulation experts are responsible for top-level CAE strategy planning, physical model abstraction or establishment of system concept model, and shall have comprehensive theoretical basis and industry background.

The application expert team is good at using simulation tools and focuses on the implementation of simulation analysis projects. Since simulation analysis involves a wide range of subject areas, the application expert team can be subdivided into experts in different subject areas, including simulation software application.

Services provided by expert teams can be accredited on the simulation cloud platform in terms of professional theory level, industry background, project experience and user feedback, thus classifying and grading the abilities of expert resources, so as to meet the user's simulation requirements.

In addition, the simulation expert team can also provide external simulation knowledge services. The simulation knowledge base contains simulation basic knowledge bases, tool software experience libraries and project case libraries, which can be provided by the simulation expert team and subject to information-based management by the cloud platform.

13.5 Summary

Taking advantage of the convenience and economy of the public cloud and through the means of Internet informatization, the simulation cloud platform aligns simulation requirements of a wealth of SMEs with simulation expert resources across China and quickly establish specialized simulation application ecosystem to provide SMEs with controllable cost and continuous high-quality simulation technology service.

With the simulation cloud platform, SMEs can obtain cost-effective software & hardware resources as well as extensive and quality external simulation technology services. Strong partnership can be forged through project cooperation to create virtual simulation department. On this basis, SMEs can build their own simulation R&D capabilities gradually, and finally achieve product innovation through technology innovation.

CHAPTER 14

Future Technology Outlook of Intelligent Digital Design and Simulation

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14.1 Development Trends of Digital Design Technologies

The general development trend of advanced machinery manufacturing is precision, flexibility, virtualization, networking, intelligence, integration and management innovation. Digital design and manufacturing technology is the foundation of advanced manufacturing technology. With the continuous improvement of computer technology, the popularization and application of Internet network technology, and the needs of users, the development of CAM, CAE, PDM and other technologies will definitely promote further development of the digital design technology. Development trends of digital design technologies mainly include:

a) Refinement of single technology integrated into multiple technologies: CAD/CAM technologies mainly include curve modeling, curve and solid integration, solid modeling and large component design.

b) Technical integration of PDM and CAD/CAPP: interface and integration technologies are the focus form present to the near future.

c) Seamless connection between digital design and virtual simulation and manufacturing: Based on CAD technologies and computer-supported CAE simulation technologies, a virtual environment, virtual design and simulation, virtual manufacturing processes, virtual products, and virtual enterprises are formed, thereby greatly shortening the product development cycle and increasing the one-time success rate.

Digitally designed networked network technologies make it possible to design in a concurrent, off-site and cooperative way. It will greatly expand and enhance the efficiency of digital design. The rapid development of network technologies has stimulated the development and wide application of network design and manufacturing technologies. Through Internet, LAN and Intranet, enterprises can take the orders from all over the world and build dynamic alliance enterprises to conduct offsite design & manufacturing, and then produce products at the production base closest to the users.

14.2 Development Trends of Digital Simulation Technologies

14.2.1 Impact of Big Data on Enterprise Digital Design and Simulation

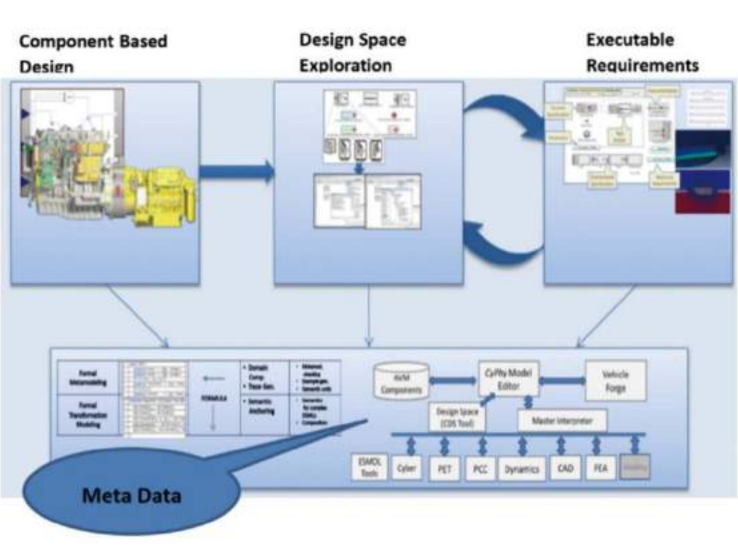
The coming big data era influences the future of enterprises, especially manufacturing. By steering the new generation of information technologies and industrial development, big data significantly affects the design and development, production and manufacturing, operation and management, sales services and other industrial chains of enterprises.

There are broad synergies and huge development potentials of big data and manufacturing. As big data grow mass, diverse, speedy and value-measured, data assets have gradually become the core of enterprise production, and big data are more and more important for product users. Enterprises must collect and master big data to conduct intelligent technology reforms if they want to stand out from the competition. Therefore, an increasing number of enterprises have started to implement the strategic layout of big data, redefine the corporate core competitiveness, and even change the overall development orientation of the enterprises.

When referring to the concept of "big data", most people think of the large amount of data, and the popular big data applications that come to mind are mostly Internet companies and financial industries such as Alibaba and Amazon. The data volume of the manufacturing industry, however, still lags far behind these industries. Is it impossible for the manufacturing industry to achieve "big data"? The answer is no. Viktor Mayer-Schonberger pointed out in The Age of Big Data that analyzing with big data is characterized by taking all data rather than part of them as data sample. Of course, in most cases, this "all data" can only be theoretically infinitely close, and the development of data collection, storage, and analysis technology makes it possible to obtain all data. In the process of traditional informatization implementation, the accuracy and completeness of data are also taken as the key points. When considering the transition from the traditional informatization construction to the leap of the "big data" era, from what aspects do we need to change in thinking?

First, data should be valued more than ever. In the past, data quality generally holds the key to successful implementation of information system, while in the future of enterprise management, data will rise to the height of enterprise strategy. Data not only serve information systems, but also directly serve R&D, design and simulation, operation and decision-making of enterprises. In recent years, concept of "data assets" was proposed, which is intended to emphasize the role of data in future enterprise R&D and management. Manufacturing enterprises should attach importance to data management at an early date.

Second, the scope of the data needs to be redefined. According to the traditional definition of enterprise informatization, an enterprise itself is analyzed as a system, where information systems are generally classified to assistant decision-making system, management information system and underlying executive control system. In the future informatization construction, we should integrate the original system data, and further expand the scope of data collection to the entire supply chain, industry and related industries, social environment and other fields. Only by collecting and analyzing the data of the product's entire life cycle, and incorporating more data into the analysis, can we provide more effective support for R & D design and management personnel's decision-making.



a) Big data provides opportunities for building a manufacturing power

Big data has become the strategic commanding height of national competitiveness. At present, the world is experiencing a new round of technological revolution and industrial transformation. By analyzing the massive data generated by the new generation of information technologies such as the Internet and the IOT, we can learn from experiences, discover rules, predict trends, facilitate decision-making, and expand human's ability to understand and reshape the world. This provides a powerful engine for human economic and social innovation and development.

Big data has opened up new ways for the transformation and upgrading of the manufacturing industry.. The era of data explosion has seen the increasingly larger and diversified data obtained, managed and utilized by manufacturing enterprises. By collecting, organizing, analyzing and using these data in a scientific way, and providing valuable decision-making reference for the full life cycles of products and each link of production and operation, enterprises can achieve a higher productivity and profit rate as well as better comprehensive development.

China has taken the high ground in developing manufacturing industry big data. 'Its manufacturing industry ranks first in scale worldwide, and there are a large number of large-scale manufacturing enterprises. As development of information technologies gathers pace, a mass of manufacturing data have been created every moment and applied in a wide variety of scenes, enjoying broad development space. To faster build China into a manufacturing power, the State Council issued policy documents such as *Made in China 2025, Guiding Opinions of the State Council on Vigorously Advancing the "Internet Plus" Action and The Action Outline for Promoting the Development of Big Data"* successively, providing development of manufacturing big data with favorable environment.

b) Big data drive comprehensive transformation and upgrading of manufacturing

Big data accurately respond to user requirements to improve manufacturing R&D and design level. By applying big data to R&D and design, enterprises can facilitate the establishment and integration of innovation platforms, extensively collect and deeply mine consumers' behavior data and feedback information, know preferences of customers precisely and allow customers to participate in product requirements analysis, R&D, design and other innovative activities through crowd innovation and crowd sourcing, thus realizing continual improvement of product design schemes.

Big data enable business scene interaction and promote the intelligent upgrading of manufacturing. If traditional automation, digitization and networking provide manufacturing with "body", "sensory" and "neurology", then big data equips the manufacturing with a "brain", making it flexible to respond to various business scenarios to achieve intelligence in real sense. By integrating and analyzing manufacturing equipment data, product data, order data, and data generated during production, production control can be made more timely and accurate, and the degree of collaboration and flexibility in manufacturing is significantly enhanced.

Big data assists enterprises in scientific decision-making and enhances manufacturing management capabilities. The application of big data can promote the establishment of cross-industry and cross-region innovation organizations and the development of new models such as cooperative design, e-commerce, crowd sourcing and crowd innovation, and enhance the operation and management capabilities of manufacturing enterprises.

Big data supports the development of production-oriented services and accelerates the manufacturing servitization. Big data accelerates the transformation of manufacturing services in three main directions:

i) Expand businesses of enterprises from production and sale to service fields;

ii) Transform the enterprise development mode from providing after-sales service oriented at product production and sale to design products oriented at providing sustained services; and

iii) Enable enterprises to make profit more from after-sales production service link than from product manufacturing and sale.

The accelerated integration of big data and traditional businesses expedites new products, new services and new business formats. China has the world's largest consumer market and the most diverse consumer demands. Incorporating big data into the functional development of wearable devices, home products, and automobile products can promote leapfrog innovation of technology products to form the new fields of manufacturing including smart wearable devices, smart home and intelligent connected vehicles, which is conducive to grasping the new growth points and commanding heights of manufacturing.

c) Promote the integrated development of big data and manufacturing

To promote the deep integration and development of big data and manufacturing in the future, it is essential to work on the following aspects:

i) To improve industrial information infrastructure:

◆Accelerate the establishment of industrial broadband networks with larger capacity and sound service quality;

◆Strengthen the planning and layout of wireless broadband networks in the manufacturing sector;

◆Deploy low-latency, highly reliable industrial Internet for intelligent manufacturing units, smart factories and IoT applications;

◆Leverage the advantages of Internet companies and industrial software companies, and guide them to integrate closely with manufacturing enterprises to achieve unified data collection, management, and efficient processing.

ii) Establish manufacturing data resources:

◆Facilitate the large-scale applications of sensors and other data acquisition terminals, and acquire data via multiple channels at different levels;

◆Guide and support key enterprises and industry organizations to build low-cost, high-efficiency manufacturing big data storage centers and analysis centers to form systematic, comprehensive, timely, and high-quality data resources;

◆Improve the relevant systems and mechanisms for constructing manufacturing data resource, innovate policy incentives, and form a data resource construction ecology in which all parties participate proactively to achieve win-win.

iii) Achieve breakthrough in the core technologies of manufacturing big data:

◆Open autonomous and controllable manufacturing big data platform software and application software in key areas and key business links;

◆Support innovative SMEs to develop specialized manufacturing industry data processing and analysis technologies and tools, and provide characteristic data services.

◆Promote cross-disciplinary integration;

◆Carry out research on key algorithms and technologies for analysis of manufacturing big data;

iv) Enhance capability to analyze and apply big data:

◆Establish a batch of high-quality manufacturing big data service platforms;

◆Promote the opening and sharing of software and services, design and manufacturing resources, and key technologies and standards;

◆Better apply manufacturing big data.

v) Improve data security ability:

◆Research and formulate the big data security system in terms of manufacturing-oriented information acquisition and control, sensitive data management and other aspects;

◆Study and draft the data classification standards, and push forward the standardization and legislation in terms of data protection, personal privacy, data resource interest, development and utilization;

◆Develop and launch standards for managing the acquisition, transmission, storage, backup and migration of manufacturing data, thus making all stages and links throughout the data lifecycle safe and reliable.

vi) Cultivate versatile big data talents:

◆Support qualified universities to introduce big data-related majors by virtue of computer, Math, statistics and other major advantages;

◆Encourage universities, scientific research institutions and enterprises to introduce big data-related strategists and innovation leaders in a planned and hierarchical manner;

◆Rely on the R&D and industrialization projects in the manufacturing big data field to introduce big data managers, analysts and other high-end talents with practical experiences.

d) Application of big data in intelligent digital design and simulation

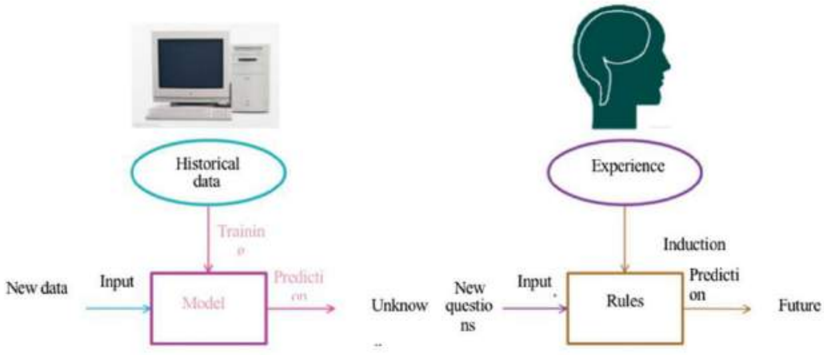
During the full life cycle of products, from conceptual design, detailed design, simulation optimization, virtual prototypes, process manufacturing, mass production, customer use and daily maintenance to the end of product life, a large amount of data can be accumulated, and such data significantly affects design and simulation. It is always necessary for us to study what data is worthy to be kept and how to use them to serve new designs and simulations.

Big data can serve the operation and maintenance of products. For a typical example of GE case, a platform is established to provide all-round services for monitoring, operation surveillance and fault diagnosis of aeroengines. During operation and maintenance of products, the passive, traditional operation & maintenance mode is replaced by analyzing and collecting sensor data of intelligent devices as a way to make big data analysis, thus taking the initiative to perform product safety monitoring, fault diagnosis, and optimize the product operation.. What is required in the application of big data? The first is to be capable of acquiring data, which means the product is required to be intelligent. Therefore, an intelligent product with sensor installed is essential for intelligent manufacturing to transfer data in real time and provides basis for the future operation and maintenance.

When the monitoring feedback is transmitted back to the enterprise data center, the enterprise can analyze these data, re-compare the simulation prediction and the actual result, find out the gaps, adjust the parameters required for simulation, and predict the potential problems and life trend of products in real time, so as to provide accurate guidance for product maintenance and parts replacement.

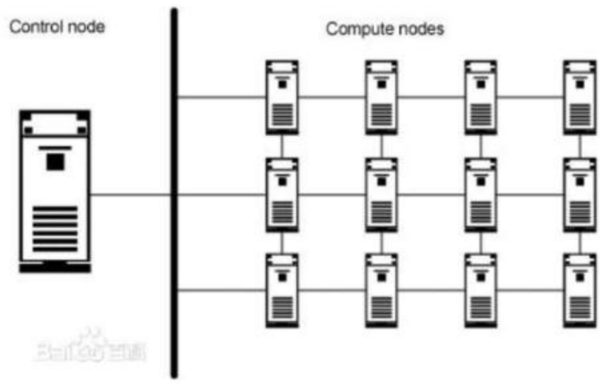
14.2.2 Application of Artificial Intelligence Technologies

The past few years have seen big explosion of artificial intelligence (AI) technologies. The key words of artificial intelligence include neural network, machine learning and deep learning, which are underpinned by mathematical algorithms and big data. By analyzing and computing numerous existing sample data, machines can perform data analysis and learn to optimize, deduce and find the right conclusion and prediction, thus delivering best solutions. The whole process aims to perform intelligent learning and optimization and seek for best solution. Although it is currently only used in certain fields, such as weichi (a game played with black and white pieces on a board of 361 crosses), image recognition and intelligent driving, AI will be applied in broader fields. In addition, AI can be integrated into all stages throughout the full life cycle of a product.



14.2.3 Development of Software and Hardware Technologies and Application of High Performance Computing

AI technologies mentioned above are put into practice through application of software and hardware technologies. Similarly, technologies such as 5G, mobile terminals, supercomputers, and cloud computing will also be gradually applied to product R&D, design and simulation. Design and simulation accompanied by mass data will cause problems in computing amount and speed while rapid transmission and communication technology for the mass data and high performance computing technology are inevitably the basis of its application. Therefore, these technologies will be indispensable components of intelligent design and simulation.



14.2.4 Application of VR Technology

In recent years, along with the development of computer imaging technologies, VR technology has flourished in many fields, such as the game industry and product advertising, where VR technology has been integrated. The post-processing in CAE simulation aims to present the results of simulation computation. If these results can be displayed through VR, amazing visual effects will be delivered. In addition to the better visual effects, product design and simulation with 3D real effects can bring a real experience to designers, allowing designers to truly feel the working conditions of the products in 3D scenes, so that they can better understand the actual effects, performance, function, space and other elements of the products in real scenes.

14.2.5 Interaction Between Intelligent Design, Simulation Technologies and 3D Printing Technology

Intelligent production plays a key role in intelligent factory. After the design is finalized by intelligent design and simulation, products will be produced in batches on automatic production lines. 3D printing, a technology increasingly used in automatic production lines for various products, is built on intelligent design and simulation. Without optimization design and simulation verification, 3D printed products are not competitive.

14.2.6 The Coming Era of Product Personalized Customization

In industrial age, when profit is generated from large-scale production, it is impractical to completely customize products. To solve this contradiction, intelligent design and simulation, along with the integration of the above technologies, make it possible to personalize product designs. In the full digital era, all demands of a customer for a product can be seen, selected, experienced and verified in a virtual environment, so that the selected product can be directly produced in a factory according to personalized customization requirements. In addition, the production line in the factory can also be configured and designed based on personalized design, thus ensuring both mass production and personalization to truly achieve personalized customization of product design.

14.3 Realization of Full Digital Product Design

The full digital product design aims to realize all processes of product design in virtual environment, from 3D CAD, CAE simulation & verification to CAM computer-aided manufacturing , and 3D display of products is also displayed in VR. The manufacturing industry has always strived to realize the full potential digital product design.

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