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Background of Electromechanical Coupling of Electronic Equipment

1.1 Introduction

Electronic equipment is a kind of special electromechanical equipment that targets the acquisition, transmission, and processing of electromagnetic signals or other electrical performance and adopts mechanical structures as the carrier.

Complex and high-performance electronic equipment is nothing but a system composed of multiple disciplines such as electronics, mechanical structures, and heat transfer. The successful acquisition of its performance depends not only on the design quality of each simple discipline but also, even more important, on the intersection and inosculation among them. This is because the mechanical structure not only guarantees the electrical performance as the carrier but also often restricts the realization and promotion of electrical performance. Therefore, it is necessary to study the electromechanical coupling of electronic equipment, toward establishing the electromechanical coupling theoretical model, making the influence mechanism of nonlinear structural factors on electromagnetic performance clear, and finally developing electromechanical coupling model and the influence mechanism-based system design theory and methodology.

Since the First Industrial Revolution, mechanical equipment has become the foundation of industrialization. Since the middle of the twentieth century, the rapid development of both electronic technology and computer technology has gradually made electronic equipment become an important equipment of modern industrial society. It has been widely applied in various fields such as land, sea, air, and space. With the development of science and technology, the demand of complex and high-performance electronic equipment is becoming more and more urgent.

The development of electronic equipment has passed through the age of electron tubes, the age of transistors, and the current era of integrated circuits. This is classified based on the devices. In terms of working frequency, it has

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experienced the low-frequency era, the high-frequency era, and is moving toward ultrahigh frequency and terahertz (THz) frequency bands. Compared with the early electronic equipment, the prominent features of the modern electronic equipment are high frequency, high gain, large frequency width, high pointing accuracy, high density, and miniaturization, all of which put forward high requirements and greater challenges for the design and manufacturing of mechanical structural parts, some of which even exceed the limits of manufacturing ability. At this time, the electrical part and mechanical structure of the electronic equipment must be considered simultaneously and comprehensively, and the electromechanical coupling design is urgently needed [1, 2]. Unfortunately, the traditional design is independent between mechanical and electronic technologies, which leads to poor performance, long cycle, high cost, and unwieldy. It significantly restricts the improvement of the level of electronic equipment.

The way to solve the problem of electromechanical separation design is the electromechanical coupling design, which includes multifield coupling problem and the influence mechanism of electronic equipment. The research content of multifield coupling problem is to make the relationship between mechanics and electronics clear from the perspective of field coupling, and the task of influence mechanism is to find the influence mechanism of nonlinear structural factors on electrical properties. These two parts complement each other and are two manifestations of electromechanical coupling theory [3, 4].

The in-depth study of the electromechanical coupling of electronic equipment is the prerequisite for the development of high-performance electronic equipment. Early researches did not start from the level of electromechanical coupling. This was because the working frequency band was not high or the volume requirements were not harsh at that time. But now it is not the case, because mechanics and electronics are inseparable, and researches must be carried out from the system level of mechanics and electronics or mechanics, electronics, and heat transfer coupling to solve the problem thoroughly. There are two manifestations of electromechanical coupling, one is the form of field coupling, and the other is the influence mechanism. In engineering, the influence mechanism was understood in earlier times, and many researches were carried out. With the development of science and technology, the roles of different physical fields have been gradually recognized, so the electromechanical coupling problem of electronic equipment has begun to be investigated from the perspective of the field.

As for the concerned influence mechanism, the purpose is to understand, discover, and master the influence mechanism of mechanical structural factors on electrical performance and then provide empirical formulas, diagrams, and design specifications for guiding the electromechanical coupling design of electronic equipment. Mechanical structural factors include structural parameters and manufacturing tolerance. The field coupling theory is to provide a mathematical relationship between different physical fields, that is the mathematical model.

Generally speaking, coupled multifield problems (CMFP) refer to a physical phenomenon in which two or more physical fields affect each other through interaction. This phenomenon is widespread in objective world and practical engineering [5]. Common coupling problems include fluid–solid coupling, gas–solid–liquid coupling, structural–electromagnetic–thermal coupling, structural–optical coupling, acoustic–structural coupling, and electrostatic–structural coupling [6–15]. Through the analysis of some coupling phenomena appearing in actual engineering and the study of the inherent physical properties of each physical field itself, the mutual influence relationship between the physical fields can be initially determined (Figure 1.1). The inside of the circle in the figure is a physical field, the directed line segment indicates the interaction between the physical fields, and the text in the line segment indicates the physical quantity acting on it.

As for the CMFP appearing in electronic equipment, the coupling relationship among the physical fields can be simply expressed as follows. Taking the reflector antenna as an example, which is used in telecommunication, navigation, radar, radio telescope, and space deployable antenna, the reflector is used as the boundary of the electromagnetic field. When it is subjected to environmental loads (self-weight, wind, temperature, vibration, shock, etc.), the antenna reflector surface is deformed, which will change the boundary conditions of the electromagnetic field and affect the realization of electrical performance, such as gain degradation, increase in sidelobe level, and poor beam pointing accuracy. This is the first fact. In reverse, as the working frequency increases (the wavelength decrease), a tiny change in the electronic performance will give rise

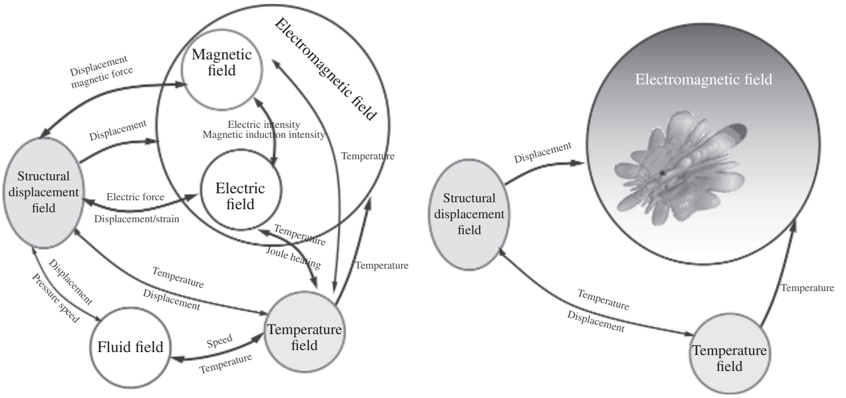

Figure 1.1 Coupling relationship diagram of each physics field.

to a big change in the antenna structure to guarantee this tiny change, which needs a large change to fit the performance. Meanwhile, as the working frequency becomes higher, the relationship between structure and electromagnetic performance becomes tier. From this viewpoint, the influence between antenna electronic and structural parameters is mutual and dual directional.

Furthermore, as the advent of the space era, the demand on spaceborne deployable antenna is urgent, of which the requirements are large diameter, high precision, light weight, and large ratio of the deployed size to furled size. To meet these requirements, the membrane antennas have been pushed in the research and application. Because of the low stiffness of membrane outside the surface, the electromagnetic pressure on membrane reflector from feed and space cannot be ignored. At this time, the influence between antenna electronic and structural parameters is mutual and dual directional [16].

1.2 Characteristics of Electronic Equipment

Modern electronic equipment have a wide variety of functions and appearances. The most typical electromagnetic signal receiving and transmitting equipment is the antenna. The reflector antenna is one of the most widely used form of antennas, such as the reflector antenna used in lunar and deep space exploration and the deployable antenna on communication satellites, as shown in Figures 1.2 and 1.3.

Figure 1.2 A 66 m-S/X-beam guide antenna for Mars detection.

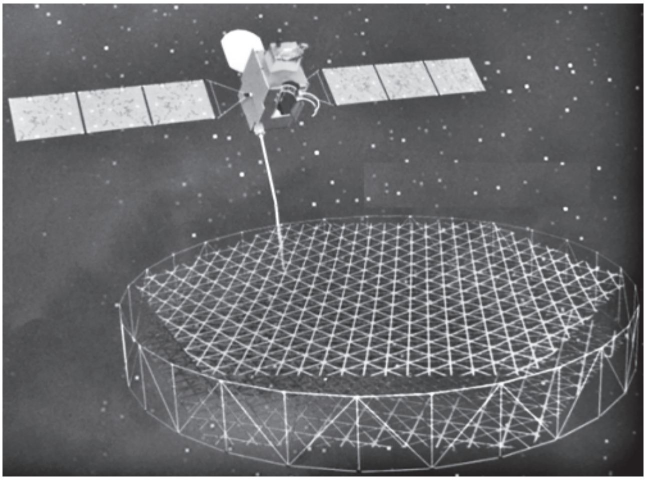

Figure 1.3 China "Tian Tong No. 1" spaceborne deployable antenna.

The earliest electromagnetic signal-processing equipment are radar transmitters, receivers, power amplifiers, and other equipment. Modern electronic technology usually uses the equipment as a functional module and then integrates them into one device, such as avionics, where each functional module is installed in the same chassis, and the lower part is a shared heat dissipation channel.

Modern electronic equipment have more powerful functions and more complex systems far beyond the scope of early electronic equipment. For example, in the Air Police 2000 early warning aircraft, as shown in Figure 1.4, not only the radar system and communication system on the aircraft are electronic equipment but

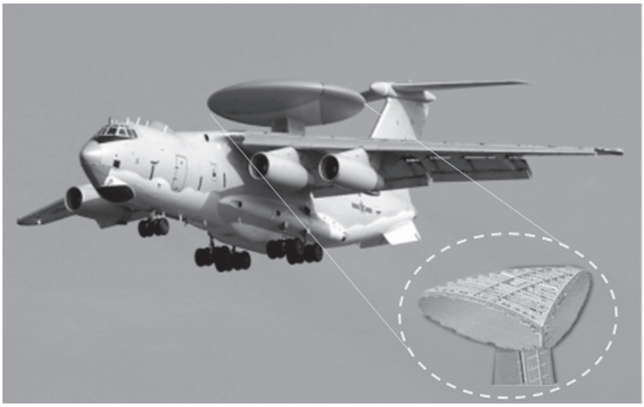

Figure 1.4 Early warning airplane – airborne phased array radar. Source: Twitter/ST.

Figure 1.5 The Yuan Wang ocean survey ship and antenna. Source: (a) baike.com.

also the entire early warning aircraft itself is an electronic equipment. Similar is the case for Yuan Wang ocean survey ship shown in Figure 1.5; regardless of its volume and size and how much pure is the mechanical equipment on it, considering the fact that the mission of the survey ship is to obtain and process the electromagnetic signals, it can also be called an electronic equipment.

The most notable feature of the electronic equipment is the integration with electromagnetic and mechanical technologies. Different from general mechanical equipment containing electrical components, the electronic equipment takes electrical performance as the main task of entire equipment, while the mechanical part is being subjected to electrical performance. That is to say, the mechanical part serves as the carrier and guarantees the realization of electrical performance.

Compared with general machines or traditional machines, the characteristics of electronic machines are embodied as follows: In terms of **purpose**, electronic machine pursues the electrical performance of electronic equipment systems, while conventional machine pursues their mechanical performance. In terms of the **realization means**, electronic machine is mainly realized by changing and optimizing mechanical structural parameters and processes, while traditional machine is mainly realized by adding electronic technology, optoelectronics, and other technologies.

Electronic equipment are one of the main research objects in the field of electromechanical engineering. Their essence is to study the crossover and integration of different disciplines, with a view to discovering theories, methods, and technical means to improve the performance of systems or equipment by studying the coupling problems between different physical quantities or physical fields. Electromechanical engineering mainly studies the mechanical design, structural design, and manufacturing of electronic equipment, information equipment, or electronic systems. Its characteristic lies in how to make the system or equipment meet the electrical performance requirements in the complex mechanical environment, electromagnetic environment, and thermal environment and retain high reliability.

1.3 Components of Electronic Equipment

1.3.1 Mechanical and Structural Part of Electronic Equipment

The mechanical and structural part of the electronic equipment includes two main aspects. One is the overall layout of the electronic equipment structure according to the working environment, the technical requirements, the overall conception of the system, and the design and planning of the subsystems. The other one is the design of mechanical parameters. For the equipment installed in the movable platform or transportation requirements, there should be sufficient strength and stiffness to resist a variety of environmental loads caused by material fatigue, structural resonance on the effects of electrical performance. If necessary, special vibration isolation and buffering measures have to be used too.

This is the most traditional area of structural design for electronic equipment and one of the earliest developed and most mature aspects of the design theory and methodology.

There are also requirements for electromagnetic compatibility (EMC) in the structural part. It also contains two aspects, one is the electrical performance and its component parts (devices) that can meet the requirements for the usage of electronic equipment, and the other one is the EMC requirements of the equipment as a whole component. The latter means that various measures are used to control electromagnetic interference from all aspects such as circuitry, structure, processing, and assembly and also to meet the cost requirements. It also contains two aspects of meaning, one is that the electronic equipment can resist external electromagnetic environment interference, and the other one is that the radiated electromagnetic waves from electronic equipment itself do not interfere with other electronic equipment.

For the structural design of electronic equipment, the key issue is to improve its electromagnetic shielding effectiveness, which is an indicator of EMC independent of the internal components and external environment. Whether the electronic equipment is shipboard, airborne, on land, or even spaceborne, there are specific requirements for electromagnetic shielding effectiveness.

Furthermore, there are also thermal control requirements on the structure of electronic equipment. The thermal design of electronic equipment is mainly for the electronic components and the whole mechanics for heat control. Unlike conventional machine and equipment, of which the heat is generated by energy or mechanical friction, the heat of electronic equipment is mainly generated from electronic devices. For modern high-density assembly equipment, the thermal capacity of the electronic component is much lower than the mechanical structure of the part; therefore, it requires more stringent thermal control measures, and the main purpose is to prevent the failure of electronic components due to high temperature.

This aspect reflects the difference between electronic equipment and other mechanical devices and has now been developed into a specific technology – thermal analysis and thermal control of electronic equipment, which encompasses three aspects of thermal analysis, thermal design, and thermal testing. Heat dissipation methods can be roughly divided into two types: air cooled and liquid cooled, both of which need to be selected according to the internal device power consumption and the external environment. Some equipment used in special environments may also require local heating, such as the space environment.

Other aspects of the structure that should be considered include the corrosion protection design, i.e. the selection of the appropriate protection measures and structure for the specific environment in which it is to be used. Ergonomic design, i.e. the requirement for ease of usage and maintenance by the operator. In addition, the design of the connections at the electrical contact points affects the reliability of the equipment and is increasingly attracting the attention of designers.

To sum up, the structural part of electronic equipment contains an extremely wide range of contents, involving mechanics, machinery, material science, thermal science, electromagnetism, environmental science, aesthetics, and many other fields, and is a marginal interdisciplinary discipline. The design should therefore also be carried out from a multidisciplinary perspective.

1.3.2 Electrical Part of Electronic Equipment

The electrical part can be divided into two categories. One is the circuit part, which includes the layout of various circuits, the design of printed boards, and even the design of a particular chip or electronic device.

The other category is the electromagnetic field section, mainly radar antennas, waveguides, etc., of which a certain distribution of the electromagnetic field in space is achieved by means of certain structures or electronic devices.

The electrical part inevitably has to be realized through the structural part, so the electrical part of the electronic equipment is inevitably influenced and constrained by the structural part.

1.4 On research of Electromechanical Coupling (EMC) of Electronic Equipment

1.4.1 Current Status of Research on Electromechanical Coupling of Electronic Equipment

The electromechanical coupling of electronic equipment is not only a wide range of fundamental theoretical issues but also one of the core technical issues that limit the electronic equipment for high performance, development cycle, and cost. It is to be regretted that few reports are known on the mechanism of mechanical, electrical, and thermal field coupling theory of electronic equipment and the mechanism of mechanical and structural factors affecting the electrical performance.

To begin with, there are some in-depth researches and applications in the component level or part [17–19]: For example, the influence of random wrinkle shapes on the transmission characteristics of electromagnetic waves [9], the electromechanical coupling and its influence coefficients in surface acoustic filters [10], the coupling between electrical and thermal fields in induction heating equipment [20], and the influence of mechanical structure manufacturing accuracy of phased array antennas on electrical performance [12]. In terms of the strong, but with very lower frequency, electromagnetic coupling of the motors, there are relatively many research references, such as the application of transient finite element method to calculate the coupling relationship between the outer coil and the rotor speed in the induction motor [13], etc.

Then, there are also sporadic reports on the system level of electronic equipment: For example, preliminary research on the integrated structural, electromagnetic, and thermal design of a spaceborne antenna reflector [14] and research on the analysis and layout of the thermal field of military electronic equipment [15].

One more aspect being worthwhile to mention is the researching activities from the Research Institute on Mechatronics of Xidian University, China. Since the early 1980s, teachers and students of the institute have successively carried out some in-depth researches [21–46]. For example, starting from the improvement of antenna gain, the optimal design of the shape for the secondary reflector of the dual reflector antenna is carried out. Starting from the concept of the antenna phase center, the problem of the field coupling relationship between the deformation field and the electromagnetic field of large reflector antenna is studied. A new mathematical relationship between structural displacement field and electromagnetic field was deduced mathematically. The influence of the supporting structure of the secondary reflector in dual reflector antenna on the electrical performance is studied. For different antenna attitudes, the influence of reflector surface deformation on antenna pattern (saying sidelobe) is analyzed. However, the abovementioned researches are limited to reflector antennas and are relatively preliminary.

Another aspect is tools; a number of commercial professional analysis software have emerged. These include ANSOFT for electromagnetic analysis, ANSYS for structural analysis, MARC, FLORMERICS, ALGOR, and SPECTRUM. These software can support the analysis of specific physical fields with good performance and later be able to add other physical field-processing functions. There are also software designs that are initially based on multifield problems, such as PHYSICA and COSMOL. There are also domain-specific multifield analysis software, such as Conventer Ware, IntelliCAD, and SOLIDIS for MEMS multifield simulation; NMSeses for fuel cell simulation; and CFD-ACE for 3D chip stack design. These tools are able to handle some multifield coupling problems but are limited to a limited number of products and lack wide applicability. They cannot establish a bridge between the electromagnetic field and the structural displacement field, and it is difficult to express the electromagnetic performance as a function of the structural design parameters. Unfortunately, simulation software for multifield coupling problems applicable to electronic equipment, especially the electronic equipment with high frequency and large wavelength dimension, has not been reported yet.

At the same time, the Research Institute on Mechatronics is also developing electronic equipment analysis and design software, including reflector antenna electromechanical comprehensive optimization design software, deployable antenna analysis and design software, and high-density assembly system analysis and design software. Prototype software systems have also been developed for the analysis and design of planar slotted and active phased array antennas. All the software are researched and developed from the perspective of multifield coupling, integrating the mathematical and quantitative relations of the coupling of each physical field into the software, ensuring the accuracy of the analysis, and improving the efficiency of the design.

1.4.2 The Development Trends of Electronic Equipment

With the rapid development of electronic technology, information technology, and even materials and processes, electronic equipment have also been developed rapidly, and its development trends are mainly reflected in the following aspects [47–61]:

1.4.2.1 High Frequency and High Gain

The resolution ability of electronic equipment, especially radar and antenna, is directly related to the wavelength, so the frequency of radar is getting higher and higher. In the early days, it was mainly meter-wave radar that achieved the basic function of ranging, but in modern times it has been developed into millimeter-wave high-resolution radar and is developing toward higher frequency. High gain is mainly used to increase the detection range of antenna. With the development of deep space exploration, the antennas with high gain are in great demand. The basic method to improve the antenna gain is to increase both the frequency and the antenna aperture. Modern large reflector antenna aperture has reached tens of meters or even hundreds of meters;

for instance, the aperture of the world's largest radio telescope named FAST is 500 m.

1.4.2.2 Broad Bandwidth, Multiband, and High Power

Other current and future requirements for electronic equipment are (i) broad bandwidth; for example, the frequency band of QTT 110 m full steerable telescope, under construction in Wulumuqi of the Northwest part of China, is between 300 MHz and 115 GHz, corresponding to wavelength from 100 cm to 2.6 mm or even wider; (ii) multiband, e.g. the requirement for the same antenna to operate on multiple bands; and (iii) high power, as in the case of equipment on satellites, where it is desirable to transmit as much power as possible while remaining the same size. These three requirements bring new problems and lead to great difficulties in the design and manufacturing of electronic equipment, for example more complex field coupling relations, higher processing accuracy requirements, the need for new materials, new structures, and new theories of exploration and research.

1.4.2.3 High Density and Miniaturization

Electronic devices are developing toward smaller, denser, and lower power consumption; for example electronic devices are being assembled more and more densely and from two- to three-dimensional assembly. Correspondingly, the size of the equipment is becoming smaller and smaller. For example, the size of a typical electronic equipment RF system has been reduced from 0.03 m^3 in 2000 to 0.01 m^3 in 2010s and is expected to reach 0.001 m^3 before long. The dramatic increase in density will lead to serious electromechanical coupling problems.

1.4.2.4 Fast Response and High Pointing Accuracy

The requirements for the mobility and responsiveness of the equipment are increasingly high, and they should be able to be precisely positioned while being fast tracking. For example, a shipboard radar antenna mount with a stabilized platform is required to be extremely fast, smooth at low speeds, and accurate in its positioning.

1.4.2.5 Good Environmental Adaptability

As human race explores space more and more fast, the environment in which electronic equipment service has become much hostile. Electronic equipment need to be able to work properly in a variety of abnormal environments such as space environments, alien environments, and deep sea. Military electronic equipment are even required to resist microwave, laser, and other new concepts of weapons attack or work under certain damage to preserve performance, while requiring the ability to combat strong electromagnetic interference and having a high degree of reliability. All of these require the electronic equipment to have a good environmental adaptability.

1.4.2.6 Integration

Integration is mainly for multidisciplinary, multifunctional, and high performance. For example, the design and manufacturing of these products require the integration with mechanical, electrical, and thermal disciplines. Secondly, the functional requirements are becoming increasingly demanding and need easy implementation of multifunctionality through modularization. Furthermore, the multifunctional requirements do not reduce the performance requirements in any way but rather place higher demands on performance.

1.4.2.7 Intelligence

Intelligence is another obvious trend in the development of electronic equipment. To realize their intelligence, the research of smart materials, smart control, and smart structures should be carried out first. In addition, artificial intelligence (AI), as enabling technology, could play an active role in the process of the intelligence of electronic equipment.

1.5 Problem of the Traditional Design Method of Electronic Equipment

1.5.1 Traditional Design Method and Problems with Electronic Equipment

For a long time, the development of electronic equipment is basically the electromechanical separation design. That is, the electrical designer first puts forward the requirements and manufacturing accuracy based on the electrical performance for mechanical or structural design. Then, it is up to the mechanical or structural designers to find ways to meet these requirements. Taking the development process of a high-density aviation chassis shown in Figure 1.6 as an example, its structural design must meet three requirements: structural rigidity, ventilation and heat dissipation, and electromagnetic screen efficiency. When the initial CAD model is provided according to the basic design requirements, the structural, thermal, and electromagnetic analysis models are established, respectively. The relevant analysis of the three disciplines is performed, and their respective preliminary design schemes are provided. The three schemes are bound to be conflicted with each other. The chief designer needs to coordinate the three schemes based on experience and finally come up with a feasible

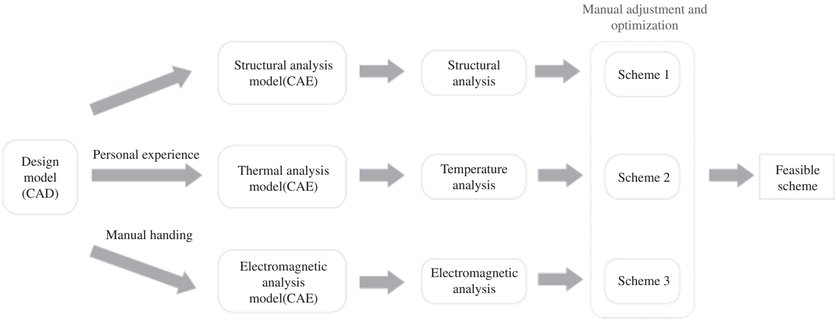

Figure 1.6 Diagram of the traditional electromechanical separation design of the chassis.

scheme. In the early days of electronic equipment development, this was a feasible design method. However, with the development of technology and the improvement of requirements, this method of electromechanical separation has become increasingly difficult to meet the design requirements of modern electronic equipment. It has become a bottleneck that restricts the improvement of equipment performance and affects the development of equipment in the next generation.

1.5.2 The Electromechanical Coupling Problem of Electronic Equipment and Its Solution

The mutual influences and restrictions of electromagnetic and mechanical structures in electronic equipment are inseparable. With the development of researching activities, it is discovered that the mechanical structure and electromagnetic interaction in electronic equipment are in the form of a field. Taking the reflector antenna shown in Figure 1.7 as an example, the antenna reflector is a boundary of the electromagnetic field. Under the load of gravity, wind, snow, etc., the antenna reflector surface will be deformed, and it will inevitably deviate from the theoretical design surface. This deformation will affect the antenna's gain (efficiency), sidelobe, and other electrical properties. Moreover, as the working frequency increases, this influence relationship becomes more prominent. Another example is the field coupling problems among the structural displacement field, electromagnetic field, and temperature field of missile-borne electronic equipment, which will seriously affect the guidance accuracy of the missile. Furthermore, the radar antenna in the airborne, shipborne, and other moving environments directly affects its pointing accuracy. It can be noticed that the field coupling relationship among the structural displacement field, electromagnetic field, and temperature field in electronic equipment is universal.

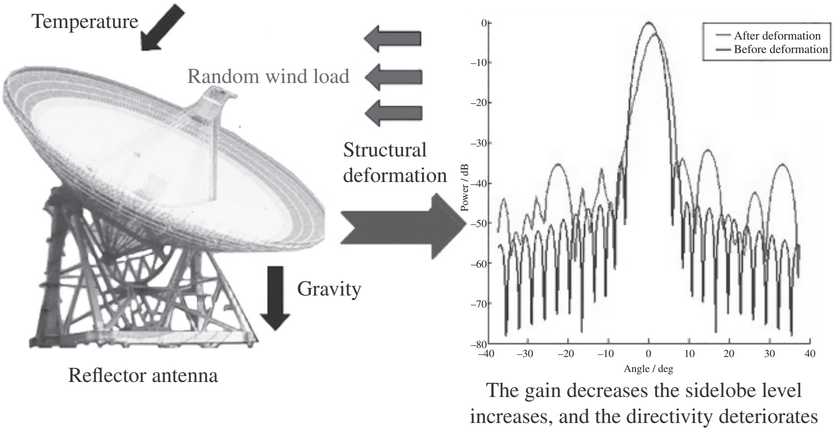

Figure 1.7 The influence of reflector antenna structure on electrical performance.

1.6 Main Science and Technology Respects of Design for Electronic Equipment

1.6.1 Holism of Electronic Equipment System Design

Electronic equipment is a system that combines multiple disciplines. Its composition mainly includes the mechanical structure part and the electromagnetic part. Its performance includes electrical performance and mechanical performance. These two parts are not separated and independent but are interacted with each other and closely related. Therefore, it should be considered as a whole system. In addition to the electrical part, the mechanical and structural part should be considered when studying the electrical performance, and the electrical performance should also be paid attention to consider the structural design. During the design, both the structural factors and electrical factors should be considered at the same time. Only by studying electronic equipment as a whole unit can we design high-performance electronic equipment that meet the requirements.

1.6.2 Electromechanical Coupling Theory of Electronic Equipment

The electromechanical coupling theory of electronic equipment includes two aspects: one is the field coupling theory, and the other is the influence mechanism.

The so-called field coupling theory refers to the mutual influence among the electromagnetic field, structural displacement field, and the temperature field existing in electronic equipment. For example, in a reflector antenna, under the external effects of its self-weight, wind, etc., the structure will be deformed, which will cause a change in the shape of the antenna reflector. It is ultimately reflected in the electrical performance of the antenna. Therefore, it is necessary to study the two-field coupling relationship between the electromagnetic field and structural displacement field. As another example, in addition to electromagnetic field and structural displacement field, high-density enclosures also need to consider thermal issues, that is a three-field coupling relationship among electromagnetic field, displacement field, and temperature field needs to be established. The purpose of establishing the field coupling relationship is to reveal the internal relationship between the fields, express the electrical performance as a function of the structural design variables, and lay a solid theoretical foundation for the electromechanical coupling design.

The so-called influence mechanism refers to the discovery of the influence law of mechanical structure factors on electrical performance. Because there is a type of problem, that is the electrical properties are difficult to be expressed in the form of fields, such as manufacturing nonparallelism, nonperpendicularity, and roughness, these quantities are mostly related to the processing route with great randomness and are generally collectively referred to as manufacturing accuracy. Material properties, stiffeners, bosses, grooves, etc. are issues that need to be considered in the structural design and are generally referred to as structural parameters collectively. The abovementioned manufacturing accuracy and structural parameters can be collectively referred to as structural factors. There are two ways to study the influence mechanism of structural factors on electrical properties, one is induction, and the other is deduction. The induction is based on the existing massive data, using the support vector regression method to get the law that satisfies the input and output samples. The deductive method is based on the problem of establishing a simulation model. Whether it is induction or deduction, the final influence mechanism is a design specification in the form of empirical formulas and diagrams.

1.6.3 Test and Evaluation Methods of Electronic Equipment

The testing of complex electronic equipment is one of the foundations of the application of electromechanical coupling theory and methods. The basic amount of test data must be obtained, otherwise it cannot be carried out. The method of evaluation of complex electronic equipment is to evaluate the correctness and effectiveness of the field coupling theory and influence mechanism. Specifically, it includes two aspects. One is the electromechanical coupling test method, referring to the modeling and calculation of the coupling degree of test factors, the test technology, and the construction of the test database. The other is the comprehensive evaluation method of electromechanical coupling model and influence mechanism, including evaluation system construction and calculation method.

The test method of electromechanical coupling is aimed at high-performance electronic equipment and to study economic and effective test strategies, methods, and techniques of electromechanical coupling based on the idea of comprehensive integration. Through the application of new test strategies, methods, and technologies to improve the efficiency and technical level of electronic equipment testing, the establishment of integrated test systems and the testing of typical cases can be guided. The specific content includes researches on new technologies and test strategies for the measurement of mechanical quantities and electrical parameters and integrated electromechanical test systems based on data integration.

The evaluation method of electromechanical coupling is to investigate the establishment and evaluation method of electromechanical coupling evaluation system based on electrical performance and manufacturability in electronic equipment. It needs to study the evaluation methods of typical electronic equipment from a theoretical perspective and provide theoretical and methodological guidance for the design and manufacturing of electronic equipment. The evaluation of electromechanical coupling based on electrical performance is to judge the improvement of the overall electrical performance index of equipment due to the application of electromechanical coupling theory and influence mechanism under the condition that the manufacturing cost remains unchanged. Based on the evaluation of manufacturability, the manufacturing cost is taken as the specific evaluation target, and the cost changes brought by the impact of the debugging cycle and manufacturing accuracy requirements are studied with the help of electromechanical coupling theory and influence mechanism with the same electrical performance. The specific research content includes the establishment method of the evaluation system and the comprehensive evaluation method of electromechanical coupling.

1.6.4 Environmental Adaptability (Thermal, Vibration, and EMC) and Reliability of Electronic Equipment

How to prevent failure of electronic equipment and make the electronic equipment work reliably under strong vibration and impact are the topics of electronic equipment design. The temperature of electronic equipment is controlled in a harsh environment so that the temperature of electronic components and devices does not exceed the allowable value. The abilities of electronic equipment are to resist external electromagnetic interference and avoid their own electromagnetic pollution to the environment. In addition, there are antimoisture, antimildew, antisalt spray corrosion, antiatom, antibiochemical weapons and so on. This involves many different disciplines such as mechanics, heat transfer, electromagnetic field theory, environmental science, chemistry, and materials science. Moreover, various protective measures must be integrated and unified in the design.

How to correctly and effectively connect, assemble, and lay out thousands of electronic components and devices to form a complete mechanics or system is also a topic of designing electronic equipment. In the assembly process, the mutual influence of various electronic components and devices must be considered internally, and the influence of various environmental factors must be considered externally. Ultimately, high reliability, easy maintenance, and easy operation must be ensured. At present, electronic assembly has developed to the level of surface mount and microassembly. In microassembly, the circuit, structure, and process are inseparable. In addition, ergonomic considerations cannot be ignored for the purpose of ensuring operators to work efficiently.

1.6.5 Special Electronic Equipment

Certain special-purpose electronic equipment must adopt special structures, such as super large or super flexible structures. Typical representatives are a new generation of large radio telescopes and large spaceborne deployable antennas.

(1) Spaceborne deployable antennas
Due to the limitation of rocket launch capacity, the antenna on the satellite generally adopts a stowed volume, which is folded when launching and deployed after into the normal space orbit. At the same time, in order to reduce weight, the cable net structure or membrane structure instead of the commonly used metal reflector is utilized as the antenna reflective surface. Both the cable net structure and membrane structure are all flexible structures. On the other hand, in order to make the antenna have enough gain, the diameter of the antenna becomes larger and larger, which increases the difficulty in design and manufacturing. Therefore, the large-scale satellite deployable antenna is not only a flexible structure but also a super large structure.

(2) Large radio telescopes
The plan for the new generation of large radio telescope (LT) [61, 62] was proposed by world astronomers at the Kyoto Conference in Japan in 1993 and had received unanimous support from 10 countries including China, the United States, Britain, and France. FAST 500 m super large radio telescope situated in Guizhou Province, Southwest part of China, named China Space Eye (CSE), as shown in Figure 1.8, became the world largest radio telescope.

In the innovation design with integration with optic, mechanical, and electronic technologies, the original rigidity support and servo system is replaced with six

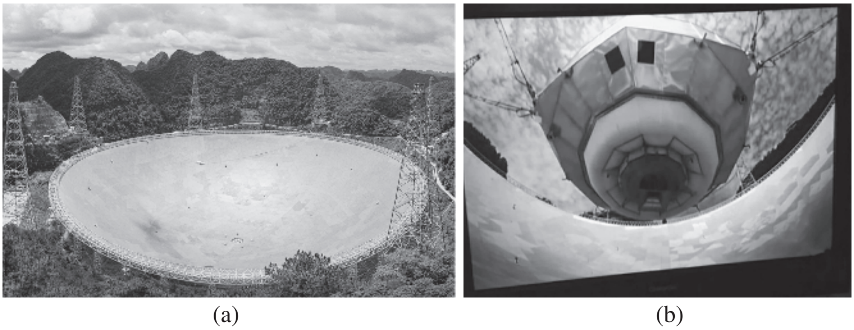
(a) (b)

Figure 1.8 FAST 500 m largest radio telescope. (a) Bird's view of the FAST telescope. (b) Feed cabin and cable system.

long suspending cables, so that about 10 000 tons self-weight of the feed cabin support structural system is decreased to 30 tons. Each suspension cable is driven by a servo system, and the six servo systems are coordinated and controlled by a central control computer. At the same time, the idea of active main reflector surface is adopted. That is, the 500-m spherical reflector surface is spliced by thousands of small regular triangular plates, and the back of each small regular triangular has three actuators to make it possible to change the orientation as required, so that the illuminated part can be turned into a parabolic surface in real time. The radio telescope is not only super large (500 m) in size but also super flexible structures with six long-span suspension cables. In order to get the millimeter positioning accuracy of the feed, a fine Stewart tuning platform is installed within the cabin. Moreover, the A/B adjusting axis is used between the cabin and Stewart platform to decrease the pressure on the Stewart platform.

1.6.6 Electromechanical Coupling Design of Electronic Equipment

As typical electromechanical devices, electronic equipment have structural characteristics and electromagnetic characteristics that influence and restrict each other. Only from the perspective of electromechanical coupling and interdisciplinary, the high-performance electronic equipment could be designed. Therefore, coupling design has become the preferred method for structural design of typical electronic equipment, including antenna parts, servo systems, and high-density chassis.

1.6.6.1 Electromechanical Coupling Design of Antennas

As early as the 1960s, researchers had noticed that the structural and electrical performances of antennas were intrinsically linked. Antenna structural designers also began to investigate the relationship between structural parameters and the electrical performance of antennas. During the times, a series of researching results were obtained, and the theory of best-fit paraboloid and conformal design was introduced and summarized in several monographs on antennas published in the 1980s. The contents of these monographs include antenna electromagnetic design, structural design, and servo system design of antenna mounts, covering almost all the fields involved in radar antennas, which became the classic work on reflector antenna design in China and has been used until now.

Since the beginning of the new century, through the long-term research, researchers have discovered that the structural parameters and electrical performance of the antenna interact through the form of fields on the basis of the best-fit parabolic, conformal design theory, and electromechanical integration design ideas. The structural displacement field and electromagnetic field are coupled. Therefore, the electromechanical coupling theory of the antenna was proposed, and the optimization design of electromechanical coupling was carried out. At the same time, the theory of electromechanical coupling is extended to other antenna forms, such as planar slotted array antennas and active phased array antennas. The design idea of electromechanical coupling is also applied to the analysis and design of the antenna servo system.

However, for optimum design by electromechanical coupling of reflector antennas, the consideration of electrical performance is still based on the Ruze formula, and the electromechanical coupling formula is not really applied yet. The surface accuracy of the reflector surface is calculated through structural deformation, and then the gain loss is calculated from the surface accuracy according to the Ruze formula. On the one hand, a single main surface accuracy cannot fully reflect the structural deformation of the antenna, and the position error of the subreflector and feed is not considered. On the other hand, gain is just one electrical performance pursued by an antenna. In most of the cases, performances such as sidelobe level and pointing accuracy are much more important. The current electromechanical coupling design lacks all these features.

1.6.6.2 Integrated Design of Radar Antenna Servo System

The electromechanical system is composed of two subsystems: mechanism (or structure) and control. The integrated design of these two systems is very necessary. The research on the integrated design of structure and control began in the 1980s. Scholars have conducted fruitful researches, mainly focusing on the following three aspects: The first is the integrated design of the space system structure and control. By changing the structural parameters (such as cross-sectional area), controller position, and gain factor, optimization methods such as nested optimization, genetic algorithm, and response gradient are used to achieve the dual goals of light weight and low control energy consumption simultaneously. The second is the integrated design of the structure and control of the DC motor. The structure and control factors are connected through the transfer function. Based on the configuration and motion demand constraints, by changing the number of coil turns, the motor's full-load rated power, and PID control parameters, the quality of the motor, control errors, and energy consumption are minimized. The first two categories are integrated optimization design problems for invariable structures and are not suitable for optimization problems of variable structures (or mechanisms). The third is the integrated design of structure and control in the mechanism system. The design is performed from the first control-oriented structural design, then the integrated design method of the optimal controller, to the subsequent two-stage nested optimization design method of structure and control iteration, and finally to the comprehensive optimization method of optimizing both the parameters of structure and control of the mechanism at the same time. According to the structural invariance of a single-rotating beam during motion, the literature combines frequency domain transformation of dynamic equations and control theory to obtain a control system and then optimizes the structural parameters to achieve the goal of minimizing quality and control energy consumption. However, this method is not suitable for complex mechanisms with variable structural characteristics and many design variables (resulting in a huge amount of calculation). For example, for a rigid four-bar linkage mechanism, it can achieve the goal of the smallest dynamic tracking error and the least energy consumption by optimizing parameters of the cross-sectional area of the rod, the weight, and the control. Unfortunately, the influence of the flexibility of the rods on the movement of the mechanism is not considered, and the natural frequency and stability constraints of the mechanism are not considered either.

The performance of the radar antenna's pointing accuracy and fast response depends on the design level of its servo system. The design of the servo system includes two parts, i.e. structural and control design. Structural design will affect the realization of the control performance. For example, the realization of servo control bandwidth depends on the natural frequency of the structure. Conversely, the control will affect the structural design. For instance, the size of the driving force in the servo system will affect the design of the antenna base structure. Therefore, in order to achieve the objectives of "seeing accurate" and "seeing clear," the structure and control have to be integrated in the design procedure.

However, the traditional design of radar antenna servo systems is separated between the structural and control design; that is, the mechanical structure and control system are designed independently and then tuned to meet the required specifications. In fact, the structure and control of the radar antenna servo system are coupled with each other; especially in high-performance tracking, these two parts are closely coupled. If the characteristics of the servo structure are not fully considered in the control design, the servo tracking performance will be reduced or even unable to achieve the required performances. On the other hand, if the control part is not fully considered in the structural design, the optimal design cannot be obtained or even fail to meet the performance requirements. This separation design approach leads to long product development cycles, high costs, poor performance, and bulky structures. Traditional design methods have constrained the development of high-performance radars. For this reason, it is necessary to integrate the structure and control together for comprehensive optimization design to achieve the best overall performance.

1.6.6.3 Coupling Design of High-Density Chassis

The three main aspects of high-density chassis design, namely, the structural rigidity, ventilation and hear transfer heat dissipation, and EMC, are contradictory to each other. It is embodied as follows: One is the contradiction between quality and rigidity. The structural strength is required to be as high as possible; namely, it is required to be able to work normally under the impact and vibration of various working conditions, and the working environment requires small size and light weight, especially for airborne and ammunition-borne equipment. The other is the contradiction between EMC efficiency and ventilation and heat dissipation. Larger holes are good for heat dissipation but not good for electromagnetic shielding. Excessive temperature will affect the working efficiency of electronic devices. Modern electronic equipment chassis is asked to meet the three requirements of structural rigidity, EMC, and ventilation and heat dissipation at the same time.

The conventional chassis design is to separately consider the above three requirements of structural rigidity, EMC, ventilation and heat dissipation, respectively, and provide separated design schemes. Since the starting points and purposes are different, there will be conflicts between the design schemes. Therefore, the chief designer is required to make a balance and trade-offs based on experience and arrives at a feasible design scheme. This is an effective design method when the early requirements are not strict in all aspects. However, with the increasing requirements of various aspects, this design method of structural–electromagnetic–thermal separation becomes much difficult to meet the requirements of various aspects at the same time. As a result, it is necessary to carry out research from the perspective of multifield coupling, establish a multifield coupling model, and then propose a multidisciplinary optimization model based on the multifield coupling model for structural–electromagnetic–thermal coupling design.

1.7 Mechatronics Marching Toward Coupling Between Mechanical and Electronic Technologies

High-precision and high-performance complex equipment have been extensively applied in the important areas such as national defense development, national economy, and high and new technologies, of which the design and manufacturing capabilities are significant embodiments of national science and technology level and strength. Complex equipment mainly consist of two categories: one is the precision mechanical equipment focused on mechanical performance, and the electrical performance is subject to mechanical performance, including manufacturing equipment such as large numerical control machines, machining center, etc., and the industrial major equipment such as armaments, chemical engineering, shipping, agriculture, energy, digging, and tunneling. The electronic technologies are mainly employed to reform, arm, or improve the mechanical performance of the traditional equipment. The other one is the electronic equipment focused on electronic performance, and the mechanical performance is subject to electronic performance, such as radar, communication, computer, navigation, antenna, and radio telescopes. Electronic equipment, of which the mechanical structures are mainly to guarantee the electromagnetic performance, are widely used and play irreplaceable roles in the key areas such as land, sea, air, and space.

Generally speaking, both categories of equipment belong to complex equipment with integration of mechanical and electronic technologies and are typical cases of key applications of mechatronic technologies. The concept of mechatronics, originated in the 1970s, is nothing but a combination of two words, i.e. mechanical and electronics, and reflects the connotation evolution and development trend of continuous fusion of mechanical and electromagnetic (electrical) technologies.

With the development of mechatronic technologies, new concepts, such as mechanical–electrical–liquid integration, fluid–sound–gas integration, and biologic–electromagnetic integration, arise in succession. These concepts, although with different names, essentially belong to the scope of mechatronics and study the interrelation among different physical systems or fields, thus improving the overall performance of systems or devices.

From the viewpoint of mechatronic design, high-performance complex equipment have experienced three different phases, i.e. Independent between Mechanical and Electronic Technologies (IMET), Syntheses between Mechanical and Electronic Technologies (SMET), and Coupling between Mechanical and Electronic Technologies (CMET). The development of high-precision and high-performance electronic equipment shows highlighted features of these three phases.

IMET means that the mechanical design and electromagnetic design of electronic equipment are separated and independent of each other, whereas the information can be conveyed and shared on/off-line. The mechanical and electromagnetic designs are independently implemented in each domain. On the boundary or within each domain, the sharing and effective transmission of information can be realized. Typical examples include the structure–electromagnetics of reflector antennas and the temperature–structure–electromagnetics of active phased array antennas.

It should be pointed out that from the design level, such kind of information sharing is still IMET, and thus the inherent problems of traditional independent design also exist. There are two most remarkable problems: one is that the requirements on the mechanical design and manufacturing precision proposed by electromagnetic designers are usually too high to be implemented, and the mechanical designers, deficient in deep comprehension of electromagnetic knowledge, can just try their best to satisfy the requirements. It is sort of blindly. The other one is that, in practical engineering, there exist strange phenomena that the manufactured products, with full effort, sometimes unsatisfied the electronic performance, whereas the electrical performance of some products with manufacturing precision below the required level may meet the requirements. Therefore, in practical engineering, the method of copies has to be utilized and the choice has to be made after electronic test and measure. These two longtime-existed problems have led to the low performance, long period, high cost, and heavy structure in electronic equipment development, thus being an open bottleneck that seriously restricts the improvement of electronic equipment performance and affects the development of next-generation equipment.

With the constant rise in electronic equipment working frequency, the interaction between mechanics and electromagnetics tends to be more remarkable, and the IMET design is confronted by more problems and more serious contradictions. Thus, the design concept of SMET arises. SMET is a relatively high level of mechatronics and is a large stride advance of IMET due to two factors: one is the establishment of the integrated design mathematical model that can consider simultaneously mechanical, electromagnetic, and thermal performance, etc. and effectively eliminate certain deficiencies and shortcomings; the other one is the establishment of integrated finite element analysis models; for example, in the analysis of high-density chassis and cabinet, the numerical analysis model of electromagnetics, structure, and temperature within the same geometrical space can be shared.

From the beginning of this century, electronic equipment take on three new developing trends such as high frequency and high gain, high density and miniaturization, and fast response and high pointing accuracy and strong coupling features of the relation between mechanical and electromagnetic technologies. In this way, mechatronics strides into the new phase of CMET.

CMET is the further step toward ideal mechatronics than SMET, which includes two main characteristics: one is that, mechanical, electromagnetic, and thermal automatic numerical analysis and simulation can be realized, and the completeness, accuracy, and reliability can be guaranteed during the information transmission among different disciplines. The other one is that the coupling theoretical model of multiphysics system is deduced mathematically based on physical quantity coupling, and the influence mechanism of nonlinear mechanical factors on electronic performance is revealed. In this way, the design becomes the CMET design based on the coupling theoretical model and the influence mechanism. Therefore, CMET is inherently different from SMET and is essentially advanced over SMET.

From IMET and SMET to CMET, mechatronic technologies show distinct generation evolution, which provide theoretical and key technology support for high-level equipment design and manufacturing. The future development of complex equipment manufacturing tends to be a deep fusion of multiphysical field, multimedium, multidimension, and multielement, and mechanics, electrical science, electronics, electromagnetics, optics, and thermology will be focused together. Huge system, extremalization, and precision treatment will be the new tendency, and greater challenges will be confronted by the design and manufacturing technologies with CMET as a breakthrough.

With the fast development of new-generation electronic technologies, information technologies, and materials and processing techniques, the development of future high-performance electronic equipment will take on two extreme features: one is extreme frequency, such as the extremely low-frequency band for submarine communication, or millimeter wave, submillimeter wave, and even terahertz wave for spaceborne microwave radiation antenna applications. The other one is extreme environments, such as the North and South Poles of the Earth, deep space and near space (20–100 km from the ground), deep sea, etc. These factors present unprecedented challenges for CMET theories and technologies, and it is urgent to carry out the following studies.

Firstly, the establishment of electromechanical coupling theoretical model of electromagnetic, structural displacement, and temperature fields. Due to the relation of interaction and inter-restriction among them, it is necessary to reveal the influence and coupling mechanism; ascertain the coupling mechanism of multifields, multidomain, multidimension and multimedium, and the influence mechanism of multiworking condition and multifactors; and represent them as quantitative mathematical relations.

Secondly, the nonlinear mechanical factors (structural parameters and manufacturing precision) and material properties of electronic equipment have apparent effect on the electromagnetic performance. It is urgent to explore the influence rules of these nonlinear factors on electromagnetic performance and further reveal the influence mechanism (IM) on electromagnetic performance.

Thirdly, CMET design methods. It is necessary to synthetically analyze the characteristics of coupling theoretical model and IM and thus propose theories and methods of electronic equipment CMET design. This involves the independent analysis model of mechanics, electromagnetics and thermology, and the treatment of difficult points such as the slide of numerical analysis meshes among them.

Fourthly, the mathematical representation and measurement of coupling degree. In theory, any coupling could be measurable. To deeply explore the coupling behavior among multiphysical systems, it is necessary to explore a general mathematical representation method for measurement coupling and further deduce the mathematical expression for quantitative calculation of coupling degree.

Finally, deep fusion in applications. CMET technologies not only exist in almost all electromechanical equipment but also play an important role in the transformation and upgrading of high-level equipment manufacturing. CMET technologies are the common key technologies for iteration development and applicable to many major industries in the development of equipment manufacturing, thus penetrating the whole historical process of industrialization and informatization. With the arrival of new scientific and technological revolution and industrial reform, especially with the appearance of intelligent manufacturing featured as digitization, networking, and intellectualization, the deep fusion of industry and information technologies is imperative. Such fusion shows itself as the application of CMET theories in the level of theories and technologies, and it can be thus seen that CMET is of profound significance and promising future.

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