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Research progress analysis of reliability design method based on axiomatic design theory

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Abstract

With the increasing complexity of the product, the conventional reliability design methods can hardly support the realization of high reliability requirements, and how to carry out high reliability design has become the bottleneck problem which is urgent to be solved in the product development. As a conceptual decision design method of product design, Axiomatic Design is combined with reliability design, which provides a new way to solve the problem of high reliability design of products. This paper analyzes the common reliability design methods and the existed problems. The concepts of Axiomatic Design theory such as the independence axiom and information axiom are introduced. The complexity theory and relationship between complexity and reliability design are reviewed. The research progresses related to the reliability Axiomatic Design method are intensively analyzed. A kind of research thought of using Axiomatic Design theory to solve reliability design problems is proposed. Finally the research trends are prospected.

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Keywords: Axiomatic Design; Reliability Design; Complexity

1. Introduction

The information age is bringing unprecedented challenges to the development of products. On one hand, the product features are becoming more and more complex, and the product updating speed is faster and faster. On the other hand, the product quality and reliability need to meet the increasing demanding level. With the increasing complexity of products, and the functions and structures becoming more complex, the coupling between modules and the uncertainty to achieve the functionality within the system will be substantially increased. In this case, traditional reliability design and analysis methods are difficult to carry out, thus how to realize the reliability design requirements for the highly reliable product becomes an important bottleneck in the product development.

Axiomatic Design was presented by Massachusetts Institute of Technology (MIT) in the 1970s. It is a design method of decision-making for product design which provides a theoretical foundation based on logic and rational thought processes and tools, so that the designer may complete a product no longer depending on the personal experience and technical information, and he can determine the best design from many designs, so as to provide a good way to reduce the cost, and improve the quality and reliability [1]. Over the years, many scholars around the world carried out a lot of research works around Axiomatic Design theory, and tried to combine Axiomatic Design theory with reliability methods to solve the reliability design problems.

This paper reviews the associated concepts and research statuses of reliability design, Axiomatic Design and complexity theory, and discusses the relationships between them. On this basis, the domestic and foreign researches of reliability design method based on Axiomatic Design theory are analyzed. Finally, a kind of research thought about the reliability design on Axiomatic Design of complex system is proposed. The method can consider the ‘top-down’ design

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features of complex system, and combine Axiomatic Design theory with the existing reliability design methods together. This provides an idea to solve the reliability design problem of highly reliable system in engineering.

2. Reliability Design Method

Reliability is a subject that struggles with the failure, and it focuses on the study to recognize failure reason and failure mechanism, thus to prevent or control the failure by using these failure rules. [2] The goal of reliability design is to meet the user's reliability needs. In the design process, various factors affecting the product reliability should be systematically considered, so as to carry out the analysis, evaluation, re-design on the product's candidate programs. For complex system, reliability is commonly characterized by the ability to maintain system function in the life cycle (or guarantee period, use life and economic life period, etc.). Reliability is unable to design itself and reliability design must be relied on other performance design or functional design, so as to design the reliability into the product.

According to the reliability requirements of the product, the common reliability methods consist of simplify design, redundancy design, fault-tolerant design, environmental protection design, thermal design and component selection and control, derating design, etc. [3]. These methods provide reliability design ideas and methods to meet the reliability requirements of the product from different angles, and play an important role in promoting the development of product design level.

However, with the increase of reliability and complexity of the high reliable products, the role of these reliability design methods becomes more and more limited. The overseas study found that the traditional reliability technologies emphasized on reliability work after the completion of the product building, which could only solve the problem of reliability of 20%. As the complexity increases, the design of the system architecture is more and more important. If we begin the reliability design in the conceptual design stage of the system architecture and product design, we can solve the problem of reliability of 80% [4]. Therefore, we must develop new reliability design methods on the new features of the system or the product.

3. Axiomatic Design Theory and Complexity Theory

3.1. Analysis on Axiomatic Design Theory

In 1970s, Nam P. Suh of Massachusetts Institute of Technology (MIT) proposed Axiomatic Design theory. Axiomatic Design is a design method based on domain and design axiom. It is not a special design, but it is the basic theory and method to study how to implement the correct design by using the design axiom.

There are two basic design axioms. The first axiom is the independence axiom, which means maintaining the independence of the functional requirements (FRs). Independence axiom refers to maintain independence of FRs, at the same time indicates the relationship of FRs and DPs. That is to say, the design project must meet each independent function demand, without affecting other functional requirements, which is implicated that DPs cannot be connected with other FRs. The second axiom is the information axiom, which means the information content of the design should be minimum. Information axiom refers to among those designs satisfying the independence axiom conditions, the design with the minimum amount of information is the best one. Because the information content is determined by the probability, this axiom also shows that the design with the highest probability of success is the best design. For the same design task, different designers may draw different design schemes, and it is also likely that these programs all meet the independence axiom, the design with the least information content is the best design during the evaluation. [1]

Axiomatic Design divides the design process into four domains: customer domain, functional domain, physical domain and process domain. The domain structure and the relationship between the domains are shown in Figure 1. The theory carries out analysis and induction through a large number of examples of successful design, abstracts the nature of the design process, expands the design in the 'top-down' design process from the high level of design abstraction concept to the low level of design details gradually. In each domain, the design problem is solved according to the shape of 'Z'. The design axioms and their reasoning theories make the originally design criterion developed from the experience even the intuition have a scientific basis, thus to provide a scientific basis and guiding principle for the design of the products. Axiomatic Design has been widely concerned in many academic and industrial areas. [1]

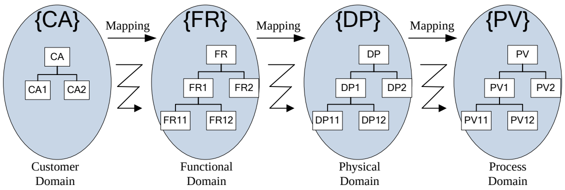


Fig. 1. Design mappings and domains

3.2. Analysis on Complexity Theory

The main effect of complexity on the development of the product is that the uncertainty to complete the desired function, and the uncertainty mainly means that the matching relationship is uncertain between the functional requirements and design results. From the point of view of whether or not the product range changing as the function of the time (static or dynamic), the complexity can be divided into time-independent complexity and time-dependent complexity.

Time-independent complexity can be divided into imaginary complexity and real complexity [5,6]. The so-called imaginary complexity refers to the increase of the product function and the complexity of the function, which leads to the difficulty of finding the reasonable design matrix. The typical situation is when lots of general modules are used to achieve a variety of functions, the corresponding relationship between the modules and the functions becoming very complex, the logic and behavior being completely in flexible configuration, and then what kind of configuration is optimal is a difficult problem to determine. The real complexity mainly refers to the uncertainty of product output due to the interference of random factors. The typical factors include the tolerance variation of design parameters and various random failures. The appearance of these random factors is irrelevant to time in essence, and it may appear in the system at any time when performing the task, which leads to the function of the system output is not within the scope of the design. For simple products, as long as the products have enough robustness and failure absorbing ability, the occurrence of failures can be avoided in great extent. But for complex systems, due to increase of the degree of coupling between modules, a failure of single point is likely to cause the paralysis of a large area of the system function, and the emergence effect may result in unpredictable behavior. Therefore, for complex systems, except to carry out necessary robust design to enhance 'immune' ability of the system, the more important thing is to handle various coupling factors in system level design to make all kinds of random factors in the controllable range [5].

Time-dependent complexity can be divided into combinatorial complexity and periodic complexity [5,6], both complexities are closely related to the working time of products, even if the initial design is in line with the requirements, but because the appearances of various complex factors change with the time, maybe loss of function or ultra poor and other unforeseen circumstances in the product will happen after running for a period of time. The fundamental cause of the combinatorial complexity is due to influence of complexity factors changing with the time, which will lead to the initial combination or allocation type not feasible. These complex factors are divided into two categories. One is regular, and namely, the module may be performance degenerated or 'dead' with the time moving, eventually leading to the loss of system function; another is irregular, and the system function failure cannot be expected. When these two failures occur, the system needs to be configured reconstructed to ensure the continuous system functions output. Periodic complexity can be considered as a special case of the combinatorial complexity, mainly for the special case of product function in a certain cycle output. If the product is to ensure that no failure happens in the whole life cycle, it is a combinatorial complexity problem. But when the product is mainly concerned about the stage output task, it is mainly the periodic complexity problem. When the system faces with the combinatorial complexity, the biggest difficulty is the limited available resources, because the combination types of the system cannot be unlimited to deal with various unexpected situations. To solve the combinatorial complexity, it is generally thought to be transformed to periodic complexity, and the allocation of resources is carried out with a period of the output of each function for a loop, at the end of a cycle, the system reset or repair can be done to maintain the operation of the next cycle. [5]

4. Research Status of Reliability Design Method Based on Axiomatic Design Theory

Massachusetts Institute of Technology [4] proposed the flow of axiomatic quality and reliability as shown in Figure 2. Axiomatic quality and reliability design was divided into three phases: CAs-FRs mapping phase, conceptual design for capability (CDFC) phase, optimization phase. The total mapping process can be achieved from customer domain to functional domain, physical domain and process domain, and finally functional reliability was used to evaluate the reliability of the design.

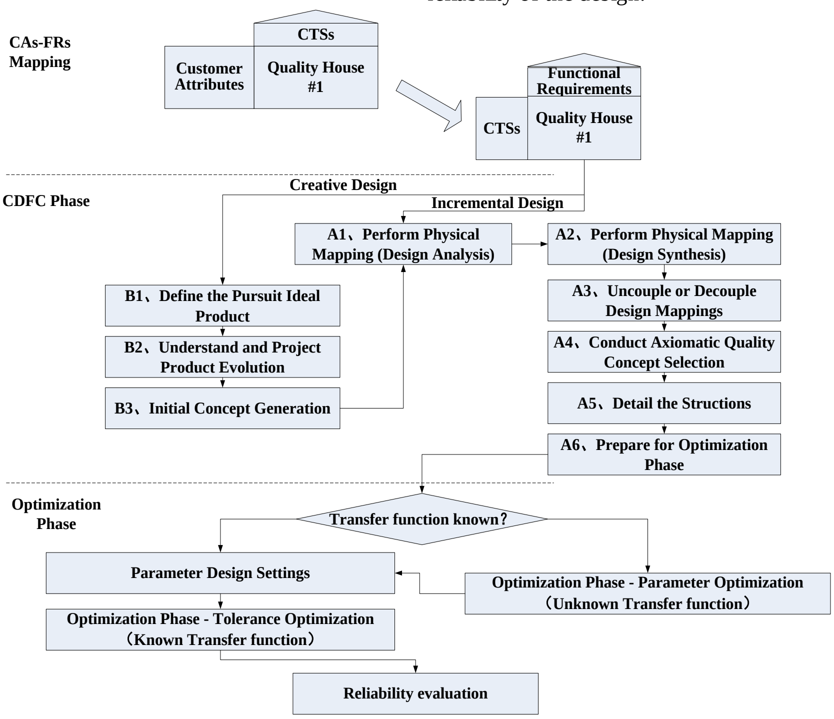


Fig. 2. Axiomatic quality and reliability process

Table 1. Failure mechanisms vs. load conditions links

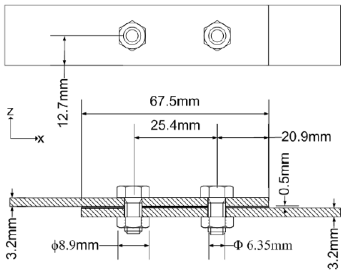
Failure mechanisms	Containment	Δ T (temperature cycle magnitude)	RH(relative humidity)	T(steady-state temperature)	Vibration/Shock	Maintenance and handling	Voltage
Brittle fracture		X		X	X	X	
Ductile fracture				X	X		
Yield		X		X	X		
Bucking		X		X	X	X	
Large elastic deformation		X		X	X		
Interfacial deadhesion	X	X	X		X		
Fatigue crack initiation	X	X	X		X		
Wear				X	X		
Creep		X			X		
Corrosion	X		X	X	X	X	
Dendritic growth	X		X	X		X	X
Fatigue crack propagation		X				X	
Diffusion				X			X

B. P. Nipal of Purdue University [7] pointed out that the development of Axiomatic Design and failure modes and effects analysis (FMEA) method made the reliability analysis work of complex systems possible. He raised failure mode and effect tree analysis (FMETA) as reliability optimization design method, and the method was universal for failure-based 'system-modular' design and could be applied to all types of product architecture. Mamadou Sy [8] thought that using Axiomatic Design method in the design phase could reduce the failure rate, and Axiomatic Design should permeate the whole process of 'module-assembly-system' design. M. Pappalardo [9] of Italy noted that Axiomatic Design method could build a relationship between stress and failure, assessed the potential failure mechanism, the possible risk of failure modes and failure location of the module, and then carried out stress design for failure location, thus to improve the product reliability. With the mechanical experience, he gave a transfer matrix of failure mode and generalized stress of the product modules, which was shown in Table 1. The 'failure-generalized stress' transfer equation was as follows:

$$[Failure]=[A][STs] \tag{1}$$

Mamadou Sy pointed out the numerical value of the 'failure-generalized stress' transfer matrix can be quantified by failure coefficient. [8] Ouellet Marc of Canada carried out 'failure-stress' design for the bolt washer [10]. The mechanical analysis was started, and the main failure mode and the possible failure factors of the module were determined. The 'failure-stress' design transfer matrix of the original design was established. The transfer matrix was analyzed, and the factors leading to coupling of the transfer matrix were found out, and the macro and micro damage mechanics modeling and analysis methods were used here. A suitable method was selected to decouple the transfer matrix. In this case, the damage mechanics experiment and finite element calculation showed that, adding washer between the bolt and the plate can improve the stress distribution. Another change was the flat edge changing to the conical head edge, thus obtaining further decoupling. The transfer matrix of the complete decoupling design is shown in Figure 3. In order to validate the decoupling design, Marc used finite element calculation method to demonstrate the effectiveness of the improved model. The results showed that the redesign could effectively reduce the peak stress and the stress concentration, thereby reducing the probability of failure. The data were well verified by the results of Axiomatic Design. Fourthly, according to Axiomatic Design theory, decoupling design met the independence axiom, in the subsequent work, the information axiom and the tolerance design method could be used for robust design to ensure that the failure-stress was in accord with the required state.

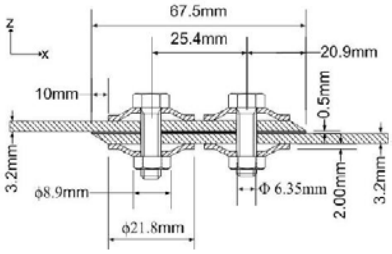
From the research of foreign countries,, it is obvious that aiming at complex systems, we can use Axiomatic Design method for stress and failure analysis, and establish the 'failure-generalized stress' transfer relationship so as to optimize the design, the method has been accepted by both academia and industry areas, and it goes to the application. [11-19] At the same time, the coupling analysis and decoupling process problem, the problem of integrating Axiomatic Design with other design method, and the information amount calculation method have become the focus of current researches, the ultimate goal is to solve the engineer practical problems when applying Axiomatic Design theory in complex systems and complex products design and manufacturing process.



(a)

	DP_1	$DP_{1.1}$	$DP_{1.2}$	DP_2	$DP_{2.1}$	$DP_{2.2}$	DP_3	$DP_{3.1}$	$DP_{3.2}$	DP_4	$DP_{4.1}$	$DP_{4.2}$
FR_1	X	0	0	0	0	0	X	0	0	X	0	0
$FR_{1.1}$	0	X	0	0	0	0	0	X	X	0	0	0
$FR_{1.2}$	0	0	X	0	0	0	0	0	0	0	X	X
FR_2	X	0	0	X	0	0	0	0	0	0	0	0
$FR_{2.1}$	0	X	0	0	X	0	0	0	0	0	0	0
$FR_{2.2}$	0	X	0	0	X	X	0	0	0	0	0	0
FR_3	0	0	0	X	0	0	X	0	0	0	0	0
$FR_{3.1}$	0	0	0	0	0	0	0	X	0	0	0	0
$FR_{3.2}$	0	0	0	0	X	0	0	X	X	0	0	0
FR_4	X	0	0	0	0	0	X	0	0	X	0	0
$FR_{4.1}$	0	X	X	0	0	0	0	0	0	0	X	X
$FR_{4.2}$	0	X	X	0	0	0	0	X	X	0	X	X

(b)



(c)

	DP_1	$DP_{1.1}$	$DP_{1.2}$	DP_2	$DP_{2.1}$	$DP_{2.2}$	DP_3	$DP_{3.1}$	$DP_{3.2}$	$DP_{3.3}$
FR_1	X	0	0	0	0	0	0	0	0	0
$FR_{1.1}$	0	X	0	0	0	0	0	0	0	0
$FR_{1.2}$	0	X	X	0	0	0	0	0	0	0
FR_2	X	0	0	X	0	0	0	0	0	0
$FR_{2.1}$	0	0	0	0	X	0	0	0	0	0
$FR_{2.2}$	0	X	0	0	X	X	0	0	0	0
FR_3	0	0	0	X	0	0	X	0	0	0
$FR_{3.1}$	0	0	0	0	0	0	0	X	0	0
$FR_{3.2}$	0	0	0	0	0	0	0	X	X	0
$FR_{3.3}$	0	0	0	0	X	X	0	X	0	X

(d)

Fig. 3. (a) Original design; (b) Transfer matrix of original design; (c) Improved design; (d) Decoupled transfer matrix of the improved design

Zhaofeng Huang [20] at the University of Southern California studied the design reliability of the conceptual design phase. He expanded the traditional stress and strength interference theory and developed a concept stress and concept strength interference theory (CSCSIT). By introducing functional design to reliability parameters, the concept of design space was parameterized. Based on CSCSIT, he presented a practical analytic framework to support the functional design reliability, and a functional design example was presented to illustrate the effectiveness of CSCSIT and the proposed framework.

Zhu Longying [21] of Nanjing University of Aeronautics and Astronautics researched on the key technologies of concurrent design based on Axiomatic Design, including design model, demand analysis, quality function deployment, product information model, evaluation and decision making and the development of the software system. He carried out studies on axiomatic six sigma design method, Axiomatic Design, Quality Function Deployment (QFD) and other tools were integrated and fused into six sigma design philosophy, so as to solve the coupling problem in the design, so that all functions and parameters of the products can meet the requirements of Six Sigma quality level, at the same time the system defects can be eliminated or reduced, so that the design process is regular, systematic and modeling. He also studied the relationship of Axiomatic Design theory and robust optimization design, which can provide a new research approach for the robust optimization design.

Zhuo Daofeng [22] of Three Gorges University put forward a reliability design method, which was based on Axiomatic Design and Failure Mode and Effects Analysis (FMEA), to solve the problem that the traditional FMEA method was difficult to analyze the multiple failures and multiple functions products. By using the Independent Axiom to complete the design parameter decomposition of the system or product and eliminate the influence of the design parameters, he made a complete and accurate FMEA analysis of the subsystem or component. The risk priority number (RPN) is analyzed in the failure risk assessment, combined with the information evaluation model based on the information axiom, a kind of reliability evaluation method based on the combined information axiom and the traditional RPN set. Through the example, the method can make more scientific ranking of risk factors, thus to guide the designers to do reliability optimization design more accurately.

Wang Weixing [23] of Armored Force Engineering Institute compared Axiomatic Design theory and reliability design theory using set theory, which showed the consistency of Axiomatic Design and reliability design, and this laid the foundation for the integration of Axiomatic Design and reliability design.

In order to solve the problem that the requirements of reliability design is hardly implied in the product design, Yang Dezhen [24] of Beihang University proposed a kind of reliability requirements implementation method based on Axiomatic Design. Firstly, he applied the principle of Axiomatic Design for preliminary design of products, so as to determine the functional requirements, and expanded the function keep demand according to various functions needs, and obtained the reliability design project of the derived parameters. Secondly, he expanded or optimized the design parameters according to the function keep demand,

5. Reliability Design Thought Based on Axiomatic Design Theory

The focus of the reliability design is to meet the customer's reliability needs as the goal. From the design methodology, the product design process is a step by step mapping process from the task demand to the functional design, to the physical module design, and finally to build the physical realization of the module. The current reliability design method is based on the typical 'build-correction-verification' iterative mode. The work focus is after the fundamental physics module is built, physical tests and numerical analysis are conducted step by step to verify if it meets the requirements. This method is feasible for simple products, but for complex systems, it is not enough, because the features and modules are separated, and the failure mechanisms are complicated. So for the reliability design of complex systems, we should transition our design ideas, follow the positive design process of 'task demand-function design-physical design-process design', pay special attention to the architecture design of the system in the top-level design, carry out specific design considering a variety of complexity factors affecting the function and behavior, thus to reduce design iterations and repeated error correction in late design period, and ensure the realization of product features. The reliability design method based on Axiomatic Design is composed of reliability design on system architecture and reliability design on module.

6. Prospects

With the increase of product complexity, reliability design problems are becoming more and more complex. The combination of Axiomatic Design theory and the existing reliability design method provides a new direction for reliability design of complex systems. Around this field, two research aspects can be carried out to solve the positive reliability design problem of the high reliable products.

(1) The existing reliability method can solve the reliability problem of the module level preliminary. With the enhancement of the system complexity, the coupling relationship between various modules within the system will be strengthened, thus the reliability design method on system architecture based on Axiomatic Design should be developed.

(2) Due to the limitation of stress-damage model, the existing reliability technology based on physics-of-failure can only solve the reliability problem of the product under a single stress. But the working environments of products are multiple stress environments, and different failure mechanism in certain conditions mean that the module failure is hard to be decoupled and analyzed. How to use reliability design method based on Axiomatic Design to solve the reliability design of modules, needs a lot of study to carry out.

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