Reliability Engineering Design Method based on Generalized Margin Design theory

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Abstract. Traditional reliability indexes in engineering are statistic parameters of failure time or failure rates, these reliability parameters are not related to products’ design parameters directly. In fact, reliability design in engineering process is margin design, for instance, the safety factors approach, the derating design approach, and even the selection of the high quality components carried out by enhancing the margin of resisting the sense stress of failures. This paper proposes a reliability engineering design method based on the general margin theory, and the quantification relationships between the statistic reliability parameters and general margin parameters are established. The general margin proposed in this paper contains the stress margin and function margin. The margin design rules and requirements are defined according to the products(or concepts design)’s loads in the predicted lifecycle; and then the stress margin parameters that satisfying the reliability could be determined based on the stress-strength interference model, and these margin parameters could support the products concepts selection; if the stress margin parameters could not satisfy the requirements, then the function margin parameters are analyzed to guide the key function redundancy design until the reliability of the products are meet. This method could improve the suitability of reliability theory in engineering field. This paper demonstrates the availability of this design method with a case study.

1. Introduction
At present, the design method of reliability is mainly based on failure physics. In the physics of failure method, first is the failure mechanism analysis, and then is the corresponding design of the variables in the mechanism model. System reliability design method such as FMEA and FTA, will propose reliability design criterions based on the system failure analysis[1-4]. However, the traditional reliability indicators such as MTBF and failure rate $\lambda$ are the values through data statistics, reflecting the overall reliability level of the product[5]. In reliability engineering activities, these indexes are often used for reliabilty assessment, rather than direct guidance for designing. This situation occurred because of the lack of a way to directly link reliability indicators to reliability design activities.

This paper proposes a reliability engineering design method based on generalized margin design theory. The paper defines the generalized margin framework, which includes the stress margin and functional margin in the product design process; the mathematical relationships between the generalized margin design theory and the traditional reliability index such as the failure rate $\lambda$ are established. And the scientific and rationality of the reliability design method based on generalized margin theory is discussed and proved by examples demonstrations.
This paper is organized as follows: Section 1 is the introduction, Section 2 introduces the framework of generalized margin theory, and expounds the theoretical basis of stress margin design and functional margin design; Section 3 establishes the relationship among the three most commonly used methods in reliability engineering such as failure physics, statistical indicators, and enhancement tests, and the process of reliability design method based on generalized margin design theory is extracted. Section 4 is based on a simple case explanation.

2. Generalized margin design theory and its framework

2.1. The framework of generalized margin
In order to guide the reliability design, the reliability requirements or indicators are transformed into the goal of the margin design. In this paper, the generalized margin is divided into two parts of stress margin and function margin. The generalized margin of the product is defined as follows:

\[ M_g = M_s + M_f \]  (1)

Where \( M_g \) represents the generalized margin of the product; \( M_s \) represents the stress margin in the product design process; \( M_f \) represents the functional margin in the product design process.

The theoretical framework of generalized margin design is shown in Figure 1.

![Figure 1. The framework of generalized margin design.](image)

2.2. Stress margin of products

2.2.1. The definition of stress margin
The stress margin of product design in reliability engineering is defined in this paper as:

In the product design process, considering the stress caused by the working load and the environmental load, the margin that is maintained after the maximum stress is stress margin. The stress margin is expressed in \( M_s \). Stress margin generally considers dispersion.

Generalized stress margin based reliability design methods include mechanical product safety factor design and electronic product derating design.

2.2.2. The basic theory of stress margin design
The stress-strength interference (SSI) model is an important method for structural reliability analysis[6-8]. SSI quantifies the external load and material strength of the structure randomly, and establishes the limit-state function for reliability calculation. As an important reliability modeling
method, the SSI model is gradually extended to reliability modeling and calculation of other problems, forming a generalized stress-strength interference (GSSI) model. The GSSI model is comprised of the generalized stresses $f(S)$ and the generalized strength $f(R)$. As shown Figure 2.

The limit-state function could be built based on the GISS mode as:

$$Z = f(R) - f(S)$$  \hspace{1cm} (2)

According to the regular reliability theory, if the generalized strength $f(R)$ is more than generalized stress $f(S)$, then the system is safety; otherwise, if the generalized strength $f(R)$ is less than generalized stress $f(S)$, the system is failure. Then, the reliability $R$ and failure probability $F$ could be expressed as:

$$R = P(R > S)$$  \hspace{1cm} (3)

$$F = P(S > R)$$  \hspace{1cm} (4)

Where $P(\cdot)$ represents probability. And $R+F=1$

The randomness of stress-strength interference model is generalized to uncertainty, then the quantify margin uncertainty (QMU) model is derived[9-10].

$$CF = \frac{M}{U}$$  \hspace{1cm} (5)

Where $M$ represents the best estimate of the performance margin

$$M = y_T - y_N$$  \hspace{1cm} (6)

Where $y_T$ is the best estimate of design performance; $y_N$ is the best estimate of the lower limit of performance threshold. $U$ represents the uncertainty that exists when the performance margin is present. When $CF > 1$, it indicates that the performance margin can cover the uncertainty, and the product meets the reliability requirement; when $CF \leq 1$, the system does not meet the reliability requirement.

2.2.3. Application of product stress margin design
For a hardware product, the main design approaches for reliability improvement are almost all manifested as stress margin design, such as safety factor design approach for mechanical products, derating design for electronic products, thermal design, anti-vibration design, and environmental protection design. Therefore, in the stress margin design process, all the factors causing product failure can be regarded as generalized stress, such as temperature stress, deformation and other characteristics factors; all factors that prevent product failure can be regarded as generalized strength, such as heat resistance, stiffness, and other characteristics factors. According to the new concept of generalized margin after expansion, for the aerospace product transmission, sealing device, heat protection structure, etc., the margin can refer to the transmission margin, sealing margin, anti-heat margin, etc., respectively.

2.3. Function margin of product

2.3.1. Definition of the function margin
The functional margin is defined in this paper as: In the functional design phase, the method of functional redundancy is used to ensure the decrease of probability of functional failure. In other words, functional margins are functional redundancy through various system functional models, including cold standby system, warm standby system, voting \( \frac{r}{n} \) system, and functional dynamic reconfiguration.

It should be noted that, mostly, the functional margin is a design method that guarantees the reliability of the product task or mission in the case where the stress margin design is limited, so the functional margin design is a supplement to the stress margin design.

2.3.2. Theoretical basis for product function margin
The system function redundancy is the theoretical base of the function margin design. For the functional margin of a typical \( \frac{r}{n} \) model, as shown in Figure 4. We can see that the use of functional margin can improve the mission reliability of the system, and the calculation formula of its mission reliability is shown in equation (7).

\[
R_s(t) = R_s \sum_{i=0}^{n} C_i^n R(t)^i (1 - R(t))^{n-i}
\]  

Where, \( R_s(t) \) represents the system reliability; \( R(t) \) represent the components reliability, \( R_m \) represents the reliability of the voter.

2.3.3. Application of the function margin
Taking the cold standby system as an example, as shown in Figure 5. In this case, if the reliability of the transfer switch is not considered, then the system reliability is twice the stress margin of a single module. It can be seen that the redundancy could compensates the shortage of stress margin. If the reliability problem is caused by the stress margin of materials of the main components, with the development of material technology, the strength of the new material can be increased enough. Equipment with a single component could meet the same reliability requirements index, and the redundancy could be canceled.
Figure 5. The redundancy of cold standby and parallel systems.

3. Reliability margin design method

3.1. Mapping of Product Margin and Reliability Statistics Parameters

A certain stress margin always corresponds to a certain failure time in real situations. For example, for fatigue reliability of materials, there is a certain relationship between the certain stress level of the material and its cycle number of vibration fatigue. And if the material dispersion is considered, the number of fatigue cycles also has a certain discrete random distribution. Figure 6 shows distributions of failure times at different stress levels. Stress margin as a designable parameter could realize the bridge the requirements of engineering design and the implement operations. These processes have mapping relationships with the help of the reliability parameters, as shown in Figure 7.

Figure 6. The design life with normal distribution.

Figure 7. The mapping between the stress margin and the reliability index.

3.2. Unified fusion of various reliability methods based on the framework of margin theory

At present, various reliability methods (system reliability, physical of failure based reliability, etc.) have differences in basic assumptions and the technical paths. This situation results in the non-coordination of reliability index and the output of these reliability methods, and also brings difficulties to the engineering application. The main reason is: the strong assumptions of various reliability methods lead to the large differences of design goals, and there is no perspective on the fundamental purpose of reliability improvement. The generalized margin design theory is trying to coordinate these reliability methods.

(1) Environmentally adaptive design

Environmental adaptability of product is the ability to characterize the product achieving all of its intended functions and performance without being disrupted by the various environments, and these environments are expected to encounter during the lifetime. Environments adaptability emphasizes...
tolerance under extreme environmental conditions. The environmental adaptability design is the process that making the (generalized) strength of product meets the requirements under the extreme environmental conditions. And mainly approach is the generalized stress-strength design. Obviously, the greater the stress margin, the stronger the environmental adaptability. Hence, the environments adaptive design could carried out by the variables.

(2) System reliability design

The system reliability design is also mainly the concept of margin design, such as component selection, thermal design, anti-vibration design, electromagnetic compatibility design, etc., all aiming at the robust design to increase the stress margin. System reliability is considered to be the stochastic failure theory that has failure from the initial use time, which is compatible with the basic industrial quality level of the theoretical origin at that time, because the discreteness of parameters such as materials and processes is large, and the discreteness of fault events is also very large). The reliability improvement design of the system is illustrated by an example of the reliability prediction of electronic components. Stress analysis model of a semiconductor component is as follows:

$$\lambda_p = \lambda_b \pi_T \pi_R \pi_S \pi_C \pi_Q \pi_E$$

where, \(\lambda_P\) is the expected failure rate of the component, \(\lambda_b\) is the basic failure rate, \(\pi_T\) is the temperature coefficient, \(\pi_R\) is the power quality coefficient, \(\pi_S\) is the power stress coefficient, \(\pi_C\) is the contact structure coefficient, \(\pi_Q\) is the mass coefficient, and \(\pi_E\) is the environmental coefficient.

The mass and environmental factors are used in almost all models, but the use and meaning of other parameters vary with the type of component. MIL-STD-217F contains the specific values of these coefficients mentioned above.

Obviously, the correction coefficient \(\lambda_X\) in the above equation is the stress margin coefficient. To reduce the failure rate, we can start from the improvement of generalized stress margins such as lowering temperature conditions, improving quality levels, and reducing environmental conditions.

(3) Physics of failure (PoF) based reliability

Reliability based on PoF focuses on the process of product failure. It is believed that the failure of any product is always caused by the intended work environment and its operating load. Environmental conditions such as temperature, vibration, humidity, electrical stress, etc. or their combined stresses lead to stress damage of the product. The failure transmits of stress damage mechanism may result in degradation of the performance parameters and logic parameters or the function loss of the product. The physical reliability of the fault mainly focuses on the mechanism of product failure, drives the results of sensitive stress analysis, etc. The PoF could support the reliability design, and the basic path is also the stress margin design.

(4) Reliability enhancement test

As an effective reliability design method, the reliability enhancement test (RET) is also aimed at improving the stress margin. The reliability enhancement test is an excitation test that accelerates the potential defects of the product by applying high test stress (usually using step stress or using a single stress higher than the design specification). The basic idea of RET is: the products’ stress resistance capacity could increase by implementing the cycle iteration of “exciting defects - design Improve”. And through RET, this capacity could achieve the best under constrains of the funding, schedule and technical. In the generalized margin design view, RET could make effort to identify and eliminate the weak points of product design, improve the design stress margin, and ensure that the product is robust in its lifetime. As Seen in Figure 8
The generalized margin method of reliability design could consider the stress factors in Environmentally adaptive design, System reliability design, Physics of failure (PoF) based reliability, Reliability enhancement test as the generalized stress $M_s$, through the connecting function of $M_g$, all these design methods could be unified in the reliability engineering.

3.3. Reliability design method process based on generalized margin

- **Reliability requirements index**
- **Product conceptual design**
- **Stress distribution of design variables**
- **Stress margin design of variables**
- **The stress margin meets the reliability requirements?**
- **Making the variables reliability design rules**
- **Obtain the general margin design rules**
- **Function margin analysis**
- **Function margin design**
- **Making the function reliability design rules**

**Figure 8.** The stress margin and RET.

**Figure 9.** The flowchart of generalized margin design method.

The reliability design method based on generalized margin is shown in the Figure 9. And the steps of reliability design method based on the generalized margin are as follows:

1) Obtain the reliability requirements index based on customers’ needs
2) Design the concept of product according to the requirements
3) Detail design of the concept, stress analysis of design parameters, including working stress and environmental stress
4) Perform stress margin design and determine whether the stress margin meets the reliability requirement
5) If the stress margin meets the design reliability requirements, the reliability design criterions are formed; if the stress margin does not meet the reliability requirements, return to the design phase.
6) Perform functional margin analysis, including redundancy or reconstruction analysis.
7) Conduct the function margin design of product.
8) Establish the functional margin design rules.
9) Achieve the final generalized margin reliability design rules.

Through the generalized margin reliability design method, the considerations of all traditional reliability design methods above will be applied in the framework. And this method could provide a scientific guideline for the reliability design engineers.

4. Application case analysis

This part will illustrate the generalized margin design method with the application of aircraft control system design as seen in Figure 10.

Figure 10. Fly by wire schematic diagram.

1) Denote the mission reliability requirements, like the reliability index as mean time between failures (MTBF) or reliability.

Aircraft control system is a very important system, its reliability, safety requirements are very high. Therefore, the system analysis should be conducted first in the process of reliability design of the control system. Currently the most commonly used is flight by Wire system, as shown in figure 10. Its main components are Side-bar controller, Rod Force sensor, Flight control, Steering gear and Actuator speed gyro plus design, overload sensor. Control/Display Interface device composition.

2) Construct the generalized margin design framework of the fly control system.

According to the function and structure of the control system, system reliability allocation is implemented to obtain the reliability indexes of the main components.

$$M_{s} = M_{s}^{FC} + M_{f}^{FC}$$

3) Select the important parts of the control system, then design this parameters based on the stress margin model.

According to the flight records of the relevant models, we can know that in fly by wire system, the servo amplifier failure, the sensor circuit failure, the computer board failure, so the failure mechanism based stress margin design could be used in the reliability design. Improving the stress resistance level of the materials according the failure mechanism of these failure modes, and proposing the environmental protection measures to decrease the stress, the fly control system’s reliability could be designed.

$$M_{s}^{FC} = \alpha \cdot \beta \cdot S^{FC}$$

Where $\alpha$ is function factor of materials’ stress resistance level, $\beta$ is the function factor of the environmental protection measures, $S^{FC}$ is the design stress level.

4) In order to guarantee the high reliability requirements of the fly control system, the function margin also be carried out.

Considering the cost and technical factors, some sensors can not meet the specified design value, so the single channel telex reliability level can not meet the requirements. Therefore, functional margin design, including 4 redundancy design and mechanical fly control as backup. The final design
is as shown in Figure 11. Through this case, it can be seen that the general margin design is implemented in the flight control systems to guarantee the high reliability.

**Figure 11.** Reliability design of FBW.

5. Summary & conclusions
The traditional reliability parameters in the engineering (such as MTBF,) are statistic parameters of failure time or failure rates, these reliability parameters are not related with products’ design parameters directly. In fact, the reliability design is margin design in the engineering, like the stress margin as safety factors approach in machine design, the derating design of electrical stress in electronic design, and even the election of the high quality components is enhance the margin of resisting the sense stress of failures. When the improvement of stress margin is limited, the reliability of products could guaranteed by function redundancy, also could be named as “function margin” in this paper. Hence, how to transfer the statistic reliability parameters to margin parameters in the urgent problems in the reliability design. This paper proposes a reliability engineering design method based on the generalized margin theory, establishes the quantification relation between the statistic reliability parameters and generalized margin parameters. The generalized margin proposed in this paper contains the stress margin and function margin. This method defined the margin design rules and requirements according to the products(or concepts design) ’s loads in the predicted lifecycle; and then the stress margin parameters that satisfying the reliability could be determined based on the stress-strength interference model, and these margin parameters could support the products concepts selection; if the stress margin parameters could not satisfy the requirements, the function margin parameters are analyzed , and guiding the key function redundancy design until the reliability of the products are meted. Paper discusses the availability of this design method with an application case.

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