Research on the Reliability Tolerance Analysis Method of Electromagnetic Relay in Aerospace

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Abstract: Electromagnetic relay in aerospace is one of the main electronic components in aerospace electronic systems for information transfer, control and power distribution, and its reliability will influence the reliability of the whole aerospace electronic systems. Reliability design is the key technique of electromagnetic relay reliability engineering. This paper synthetically analyzes the present reliability design methods, and presents the reliability tolerance analyzing mathematic models of electromagnetic force basing on orthogonal design, mechanical spring force basing on probability statistics theory, and matching characteristics of electromagnetic force and mechanical spring force basing on method of stress-strength interference. Some instructive conclusions are draw by researching on the reliability tolerance of some type electromagnetic relay in aerospace.

Key words: reliability; electromagnetic relay in aerospace; tolerance analysis; orthogonal design; probability statistics

航天电磁继电器可靠性容差分析技术的研究. 梁慧敏, 任万滨, 叶雪荣, 翟国富. 中国航空学报(英文版), 2005, 18(1): 65-71.

摘 要: 航天电磁继电器是在航天电子系统中完成信号传递、执行控制、系统配电等功能的主要电子元器件之一, 其可靠性直接影响整个航天电子系统的可靠性。航天继电器可靠性设计技术是其产品可靠性工程的关键技术。本文分析了当前各领域可靠性研究现状及航天电磁继电器产品的可靠性现状与问题, 提出并建立了基于正交试验表的电磁吸力可靠性容差分析数学模型、基于概率统计方法的机械反力可靠性容差分析数学模型及基于"应力—强度干涉法"的吸反力配合特性可靠性容差分析数学模型。以某型号航天电磁继电器为例, 进行了可靠性容差分析与研究, 给出了对航天电磁继电器可靠性设计具有指导作用的重要结论。

关键词: 可靠性; 航天继电器; 容差分析; 正交试验设计; 概率统计

文章编号: 1000-9361(2005)01-0065-07 中图分类号: TM581.3; V242.4+2 文献标识码: A

Aerospace electromagnetic relay is one of the main electrical apparatus used in the national defense electrical system to transfer the signal, accomplish control aim, distribute the power, insulate the circuit and so on, and its reliability will influence the system's reliability directly. Reliability engineering is a series of works—correlative design, experiment, produce, management and so on[1]. Its purpose is to achieve the requirement of system's reliability. Among these works, reliability design is the basic part of reliability engineering. "The reliability of the products is based on design, produce and management"[2]. The reliability design is the important work to realize the reliability can be done from the headstream of design. The reliability design of aerospace electromagnetic relay is mainly finished by the reliability tolerance design. Thus, the research on aerospace electromagnetic relay's reliability tolerance design has practical significance for the reliability of the whole national defense electrical system.

At present, the reliability forecasting and tolerance design methods for large systems are investigated in the fields of electric circuits design and mechanism design[3, 4], and the reliability testing and analysis are researched in the field of electrical apparatus[5]. A little work for the reliability design and tolerance design of electrical apparatus products

Received date: 2004-06-02; Revision received date: 2004-10-28

Foundation item: Science Research Fund of Harbin Institute of Technology (HIT. 2002. 20)

has been done. Viewing the reliability of aerospace electromagnetic relays in existence, the problem is not the products' lives being too short, but the products' lives not being centralized. That is to say, the reliability index is low. The main reason of this phenomenon is that the tolerance design has not been carried out. There are two aims of reliability tolerance design. The first is to control the consistency of the output quality by the reliability tolerance analysis and distribution. The second is to reduce the cost under the condition of guaranteeing the reliability requirement[6]. Fig. 1 is the diagram of the reliability tolerance design.

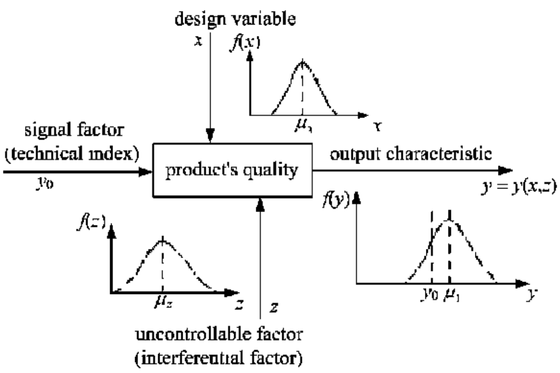


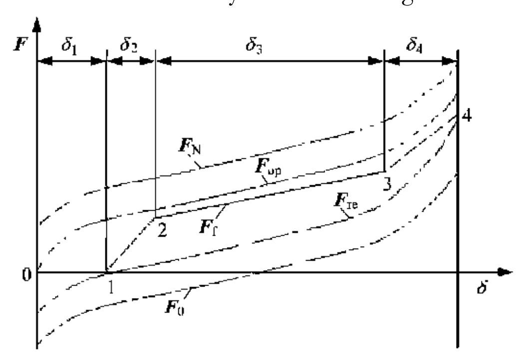
Fig. 1 Diagram of reliability tolerance design

So, the main problems being solved in the reliability tolerance design are listed as follows: (1) which factors (include controllable factors and uncontrollable factors) have obvious influence on the output characteristic y; (2) how to set the controllable factor x in order to make the expectation μ_y of y approximate the requirement value y_0; (3) how to set the controllable factor x in order to get the minimum value of the variance σ_y^2 of y (the consistency of the output characteristic is good); (4) how to set the controllable factor x in order to make the uncontrollable factor z has the minimum effect on y; (5) giving the allowed variance σ_z^2 of the uncontrollable factor z when σ_y^2 is given; (6) how to distribute variance σ_x^2 of the controllable factor x when σ_y^2 is given in order to reduce the cost.

The quality of aerospace electromagnetic relay can be influenced by controllable factors (such as design variables whose sizes are distributed due to technology) and uncontrollable factors (such as noise factors, including temperature, air pressure, impact and so on, which are distributed too due to factors randomicity). The quality characteristics are also distributed. Through controlling the quality distribution of characteristic parameters based on the electromagnetic relay's reliability requirement, the paper adopts probabilistic and orthogonal methods to research the tolerance analysis, tolerance control and tolerance distribution of the influence factors in order to improve the quality and reliability of relay.

1 The Models of Aerospace Electromagnetic Relay's Reliability Tolerance Analysis

The key technique of aerospace electromagnetic relay's reliability tolerance design is the optimum cooperation technique of electromagnetic force and spring force. The requirements of the cooperation are: after the parameters design, the electromagnetic force characteristic must be lower than the spring force characteristic at release voltage and the electromagnetic force characteristic must be higher than the spring force characteristic at attractive voltage (Fig. 2); after the reliability tolerance design, the cooperation of electromagnetic force tolerance band and the spring force tolerance band should be satisfied with the requirement of reliability index. The reliability tolerance design of aerosp-



δ_1—Free travel of pushing rod; δ_2—Breaking over travel; δ_3—Transferring gap; δ_4—Closing over travel; $\boldsymbol{F}_N$, $\boldsymbol{F}_{op}$, $\boldsymbol{F}_{re}$, $\boldsymbol{F}_0$—Electromagnetic force under rating voltage, attractive voltage, release voltage, 0V; $\boldsymbol{F}_f$—Spring force

Fig. 2 The principle of electromagnetic force and spring force characteristics' cooperation ace electromagnetic relay can be divided into reliability tolerance design of spring force characteristic, reliability tolerance design of electromagnetic force characteristic, and reliability tolerance design of electromagnetic force and spring force's cooperation. Generally, the mathematic model of spring force characteristic and design variables can be expressed by analytical expression, so probabilistic method can be used for the reliability tolerance design of spring force characteristic. However, because of the electromagnetic system's non-linear and flux leakage, the model of electromagnetic force characteristic and design variables can not expressed by analytical expression, and the orthogonal design method is adopted for the reliability tolerance design. And the stress-strength interference model can realize the reliability tolerance design of electromagnetic force and spring force characteristics' cooperation.

Suppose $\boldsymbol{x} = [x_1 \quad x_2 \quad \cdots \quad x_n]^{\mathrm{T}}$ as the design variable (spring force characteristic: the size and performance parameters of spring, contact and so on; electromagnetic force characteristic: the size and performance parameters of coil, armature, polar, permanent magnet and so on), the expression of spring force characteristic or electromagnetic force characteristic is

$$\boldsymbol{F} = f(\boldsymbol{x}) \tag{1}$$

1.1 The mathematic model of spring force's reliability tolerance analysis

Let x be the parameter-designed vector (random) of the spring system of relay. The center value $\boldsymbol{x}_0 = [x_{01} \quad x_{02} \quad \cdots \quad x_{0n}]^{\mathrm{T}}$ can be got by the parameters design of spring system. Then $\boldsymbol{x}$ will vary slightly within a small region around the center value $\boldsymbol{x}_0$. From Taylor polynomials, it can be obtained that

$$F_{\mathrm{f}} = f(\boldsymbol{x}) \approx f(\boldsymbol{x}_0) + \sum_{i=1}^{n} \frac{\partial f}{\partial x_i}\bigg|_{x_i = x_{0i}} \Delta x_i \tag{2}$$

$$\Delta F_{\mathrm{f}} = f(\boldsymbol{x}) - f(\boldsymbol{x}_0) = \sum_{i=1}^{n} \frac{\partial f}{\partial x_i}\bigg|_{x_i = x_{0i}} \Delta x_i = \sum_{i=1}^{n} S_{x_i} \Delta x_i \tag{3}$$

where $\Delta x_i = x_i - x_{0i}$; $S_{x_i} = \frac{\partial f}{\partial x_i}\bigg|_{x_i = x_{0i}}$ $(i \in \{1, n\})$ is the differential sensitivity of function f. Generally, x_i are independent random variables, and the expected value and variance of ΔF_{f} are

$$E(\Delta F_{\mathrm{f}}) = \sum_{i=1}^{n} S_{x_i}(E(\Delta x_i)) \tag{4}$$

$$D(\Delta F_{\mathrm{f}}) = \sum_{i=1}^{n} (S_{x_i})^2 D(\Delta x_i) \tag{5}$$

The standard deviation is

$$\sigma_{\Delta F_{\mathrm{f}}} = \sqrt{D(\Delta F_{\mathrm{f}})} \tag{6}$$

For the consistency of output characteristic in practical application, hope $\sigma_{\Delta F_{\mathrm{f}}}$ as low as possible.

The principle of selecting parameters in the mathematic model of spring force's reliability tolerance analysis is: select the sizes and performance parameters which can influence the spring force characteristic obviously, and their tolerance should be as small as possible based on the factory's manufacturing ability and decreasing the producing cost.

1.2 Foundation of the mathematic model of electromagnetic force's reliability tolerance analysis

To satisfy the restrict of the national defense electrical system's environment, aerospace electromagnetic relay should be small volume, light weight, low power waste, high sensitivity, fast operate speed and so on, so its electromagnetic system usually has permanent magnet (forming polarized magnetic system). Because of flux leakage and the non-linear of polarized magnetic system, the relationship between the output characteristic of polarized magnetic system and the parameters of magnetic system is non-linear. Thus, the orthogonal design method is used for the reliability tolerance design of electromagnetic force here.

1.2.1 The mathematic model of polarized magnetic system's electromagnetic force characteristic

Fig. 3 shows the polarized magnetic system's configuration sketch of a relay with permanent magnet and its equivalent magnetism circuit.

The equivalent math model of the polarized magnetic system shown in Fig. 3 is

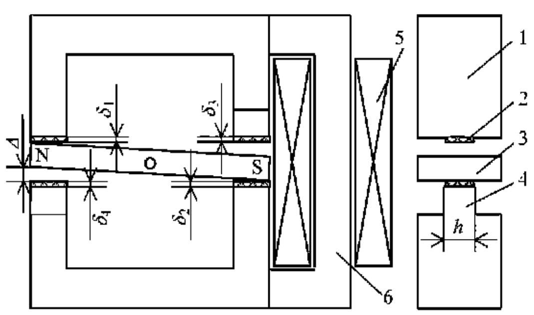
$$\left.\begin{aligned}(R_2+R_3+R_5)\Phi_0-R_3\Phi_1-R_2\Phi_2&=IW\\(R_1+R_3+R_m+R_7)\Phi_1-R_3\Phi_0-R_m\Phi_2&=-P_m\\(R_2+R_4+R_m+R_6)\Phi_2-R_2\Phi_0-R_m\Phi_1&=-P_m\end{aligned}\right\}\quad(7)$$

where $R_1=\frac{\delta_{01}+\delta_1}{\mu_0 ab}$; $R_2=\frac{\delta_{02}+\delta_2}{\mu_0 ab}$; $R_3=\frac{\delta_{03}+\delta_3}{\mu_0 ah}$; $R_4=\frac{\delta_{04}+\delta_4}{\mu_0 ah}$; a is the length of polar; b is the width of big polar; h is the width of small polar; δ_{01}, δ_{02}, δ_{03} and δ_{04} are the distance from corresponding spacers to armature; δ_1, δ_2, δ_3 and δ_4 are the thicknesses of spacers.

From Eq.(7), obtain the values of δ_{01}, δ_{02}, δ_{03} and δ_{04}, then get the magnetic flux of every working gap's magnetic resistance, substitute them in Maxwell equation for electromagnetic force torque of every working gap, finally achieve the total electromagnetic force.

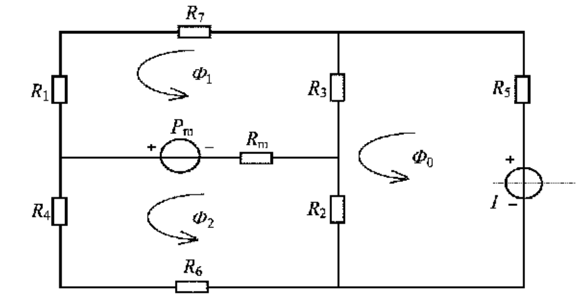
1.2.2 The reliability tolerance analyzing mathematic model of electromagnetic force based on orthogonal design

In this paper, the polarized magnetic system of the relay shown in Fig. 3 is taken as an example to carry out the reliability tolerance analyzing mathematic model of electromagnetic force based on orthogonal design method.



1—Yoke and big polar; 2—Non-magnetic conduction spacer; 3—Armature; 4—Small polar and yoke; 5—Coil; 6—Iron core; δ_1, δ_2, δ_3, δ_4—Thickness of spacer; Δ—Working gap

(a) Elevation and side view of polarized magnetic system's



R_5—Magnetic resistance of iron core; R_6, R_7—Magnetic resistances of yokes; Φ_0, Φ_1, Φ_2—Fluxes of circuits; R_1, R_2, R_3, R_4—Magnetic resistances of working gaps; P_m, R_m—Equivalent magnetic potential and magnetic resistance of permanent magnet

(b) Equivalent magnetic circuits

Fig. 3 The configuration sketch of the polarized magnetic system and its equivalent magnetic circuit

(1) Determining the tolerance level

There are six main factors that influence the electromagnetic force characteristic (called controllable factor below). They are spacers δ_1, δ_2, δ_3 and δ_4, working gap Δ, and width of small polar h. Suppose the center values are $\delta_{1,0}$, $\delta_{2,0}$, Δ_0, $\delta_{3,0}$, $\delta_{4,0}$ and h_0. Table 1 shows their tolerance levels on the foundation of technology requirement.

(2) Determining orthogonal table

According to Table 1, the orthogonal table $L_{18}(2^1\times3^7)$ (Table 2) is chosen to carry out the tolerance design of electromagnetic force. In Table 2, A, B, C, D, E and F represent the tolerance levels of parameters δ_1, δ_2, Δ, δ_3, δ_4 and h.

(3) Tolerance analysis

The tolerance (standard variance) of electromagnetic force at attractive voltage in node i ($i=0, 2, 4$) is $\sigma_{F_{op}}$

$$\sigma_{F_{op}}=\sqrt{\frac{1}{17}\left(\sum_{j=1}^{18}F^2_{op,ij}\right)}\qquad(8)$$

Table 1 Tolerance level talble

Level	δ_1/mm	δ_2/mm	δ_3/mm	δ_4/mm	Δ/mm	h/mm
1	$\delta_{1,0}-0.003$	$\delta_{2,0}-0.003$	$\delta_{3,0}-0.003$	$\delta_{4,0}-0.003$	$\Delta_0-0.1$	$h_0-0.1$
2	$\delta_{1,0}$	$\delta_{2,0}$	$\delta_{3,0}$	$\delta_{4,0}$	Δ_0	h_0
3	$\delta_{1,0}+0.003$	$\delta_{2,0}+0.003$	$\delta_{3,0}+0.003$	$\delta_{4,0}+0.003$	$\Delta_0+0.1$	$h_0+0.1$

Table 2 Orthogonal table

No.	A	B	C	D	E	F	Electromagnetic force					
							Electromagnetic force F_{op} at attractive voltage			Release force F_{re} at release voltage		
							Node 0	Node 2	Node 4	Node 1	Node 3	Node 4
1	1	1	1	1	1	1	$F_{op,01}$	$F_{op,21}$	$F_{op,41}$	$F_{re,11}$	$F_{re,31}$	$F_{re,41}$
2	1	2	2	2	2	2	$F_{op,02}$	$F_{op,22}$	$F_{op,42}$	$F_{re,12}$	$F_{re,32}$	$F_{re,42}$
3	1	3	3	3	3	3	$F_{op,03}$	$F_{op,23}$	$F_{op,43}$	$F_{re,13}$	$F_{re,33}$	$F_{re,43}$
4	2	1	1	2	2	3	$F_{op,04}$	$F_{op,24}$	$F_{op,44}$	$F_{re,14}$	$F_{re,34}$	$F_{re,44}$
5	2	2	2	3	3	1	$F_{op,05}$	$F_{op,25}$	$F_{op,45}$	$F_{re,15}$	$F_{re,35}$	$F_{re,45}$
6	2	3	3	1	1	2	$F_{op,06}$	$F_{op,26}$	$F_{op,46}$	$F_{re,16}$	$F_{re,36}$	$F_{re,46}$
7	3	1	2	1	3	2	$F_{op,07}$	$F_{op,27}$	$F_{op,47}$	$F_{re,17}$	$F_{re,37}$	$F_{re,47}$
8	3	2	3	2	1	3	$F_{op,08}$	$F_{op,28}$	$F_{op,48}$	$F_{re,18}$	$F_{re,38}$	$F_{re,48}$
9	3	3	1	3	2	1	$F_{op,09}$	$F_{op,29}$	$F_{op,49}$	$F_{re,19}$	$F_{re,39}$	$F_{re,49}$
10	1	1	3	3	2	2	$F_{op,010}$	$F_{op,210}$	$F_{op,410}$	$F_{re,110}$	$F_{re,310}$	$F_{re,410}$
11	1	2	1	1	3	3	$F_{op,011}$	$F_{op,211}$	$F_{op,411}$	$F_{re,111}$	$F_{re,311}$	$F_{re,411}$
12	1	3	2	2	1	1	$F_{op,012}$	$F_{op,212}$	$F_{op,412}$	$F_{re,112}$	$F_{re,312}$	$F_{re,412}$
13	2	1	2	3	1	3	$F_{op,013}$	$F_{op,213}$	$F_{op,413}$	$F_{re,113}$	$F_{re,313}$	$F_{re,413}$
14	2	2	3	1	2	1	$F_{op,014}$	$F_{op,214}$	$F_{op,414}$	$F_{re,114}$	$F_{re,314}$	$F_{re,414}$
15	2	3	1	2	3	2	$F_{op,015}$	$F_{op,215}$	$F_{op,415}$	$F_{re,115}$	$F_{re,315}$	$F_{re,415}$
16	3	1	3	2	3	1	$F_{op,016}$	$F_{op,216}$	$F_{op,416}$	$F_{re,116}$	$F_{re,316}$	$F_{re,416}$
17	3	2	1	3	1	2	$F_{op,017}$	$F_{op,217}$	$F_{op,417}$	$F_{re,117}$	$F_{re,317}$	$F_{re,417}$
18	3	3	2	1	2	3	$F_{op,018}$	$F_{op,218}$	$F_{op,418}$	$F_{re,118}$	$F_{re,318}$	$F_{re,418}$

The tolerance (standard variance) of electromagnetic force at release voltage in node i ($i = 1, 3, 4$) is $\sigma_{F_{re}}$

$$\sigma_{F_{re}} = \sqrt{\frac{1}{17}\left(\sum_{j=1}^{18} F_{re,ij}^2\right)} \tag{9}$$

1.3 The reliability tolerance analysis model of electromagnetic force and spring force characteristics' cooperation

The influence of the controllable and uncontrollable factors results in the distributions of electromagnetic force characteristic and spring force characteristic of relay (belonging to normal distribution), which are the tolerance bands of electromagnetic force characteristic and spring force characteristic (Fig. 4).

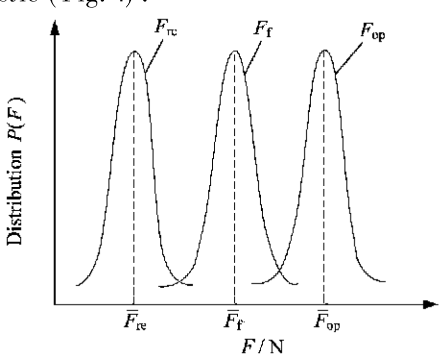


Fig. 4 Distributions of electromagnetic force and spring force characteristics

According to the stress-strength interference model, if the values of α_{op} and α_{re} are given (sometimes $\alpha_{op} = \alpha_{re} = \alpha$), where α_{op} and α_{re} represent the reliabilities of attraction and release respectively, the relationship of statistic values between electromagnetic force and spring force can be determined as follows

$$1 - \alpha_{op} = P(F_{op} < F_f) = \int_{-\infty}^{Z_{op}} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{y^2}{2}\right) dy \tag{10}$$

$$Z_{op} \geqslant -\frac{\bar{F}_{op} - \bar{F}_f}{\sqrt{\sigma_{F_f}^2 + \sigma_{F_{op}}^2}} \tag{11}$$

$$1 - \alpha_{re} = P(F_f < F_{re}) = \int_{-\infty}^{Z_{re}} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{y^2}{2}\right) dy \tag{12}$$

$$Z_{re} \geqslant -\frac{\bar{F}_f - \bar{F}_{re}}{\sqrt{\sigma_{F_f}^2 + \sigma_{F_{re}}^2}} \tag{13}$$

where $\bar{F}_{op}$, $\bar{F}_{re}$ and $\bar{F}_f$ represent the mean values of F_{op}, F_{re} and F_f, respectively; $\sigma_{F_{op}}$, $\sigma_{F_{re}}$ and σ_{F_f} represent the standard deviations of F_{op}, F_{re} and F_f, respectively.

2 Workflow of the Reliability Tolerance Design

The reliability tolerance design of relay is based on configuration design and parameter design. The workflow of aerospace electromagnetic relay's reliability tolerance design is shown as Fig. 5.

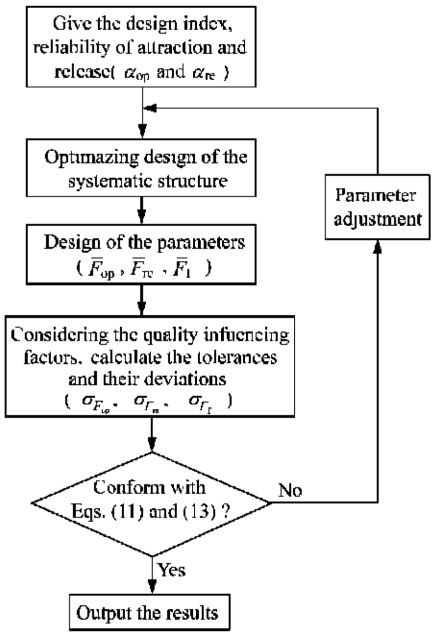


Fig. 5 The flow chart of reliability tolerance design

Table 3 The calculation values of reliability tolerance design

Working state		Attraction	Release
$\alpha_{op} = \alpha_{re}$		0.9987	0.9987
$Z_{op} = Z_{re}$		3.0	3.0
Electromagnetic force at attractive voltage/N	Average $\bar{F}_{op}$	0.032	
	Tolerance $\sigma_{F_{op}}$	0.0107	
Spring force/N	Average $\bar{F}_f$	0.025	0.219
	Tolerance σ_{F_f}	0.01	0.0248
Electromagnetic force at release voltage/N	Average $\bar{F}_{re}$		0.191
	Tolerance $\sigma_{F_{re}}$		0.0092

3 Example

Some type of electromagnetic relay's technique indexes are: volume is 10mm × 10mm × 10mm, sensitivity is 30mW, power dissipation is 83mW, the form of contacts is 2C, the load of the contact is 28Vdc, 0.5A, the relay's life is 1×10^5 operations, the reliability of attraction and release are all 0.9987. According to the workflow of the reliability tolerance design shown in Fig. 4, the reliability tolerance analysis of electromagnetic force and spring force characteristics' cooperation at the gap corresponding to node 2 (Fig. 2) is carried out. The result is shown in Table 3.

4 Conclusions

In the process of design, controllability and consistency of the product's output characteristic are two important concepts, which greatly influence the product's reliability. The method of reliability tolerance design for aerospace electromagnetic relay presented here is to make the cooperation between the tolerance of electromagnetic force characteristic and that of spring force characteristic be optimized by adjusting the design variable and its tolerance based on the optimum designs of system configuration and parameter and the conditions of attraction and release reliabilities being given. In this way, the quality of products can be controlled from the period of design. This method also can be used in the other reliability designs of aerospace electrical apparatus.

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