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Discussion on dynamic reliability tolerance design technology of electromagnetic relay*

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Abstract: Reliability tolerance design of electromagnetic relay during its design period plays an essential role in guaranteeing the consistencies of reliability and output characteristic. The reliability tolerance design can ensure that the products would work well under the influence of disturbing factors (including internal interference, external interference, and machining dispersion). Compared with static characteristic, dynamic characteristic of electromagnetic relay can describe its operating process better. This article researches influence of the three kinds of disturbing factors on the dynamic characteristic of electromagnetic relay based on calculating dynamic characteristic. Then, the dynamic reliability tolerance design method of electromagnetic relay is discussed considering three kinds of disturbing factors. Conclusions reached can help to assure the reliability of electromagnetic relay from the beginning of design.

Key words: Electromagnetic relay, Tolerance design, Reliability, Dynamic characteristic
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INTRODUCTION

Electromagnetic relay is widely applied in many fields such as industrial control, national defense, military affairs, aerospace, etc.; its performance will directly affect stability and reliability of electric system. Affected by three kinds of disturbing factors—internal interference (such as contact wear, aging, etc.), external interference (such as ambient temperature, humidity, vibration, impulsion, acceleration, etc.) and machining dispersion, the quality characteristic of electromagnetic relay shows distribution character. Dynamic characteristic of relay could truly reflect the operating process better than static characteristic. Consequently, through analyzing the influence of the three kinds of disturbing factors on the dynamic characteristic of electromagnetic relay, the application of dynamic reliability tolerance design method to electromagnetic relay would be of great benefit for improving the reliability of products and shortening the cycle of design, production and test.

At present, when designers carry out on reliability design of electromagnetic relay, they mainly depend on margin design method that could not assure the reliability index of the product. As the electromagnetic relay has complicated structure and working principle involved in many subjects, only some work on reliability test and reliability experiment had been done in this field (Li *et al.*, 2000; Yin *et al.*, 2005). On the aspect of reliability prediction and reliability design, Ding *et al.*(2004) established the mathematical model and analyzed the reliability for digit relay. Su *et al.*(1999) named the minimum of working voltage “intensity”, named the pick-up voltage measured “stress”, and established the mathematical model of optimum design for miniature relay. However, they did not study the integral reliability design for electromagnetic relay. Based on the static characteristic, Military Apparatus Research Institute in Harbin Institute of Technology established the mathematical model of reliability tolerance design for electromag-

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netic relay, which only considers machining dispersion (Zhai *et al.*, 2004; Liang *et al.*, 2005a; 2005b). Therefore, this paper investigated further the reliability tolerance design method of electromagnetic relay considering three kinds of disturbing factors.

DYNAMIC CHARACTERISTIC OF ELECTROMAGNETIC RELAY

Dynamic characteristic of electromagnetic relay is the function relationships between time and relay parameters such as coil current i, armature movement x (or rotation angle α), electromagnetic force F (or electromagnetic torque M), spring force (or spring torque), armature operating speed v (or ω), and so on. Whether electromagnetic relay can work reliably or not directly rests on the combined electromagnetic force and spring force. Consequently, the calculation of dynamic characteristic is the foundation of dynamic reliability tolerance design of electromagnetic relay. A large number of dynamic characteristics should be calculated when the disturbing factors had been taken into account. As long calculating time and finite element software cannot meet the requirement of design and analysis so "magnetic circuit" method and numerical analyzing method were adopted here to obtain the dynamic characteristic. Compared with the finite element method, "magnetic circuit" method is better for tolerance computation. Although the precision is not so good, the calculation models can be modified by experiments so that the increased precision could meet the requirement of engineering.

EFFECTS OF DISTURBING FACTORS

From the machining process to finally being applied to control system, the relay performance will be impacted by various disturbing factors including internal interference, external interference and machining dispersion. Due to the effects of these disturbing factors, the curve of the failure rate is the bathtub curve shown in Fig.1. As the product reliability is mainly due to the impact of machining dispersion, studying the influence of machining dispersion on relay reliability can increase the passing rate, and make the relay reach the period of occasional failure as soon as possible. The occasional failure mainly comes from the external interference, study of which can help to reduce failure rate or occasional failure, and make the relay work steadily and reliably. During relay wear-out, the main factor inducing failure is the internal interference. To carry out the reliability tolerance design taking into consideration that the internal interference can delay the relay from entering the period of wear-out and increase relay life.

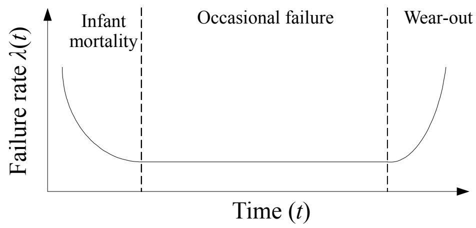

Fig.1 Bathtub curve of product failure rate

Machining dispersion

In the mechanism machining, even if machining equipment works normally and machining process is in the state of being controlled, the size of parts with the same size requirement is not exactly the same. These size values fluctuate within a certain range and present distributed characteristic. Generally, this distribution obeys normal distribution. Owing to the characteristic of mechanism machining and the requirement of relay assembly, designers would not only determine the design parameters central value, but also provide the tolerance during design. Hence, during analyzing quality characteristics of the designed relay, it is very important to take the fluctuation of parameters into account, namely, dynamic characteristics of electromagnetic force and spring force considering the influence of machining dispersion should be studied. Monte Carlo simulation method is a numerical method for solving problems of mathematics, physics and engineering approximately by statistical testing or stochastic simulation of stochastic variable. It has strong practicability and high calculating precision. We can employ this method here to find the distribution of dynamic characteristics. The process is as follows:

(1) Determine the function for dynamic characteristic of electromagnetic force and spring force $y=f(X_1,X_2,\ldots,X_n)$ and the corresponding design variable $X_1,X_2,\ldots,X_n$.

(2) Determine the probability density function of each stochastic variable X_i in $y=f(X_1,X_2,\ldots,X_n)$. As

mentioned above, the distribution of parts size obeys normal distribution, so the expectation of distribution is the median of the size value and the standard deviation is equal to 1/6 of the machining tolerance.

(3) Determine the cumulative distribution function $F(X_i)$ of each stochastic variable X_i in $y=f(X_1, X_2,\ldots,X_n)$.

(4) For each stochastic variable X_i in $y=f(X_1, X_2,\ldots,X_n)$, create fake random series obeying equality distribution in [0,1] section

$$Rn_{x_{ij}} = \int_{-\infty}^{x_{ij}} f(X_i)\mathrm{d}X_i, \quad (1)$$

where i is the tab of stochastic variable, i=1,2,…,n; j is the tab of simulation time, j=1,2,…,1000 or greater.

As a result, a set of theoretical random values for every stochastic variable can be obtained in every simulation. The set of theoretical random values come from j, whose simulation is expressed by X_{ij} (i=1,2,…,n; j=1,2,…,1000,…).

(5) Put the set of theoretical random value X_{ij} into the equations for electromagnetic force and spring force characteristic, calculate the relevant value y_j

$$y_j = f(X_{1j}, X_{2j},\ldots, X_{nj}). \quad (2)$$

(6) Repeat the above process. The simulation times (j) should be large enough so that it can satisfy the requirement of calculation precision.

(7) Draw the histogram of y and select some appropriate distributions from normal, lognormal and Weibull distribution.

(8) Verify these distributions by the numerical verifying method (such as χ^2 method, K-S method) in order to get the fittest distribution for the dynamic characteristics of electromagnetic force and spring force.

Internal interference

With the increase of the electromagnetic relay's operating times, its parts will be subjected to wear and tear gradually and will certainly affect the relay's movement characteristic. When this influence reaches a certain degree, the relay will fail. We call this influence internal interference. The common internal interference factors consist of fatigue and wear.

The impact of fatigue on dynamic characteristics is mostly reflected by spring movement. In the relay's movement process, the moving spring is acted on cyclic load. Therefore, the stress-life curve of spring material, namely S-N curve (Fig.2) can be used for the reliability design during spring fatigue would be taken into account. The stress on spring movement should be smaller than the fatigue limit stress S_r if possible. If the stress is required to be greater than S_r, designers should analyze whether corresponding fatigue life N_x could satisfy the requirement of relay life or not.

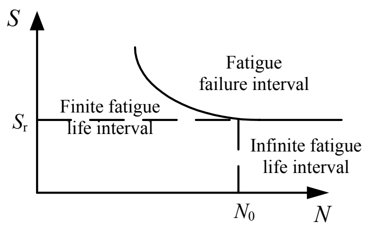

Fig.2 Material *S*-*N* curve

The influence of wear on electromagnetic relay is mainly represented by electrical wear of contacts. There are two kinds of electrical contacts wear modes: bridge transfer (The metal bridge in liquid state results from the last contact point of contacts melted because of heating before the contact is broken. The material of contacts will move from one electric pole to the other when the metal bridge breaks.) and electric arc transfer (under certain condition, arc will be generated after contacts break away, and surface material of contacts will be melted or gasified due to the high arc temperature). Electrical wear of contacts relates to the relay's life directly. Over travel of relay contacts reduced due to loss of contacts material will affect the cooperation between electromagnetic force and spring force, which can make the relay attract/release unreliable. On the other hand, it may happen that the contacts act, but they cannot switch the electric signal. All of these will lead to relay failure.

The speed of contacts wear is an important factor determining contacts life, and the transfer rate of contacts material is an important parameter to judge wear speed. There are two ways to define this parameter: one is the average transfer quantity (volume or weight) in one operation; the other is the average quantity (volume or weight) of transfer in unit time. The former is usually used in bridge transfer, and the latter in electrical arc transfer (Cheng, 1985). For bridge transfer, numerical expression of bridge transfer volume can be deduced from theory of metal bridge. For example, when Pd contacts is in nitrogen, Kohler Effect will play a major role, the expression for bridge transfer volume is:

$$\pi a^2 x = \frac{\pi}{4}\frac{\sigma\rho}{U_b^2} I_b, \quad (3)$$

where σ is tunnel resistivity; ρ is material resistivity; U_b is voltage drop of bridge; I_b is current of bridge; a is radius of cylindrical metal bridge; x is distance between the smallest cross section and the major heat cross section of bridge.

For electric arc transfer, contacts wear is mainly tested by weighing method, where wear quantity in unit time (or unit quantity of electricity) can be employed to indicate attrition rate (Cheng, 1985):

$$\frac{dV}{dt} = KI^{\alpha}, \quad (4)$$

where V is wear quantity; K is coefficient correlating with constriction resistance, melt and gasification latent heat. Obviously, K has some relationship with contacts material; I is arc current; α is current exponential, with value between 1 and 2.

If there is only metal bridge, the electric wear caused by metal bridge should be considered. If there is arc, the electric wear caused by arc should only be considered as the wear resulted from bridge transfer is far less than that resulted from arc.

To carry out reliability design considering electric wear, firstly, electric wear extent corresponding to certain life of relay should be calculated through the equation for electric wear quantity of bridge transfer or arc transfer. Then variety of over travel can be obtained according to this value and size of relay contacts. Finally verify whether the relay can operate properly or not through the dynamic characteristics of electromagnetic force and spring force, and direct reliability tolerance design of over travel.

External interference

External interference is the influence of the outside environment on the relay, and includes vibration, impulsion, acceleration, ambient temperature, etc. Among these factors, impact of ambient temperature on movement characteristics is mainly shown by coil. The change of temperature will induce varying coil resistance, and moreover, affect electromagnetic force. Relay designers should design coil of relay based on Eq.(5) considering temperature range of the relay's future working environment:

$$R_t = R_0 + \alpha(t - t_0), \quad (5)$$

where α is temperature coefficient of coil wire (e.g. for copper wire, α=0.0043); R_0 is resistance when temperature is t_0; R_t is resistance when temperature is t.

Besides temperature, vibration, shock and acceleration can also influence the relay characteristics a lot. These three disturbing factors will mostly result in the change of contacts position, which cannot ensure steady signal transmission and lead to the relay's failure. Thus during reliability design considering the above mentioned three factors, firstly, the movement law of moving contact should be researched corresponding to certain vibration environment (or shock/acceleration environment). Then, examine whether the position change is within the permitted range or not, and construct tolerance design of springs and over travel in relay spring system.

DYNAMIC RELIABILITY TOLERANCE DESIGN UNDER THREE KINDS OF DISTURBING FACTORS

After parameter design, central values of relay parameters will be determined. Dynamic relay characteristics correspond exclusively to a design scheme. However, the dynamic characteristics of electromagnetic force and spring force apparently have certain distribution characteristics because the relay is affected by disturbing factors. As a result, the cooperation of relay dynamic characteristic is the cooperation of two distributions, which are the dynamic electromagnetic force distribution and dynamic spring force distribution. In other words, the relationship between dynamic electromagnetic force distribution and dynamic spring force distribution should be studied during the reliability design of relay taking disturbing factors into account. Suppose dynamic electromagnetic force and dynamic spring force are represented by c and s, and probability density function are $f(c)$ and $f(s)$, as shown in Fig.3. Pick-up reliability is:

$$R = P(c > s) = p[(c - s) > 0]. \quad (6)$$

The probability that electromagnetic force is greater than spring force should be:

$$P(c > s_0) = \int_{s_0}^{\infty} f(c)\mathrm{d}c. \quad (7)$$

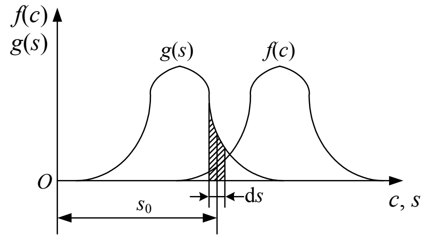

Fig.3 Distributions of electromagnetic force and spring force characteristics

The probability of spring force in ds interval is:

$$P\left(s_0 - \frac{\mathrm{d}s}{2} \le s \le s_0 + \frac{\mathrm{d}s}{2}\right) = g(s_0)\mathrm{d}s. \quad (8)$$

When c and s are stochastic variables independent of each other, the probability of the event (electromagnetic force greater than a certain spring force and spring force is in interval of ds) occurred is:

$$g(s_0)\mathrm{d}s\int_{s_0}^{\infty} f(c)\mathrm{d}c. \quad (9)$$

By calculating integral of all these possible spring force, the pick-up reliability of electromagnetic relay is:

$$R = P(c > s) = \int_{-\infty}^{\infty}\left[\int_{s}^{\infty} f(c)\mathrm{d}c\right]g(s)\mathrm{d}s. \quad (10)$$

Similarly, drop-out reliability of relay also can be worked out. Designers can use these mathematical models to estimate the reliability of designed electromagnetic relay, and get some useful design guidelines.

CONCLUSION

With influence of disturbing factors, the quality of a batch of electromagnetic relays presents certain distribution characteristics. Based on dynamic characteristics, dynamic reliability tolerance design technology of electromagnetic relay was discussed in this paper.

(1) For machining dispersion, this paper adopted Monte Carlo random simulation method to determine the distribution of dynamic characteristics.

(2) The reliability tolerance design method and correlated research content of electromagnetic relay were discussed considering internal interference (contact wear and aging) and external interference (vibration, shock, acceleration and ambient temperature).

(3) A series of mathematical models that can analyze the relationship between dynamic electromagnetic force characteristics and dynamic spring force characteristics were presented here. The reliability of electromagnetic relay can be calculated based on these models.

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