Consistent robust design of bistable crystal cover relay

Liang Huimin¹, Zhu Xuqing¹,Deng Jie¹,Tang Wei¹ and Chen Hao¹

¹School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin, China
E-mail:hitzhuxuqing@163.com

Abstract. Bistable crystal cover relays are widely used in aerospace and other electronic systems due to their outstanding resistance to mechanical environment. However, the bistable crystal cover relays have a complicated structure and are difficult to design and debug. There are still quality problems in this kind of relay such as low electromagnetic efficiency, small commissioning margin and large product dispersion. This paper aims at solving the problems of poor anti-interference of output characteristics caused by the imperfection of the reliability design. The finite element model of the electromagnetic system of the relay was established by using FLUX software and the electromagnetic characteristics of the relay were simulated and analyzed firstly. By comparing with the actual measurement, verified the correctness of the simulation results and guaranteed the accurate calculation of the experimental research. On the basis, this paper adopts the robust design method proposed by Taguchi Genichi to optimize the product parameters and tolerances of the relays. At present, the research conclusion is applied to the improvement of a certain type of aerospace electromagnetic relay. This paper provides necessary research means and basis for the robustness design of aerospace electromagnetic relay. The related methods and technologies can also be applied to the design of other electrical products.

1. Introduction

The indicators of a single aerospace relays product in China can meet or even surpass similar foreign products. However, the quality of the entire batch of products has dropped due to the dispersion of product quality, it may even lead to batches becoming obsolete. Product dispersion issues have become key factors that lead to poor reliability and low precision of weapons and equipment [1-2].

The margin design method is usually used to determine the tolerance in the design of bistable crystal cover relay products [3]. As the parameter tolerance decreases, the quality consistency will improve accordingly. However, if the production link is not a key link that has a significant impact on consistency and with a large input cost increase, the effect received is very limited. Due to the inability to determine key design parameters (including processing parameters and debugging parameters) and their tolerances that have a significant impact on product consistency. It is impossible to determine the appropriate manufacturing level for each process during the manufacturing process. In addition, it is impossible to determine which process is needed to design tools to assist debugging, so the level of key processes in the batch production process cannot meet the requirements of reliability and consistency [4].

This paper takes a certain type of bistable crystal cover relay as the research object and adopts robust design method [5-7] to carry out consistent optimization design of its suction characteristics to improve the consistency and stability of static output characteristics of batch relay products. The key design parameters that affect the electromagnetic attraction of relays are determined through parameter design
and their performance indicators are improved\cite{8-9}. Tolerance design is used to determine the significant degree of influence of parameter fluctuations on output consistency. According to the requirements of consistent design, appropriate tolerances are allocated for key design parameters which have a significant impact, so that the specifications of each process are specified during the product manufacturing process \cite{10-13}. The commissioning margin of relay products is increased by the above design and the production qualification rate and application reliability of batch products are improved. The optimal design of the suction force characteristic is a common problem of electromagnetic relays and the completion of this article has general reference and guiding significance for the solution of the above problems.

2. Establishment of simulation model

The electromagnetic system components of this type of relay include armature, yoke, magnetic steel, coil, and S-N-S permanent magnet, the structure is shown in Figure 1. The working principle of its electromagnetic system is as follows: when the coil is not energized, the permanent magnetic flux passes through the small air gap and the relay armature is maintained. When the left (right) coil is pulsed, a magnetic flux in a direction different from that of the permanent magnet will be generated at the air gap to switch the armature.

![Figure 1. Electromagnetic system structure.](image1)

![Figure 2. Electromagnetic system model.](image2)

The analysis of the relay electromagnetic system is mainly carried out by simulation of the electromagnetic system in FLUX software. The model of the relay electromagnetic system as shown in Figure 2 is based on the bluprints and actual product measured values. The electromagnetic suction under different voltages is simulated as shown in Figure 3. It can be seen from Figure 3 that the calculated results are in good agreement with the measured results. The maximum deviation at the initial position of 8V and the right-hand end of the 13V is only 6.7%.

![Figure 3. Simulation and comparison results.](image3)
3. Optimized design of relay parameters

Due to the suboptimal design of the electromagnetic system parameters and magnetic saturation problems in the magnetic circuit, there is insufficient design margin for electromagnetic suction in this type of relay, which causes a contradiction between the operating voltage and the vibration resistance index. This section takes the electromagnetic system model established in section 2 for simulation, the matching characteristics of the suction and reaction forces of the relay are shown in Figure 4.

![Figure 4. Matching of the suction force of the original scheme.](image)

It can be seen from the matching curve of the suction of the original scheme that the 13V electromagnetic suction at the initial position is significantly smaller than the reaction force, resulting in a higher operating voltage of the original product. If the reaction force is debugged with the target of 13V electromagnetic suction value, it will cause a small magnetic holding force and affect the anti-vibration performance of the product. Therefore, this paper optimizes the overall electromagnetic system, analyzes the parameters that significantly affect the operating voltage of the electromagnetic relay, determines the key design parameters of the electromagnetic system and uses the inner and outer orthogonal table direct product method to arrange the test to obtain the signal-to-noise of each key parameter. Then take the ratio and sensitivity to determine the optimal level of the electromagnetic system combination and verify the parameter design results experimentally. At last, the goals of improving the coil driving ability and reducing the operating voltage are achieved under the condition of maintaining or increasing the magnetic holding force.

3.1. Determination of key factors and optimal levels

In order to determine the key parameters that have a significant impact on electromagnetic suction, perform a single factor analysis on the size parameters of the electromagnetic system and give the amount of parameter changes in the single factor firstly, when the voltage of the coil is 0V, observe the effect of the parameter changes on the suction. It can be obtained that the key parameters that have a large impact on the electromagnetic attraction of the electromagnetic system are the yoke length, yoke thickness, armature length, armature width, armature step length, armature step height, permanent magnet size, and core radius.

| Parameters                | Contribution rate |
|---------------------------|-------------------|
| Armature step height      | 35.79%            |
| Armature width            | 17.85%            |
| Permanent magnet length   | 0.70%             |
| Permanent magnet width    | 20.20%            |
| Permanent magnet thickness| 19.38%            |
| Core radius               | 4.70%             |

Secondly, based on the simulation results of the single factor analysis, design the orthogonal
experiment and simulation analysis of key parameters of the electromagnetic system. There are 6 test factors which are armature step height, armature width, permanent magnet length, permanent magnet width, permanent magnet thickness, and core radius.

The electromagnetic system simulation model was used to simulate the electromagnetic suction of each group of test schemes with 0V initial electromagnetic suction as the objective function. Then use the contribution rate analysis method to calculate the contribution rate of each parameter to the electromagnetic attraction, as shown in Table 1.

From the results of contribution rate, it can be seen that the parameters with higher contribution rate of the electromagnetic system are the armature step height, the armature width, and the width and thickness of the permanent magnet. The internal and external direct product method was used to simulate the selected key parameters and analyze the signal-to-noise ratio (SNR) to find the optimal level combination that maximizes the SNR, that is, the best stability. The results are shown in Table 2. It can be known from Table 2 that the SNR of Test No. 9 is the largest, and the corresponding parameter values are the optimal level combinations.

| Test No. | Armature step height (mm) | Armature width (mm) | Permanent magnet thickness (mm) | Permanent magnet width (mm) | SNR     | Sensitivity |
|----------|--------------------------|---------------------|--------------------------------|---------------------------|---------|-------------|
| 1        | 0.47                     | 2.96                | 1.68                           | 3.82                      | 19.3602 | -7.1446     |
| 2        | 0.47                     | 3.7                 | 1.8                            | 4.1                       | 14.8849 | 3.26344     |
| 3        | 0.47                     | 4.44                | 1.92                           | 4.38                      | 17.3904 | 7.52119     |
| 4        | 0.57                     | 2.96                | 1.92                           | 4.1                       | 16.23   | 0.47132     |
| 5        | 0.57                     | 3.7                 | 1.68                           | 4.38                      | 18.5732 | 2.3165      |
| 6        | 0.57                     | 4.44                | 1.8                            | 3.82                      | 16.5125 | 4.74093     |
| 7        | 0.67                     | 2.96                | 1.8                            | 4.38                      | 20.6752 | 2.88224     |
| 8        | 0.67                     | 3.7                 | 1.92                           | 3.82                      | 17.31   | -0.5397     |
| 9        | 0.67                     | 4.44                | 1.68                           | 4.1                       | 20.8807 | 1.72314     |

3.2. Optimization verification
The final scheme determined through parameter design is: the armature step is thickened by 0.2mm, the armature width is widened by 0.7mm and the permanent magnet thickness is reduced by 0.2mm. The verification results are shown in Figure 5.
Comparing the suction and reaction curve matching diagrams obtained from the optimized solution simulation with those before optimization, it can be clearly seen that the electromagnetic suction at 13V voltage has increased and there is no intersection between the suction and reaction curves at 0V. The median problem has been significantly improved, therefore the optimization scheme is feasible and effective.

4. Relay robustness tolerance design

The main idea of tolerance design is that considering whether it is necessary to give a small tolerance to the parameter with a large impact from an economic point of view according to the contribution of various parameters to the product quality characteristics.

Suppose the production cost of a product is $P$ and its quality loss is $L$, then the total loss is

$$L_T = P + L$$  \hspace{1cm} (1)

The goal of tolerance design is to make the total loss $L_T$ be minimized and find the best solution for tolerance design. The contribution rate analysis method is an important method for processing data during the tolerance design process. Parameters that have a significant effect on the dispersion of the objective function can be obtained through statistical analysis of the test results and then get the change in the dispersion of the objective function when the tolerances of each parameter are changed individually or simultaneously.

Variance is a parameter used to measure the degree of deviation between a random variable and its mathematical expectation (the mean). In the robustness design method, Taguchi Genichi uses the variance $V$ to describe the degree of dispersion of the output characteristic $y$. The smaller the variance, the higher the concentration of the output characteristics of a batch of products.

$$V_T = \frac{1}{n} \sum_{i=1}^{n} (y_i - m)^2$$ \hspace{1cm} (2)

$$\bar{L} = \frac{A}{\Delta^2} V_T$$ \hspace{1cm} (3)

In the equation above, $m$ is the target value of the output characteristic and $y$ is equal to the average value of the output characteristic. $A$ is the loss of non-conforming product and $\Delta$ is the parameter tolerance value.

When the tolerance $\Delta_i$ of the test factor $X_i$ changes to $\Delta_i'$, the variance value reflecting the degree of dispersion of the output becomes

$$V_n = \delta V_T$$ \hspace{1cm} (4)

The new average mass loss becomes

$$\bar{L}_N = \delta \bar{L}$$ \hspace{1cm} (5)

We can get the relation describing the change in the degree of dispersion of the output characteristics when the tolerance of the test factors changes by analyzing the contribution rate of the test results, that is shown in the tolerance design equation (6).

$$\delta = \sum_{i=1}^{n} \left( \rho_{X_i} \left( \frac{\Delta_i}{\Delta_i'} \right)^2 + \rho_{X_i q} \left( \frac{\Delta_i}{\Delta_i'} \right)^4 \right) + \rho_e$$ \hspace{1cm} (6)

$\rho_{X_i}$ represents the first-order contribution rate of the factor $X_i$, $\rho_{X_i q}$ represents the quadratic term contribution rate of the factor $X_i$, and $\rho_e$ is the error term contribution rate.

Similar to the parametric design, the tolerance design of this relay product is the process of seeking the best design solution by designing experiments. Firstly, arrange experiments and use the contribution rate analysis method to find parameters that contribute to product quality characteristics significantly, then analyze the changes of loss function tolerance changes and carry out changes with production costs. At last, determine a production scheme that minimizes the total product loss (the sum of quality loss and product cost), evaluate the existing tolerance allocation method and give an improved design scheme.
4.1. Experiment design and simulation analysis

According to the conclusions in the design of the key parameters of the electromagnetic system, the armature step height, armature width, permanent magnet thickness and permanent magnet width were initially determined as the key parameters. When designing tolerances, take the center value of the actual product due to the differences in actual production technology. In addition, some assembly parameters and other uncontrollable factors such as the armature left and right position, armature front and back position, yoke parallelism and permanent magnet installation level, Br value of the starting point of the permanent magnet and armature copper plating thickness are also considered in the tolerance design. Take the parameters below as the error factors: the level of permanent magnet installation, the left and right positions of the armature, the front and rear positions of the armature, the parallelism of the yoke, the Br value of the starting point of the permanent magnet, the copper plating thickness of the armature, the armature width, the armature step height, the permanent magnet width and the permanent magnet thickness. For the above 10 error term factors, the central value and the upper and lower limits of the design tolerance fluctuation are taken as the horizontal values, and the horizontal value is assigned to each error factor according to equation (7).

\[
\begin{align*}
\text{Level 1} & = m_i - \Delta_i \\
\text{Level 2} & = m_i \\
\text{Level 3} & = m_i + \Delta_i
\end{align*}
\]  

(7)

Table 3. Table of error factor levels.

| Level | A(mm) | B(mm) | C(mm) | D(mm) | E(T)  |
|-------|-------|-------|-------|-------|-------|
| 1     | -0.065| -0.1  | -0.075| -0.1  | 0.72  |
| 2     | 0     | 0     | 0     | 0     | 0.74  |
| 3     | 0.065 | 0.1   | 0.075 | 0.1   | 0.76  |

| Level | F(mm) | G(mm) | H(mm) | I(mm) | J(mm) |
|-------|-------|-------|-------|-------|-------|
| 1     | 0.008 | 3.6625| 0.55  | 4.0625| 1.77  |
| 2     | 0.009 | 3.7   | 0.57  | 4.1   | 1.8   |
| 3     | 0.01  | 3.7375| 0.59  | 4.1375| 1.83  |

Select the orthogonal table regardless of the interaction between the factors and proceed 27 experiments, take the quality of magnetism holding force and median margin as objective functions. Then compare the results of electromagnetic suction with the matching reaction force curve of each tolerance scheme simulation. Analyze the contribution rate of the magnetic holding force and the median margin according to the objective function, as it is shown at Table 4 and Table 5. From the analysis results, it can be concluded that the parameters which have a greater effect on the magnetic holding force are the permanent magnet installation position and the armature front and rear position. The influence of other factors is compressed for their large contribution rate, so remove them temporarily and calculate the contribution rate again, filter out the key parameters: the armature left-right position and the yoke parallelism. And so on, remove the thickness of the permanent magnet and the front and rear positions of the armature and filter out the two key parameters of yoke parallelism and left and right position of the armature from the Table 5.

It can be concluded that the thickness of the permanent magnet has a slight effect on the median problem, changing the tolerance of the parameters of the electromagnetic system has little effect on the two objective functions and the assembly parameters have a greater effect on the objective function. According to the analysis results of the contribution rate of each objective function, the tolerance design formula corresponding to each objective function can be obtained by bringing the contribution coefficient \( \rho\% \) into equation (8). Allocate the tolerances of the key parameters with the goal of reducing the consistency to 50% after the optimization.
Table 4. Analysis of the magnetic retention force contribution rate.

|        | Freedom | Variance        | fluctuation $S'$ | Contribution rate /% |
|--------|---------|-----------------|------------------|----------------------|
| m      | 1       | -               | -                | -                    |
| $A_i$  | 1       | 5.11888E-08     | 4.89671E-08      | 0.00155778           |
| $A_q$  | 1       | 1.88716E-07     | 1.86494E-07      | 0.00593289           |
| $B_i^\Delta$ | 1 | -               | -                | -                    |
| $B_q$  | 1       | 3.18325E-07     | 3.16104E-07      | 0.0100561            |
| $C_i$  | 1       | 4.23299E-07     | 4.21077E-07      | 0.0133956            |
| $C_q^\Delta$ | 1 | -               | -                | -                    |
| $D_i$  | 1       | 2.26156E-07     | 2.23934E-07      | 0.00712395           |
| $D_q$  | 1       | 8.2821E-07      | 8.25989E-07      | 0.026277             |
| $E_i$  | 1       | 7.68652E-07     | 7.6643E-07       | 0.0243822            |
| $E_q$  | 1       | 1.41119E-07     | 1.38897E-07      | 0.00441869           |
| $F_i$  | 1       | 4.8906E-07      | 4.86838E-07      | 0.0154877            |
| $F_q$  | 1       | 8.24351E-07     | 8.22129E-07      | 0.0261542            |
| $G_i$  | 1       | 6.00041E-08     | 5.77824E-08      | 0.00183821           |
| $G_q$  | 1       | 3.2749E-07      | 3.25268E-07      | 0.0103477            |
| $H_i$  | 1       | 1.35454E-07     | 1.33233E-07      | 0.00423849           |
| $H_q$  | 1       | 3.2749E-07      | 3.25268E-07      | 0.0105065            |
| $I_i$  | 1       | 4.43322E-08     | 4.21104E-08      | 0.00133965           |
| $I_q$  | 1       | 7.72972E-07     | 7.7075E-07       | 0.0245197            |
| $J_i$  | 1       | 1.33808E-05     | 1.33785E-05      | 0.425608             |
| $J_q^\Delta$ | 1 | -               | -                | -                    |
| $K_i$  | 1       | 1.31657E-06     | 1.31435E-06      | 0.0418132            |
| $K_q^\Delta$ | 1 | -               | -                | -                    |
| $L_i$  | 1       | 8.85708E-06     | 8.85486E-06      | 0.281697             |
| $L_q$  | 1       | 2.16486E-07     | 2.14264E-07      | 0.00681633           |
| $M_i$  | 1       | 5.44329E-07     | 5.42107E-07      | 0.0172459            |
| $M_q$  | 1       | 1.1758E-06      | 1.17358E-06      | 0.0373348            |
| $e$    | 27      | 1.16422E-06     | 3.1434E-05       | 1                    |

$^\Delta$ is a minor term and is incorporated into the error term.
Table 5. Analysis of the contribution ratio of the median margin.

| Freedom | Variance | fluctuation S' | Contribution rate /% |
|---------|----------|----------------|----------------------|
| m       | 1        | -              | -                    |
| A_q     | 1        | 1.04702E-05    | 1.04655E-05          | 0.121268   |
| B_q     | 1        | 1.09506E-06    | 1.09035E-06          | 0.0126344 |
| C_q     | 1        | 1.05115E-06    | 1.04645E-06          | 0.0121257 |
| D_q     | 1        | 2.1347E-07     | 2.08766E-06          | 0.00241907|
| E_q     | 1        | 3.91954E-07    | 3.8725E-07           | 0.00448724|
| F_q     | 1        | 3.88227E-07    | 3.83524E-07          | 0.00444406|
| G_q     | 1        | 8.35451E-08    | 7.88414E-08          | 0.00091357|
| H_q     | 1        | 1.28198E-07    | 1.23494E-07          | 0.00664359|
| I_q     | 1        | 5.25723E-07    | 5.21019E-07          | 0.00603728|
| J_q     | 1        | 3.88227E-07    | 3.83524E-07          | 0.00444406|
| K_q     | 1        | 4.21117E-07    | 4.16414E-07          | 0.00482517|
| L_q     | 1        | 3.09961E-07    | 3.05258E-07          | 0.00353716|
| M_q     | 1        | 1.88698E-06    | 1.88227E-06          | 0.0218107 |
| N_q     | 1        | 5.79994E-07    | 5.75291E-07          | 0.00666615|
| O_q     | 1        | 2.38384E-06    | 2.37913E-06          | 0.0275681 |
| P_q     | 1        | 5.19224E-07    | 5.1452E-07           | 0.00596197|
| Q_q     | 1        | 5.3297E-05     | 5.32923E-05          | 0.617521  |
| R_q     | 1        | 1.36575E-07    | 1.31871E-07          | 0.00152805|
| S_q     | 1        | 3.25236E-06    | 3.24765E-06          | 0.037632  |
| T_q     | 1        | 7.06718E-06    | 7.06248E-06          | 0.0818361 |
| e       | 6        | 4.70367E-09    | 1.26999E-07          | 0.00147159|
| T       | 27       | 3.19631E-06    | 8.630003E-05         | 1         |

\(\Delta\) is a minor term and is incorporated into the error term.
According to the current product measurement, if the left and right positions of the armature take the threshold of 0.005mm, the pass rate is 81%. In the initial tolerance process, the given tolerance is ±0.045mm, which is much larger than the actual measurement. When consider the cost issues, the tolerance is still taken as ±0.005mm. The yoke parallelism tolerance of the measured product is ±0.1mm, which is much larger than the tolerance given in the process of tolerance design, and the given tolerance in the improvement scheme is ±0.02mm. The armature cooperates with the small shaft, the process size of the small shaft and the armature affects the front and rear positions of the armature. The inner and outer diameter drawing tolerances of the small shaft are ±0.005mm. From the actual measurement results, the fluctuation range of the small axis is ±0.01mm, the fluctuation range of the armature step height is ±0.05mm and the fluctuation range of the armature front and rear positions is ±0.065mm, which is the same as the expected tolerance value under the overall cooperation. So decrease the fluctuation range of small axis coaxiality and armature step height as ±0.04mm. The permanent magnet is installed on the skeleton and the gap is too small, the actual distance is measured by plugging the gap into the gap to estimate the distance. So there is no measured distribution, assign the tolerance of ±0.03mm instead of tolerance of ±0.05mm in the improvement plan.

Table 6. Result of improved tolerance on consistency of objective function.

| Left and right position of the armature | Yoke parallelism | Front and rear position of the armature | Position of permanent magnet |
|----------------------------------------|-----------------|----------------------------------------|-----------------------------|
| Original tolerance (mm)                | 0.005           | 0.1                                    | 0.065                       | 0.05                        |
| Improved tolerance (mm)                | 0.005           | 0.02                                   | 0.04                        | 0.03                        |
| Magnetic force $\delta$               | 50.18%          |                                        |                             |                             |
| Median margin $\delta$                | 49.68%          |                                        |                             |                             |

Substitute the allocation scheme into equation (8) to get the consistency after optimization. It can be seen in Table 6 that the goal of consistency optimization is achieved through tolerance improvement.

5. Conclusion
This paper establishes a finite element simulation model of the relay electromagnetic system and compares the simulation results with the actual measurement to verify the correctness of the model. At the same time, it provides a guarantee for the accurate calculation of the electromagnetic system experimental research.

Determines the operating voltage and magnetic holding force as the objective functions of the study by analyzing the key parameters with significant effect on the pull-in voltage of the relay. Determines the key design parameters of the electromagnetic system by analyzing the influence of various design parameters of the electromagnetic system on the objective function. Obtains the optimized scheme of parameter design through the single-factor sequential optimization process of key parameters, and compares with the original scheme, the pull-in voltage decreased significantly, and theoretically could be reduced from 13.5V to 9.3V. It can be improved theoretically by 17.43% compared with the original
scheme. Finally, it is concluded that the optimization scheme meets the requirements of parameter design, which is consistent with the actual production situation.

Determines the magnetic holding force and the median margin as the objective function of the tolerance design, and optimized the electromagnatic system and consistency. Obtains the tolerance design formula of the electromagnetic relay based on the orthogonal test design and contribution rate analysis method, and achieves the quantitative allocation of the electromagnatic system. The optimized consistency $\delta$ is successfully reduced to 50% of the original and improves the product consistency effectively.

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