Analysis of the anti-vibration qualified rate of relay considering manual debugging process

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Abstract. As an important switching device, the relay’s mechanical resistance has been receiving much attention. However, the manual debugging process has an important impact on it. This article starts with the analysis of manual debugging factors that affect the anti-vibration qualification rate. The quality characteristic parameters of the debugging process and their thresholds that affect its anti-vibration qualification rate are obtained by designing contrast tests. Secondly, the object’s qualitative characteristic parameters and debugging parameters are constructed by an approximate calculation model based on the virtual prototype. Finally, the impact of manual debugging process on product quality characteristics is analyzed. And suggestions on the parameters to be controlled by manual debugging are given. The adjustors strictly control the parameters of the debugging process according to the above suggestions. And the current qualification rate of the product has been greatly improved. It shows that the research on the manual debugging process based on the anti-vibration qualification rate is great significant.

1. Introduction
Electromagnetic relay is a basic component with important functions such as circuit regulation, circuit protection and circuit conversion. Electromagnetic relays are widely used in daily household appliances, industrial control circuits, and Aerospace because of its good versatility, high stability, long life, small size, high conversion depth, strong anti-interference ability and low price.

With the booming development of the relay industry, relay products are also continuously developing towards high reliability, high sensitivity and miniaturization\cite{1}. The antivibration ability is an important index for evaluating its mechanical resistance and affecting the quality of the product. There are various failure modes of relays. Also the failure mechanisms and causes are different. However, contact failure is the most common failure mode of relays, accounting for more than 80\% of the total failure modes. Therefore, good anti-vibration performance is great significant strategically for the normal operation of the relay and the reliable operation of the system chain.

However, due to the backward development of China’s relay industry and the lack of relevant research and development theories, the assembly process is mainly based on fixtures that workers made according to their experience\cite{2-3}. The important debugging process mainly depends on manual debugging. Because human beings are affected by physical, psychological, and...
environmental factors. And they have very great uncertainty. And the occurrence of human errors is strictly necessary. In engineering practice, especially for those industrial departments that require high reliability and safety, human error can induce very serious consequences. According to statistics, more than 60% various types of accidents occurring at internal and abroad are related to human error each year. And the proportion of major disasters caused by them is more than 80%, which may become higher in the future. The proportion of accidents caused by human errors is higher in nuclear power plants, aerospace, petrochemical and other fields that are high-risk and complicated. In the nuclear industry, 70%-90% of accidents are due to human error. In the field of aerospace, human-related accidents account for more than 90% [4-10]. Many scholars have done a lot of research on human reliability. A case study in tanker shipping industry with 18 crew members is analyzed by a quantitative human reliability analysis (HRA) model based on fuzzy logic theory, Bayesian network, and cognitive reliability & error analysis method (CREAM) for the tanker shipping industry [11]. The LEC method is used to evaluate the human factor reliability of the assembly line production efficiency and its stability. And it is applied and verified to the automobile assembly line [12]. A modified CREAM is proposed to analyze the human reliability of risk events in space launch site [13]. A methodology for Dynamic Human Reliability Analysis in Robotic Surgery based on a modified version of human error assessment and reduction technique (HEART) integrated is proposed to analyze surgical procedures [14]. A methodology based on a hierarchical Bayesian network accounting for causal dependencies among environmental factors, human error modes, and scenario-based activities was developed to quantify the effect of harsh environmental conditions on the reliability of human actions in performing complex physical operations [15]. It can be seen that human reliability has an important impact on product quality for production process related human. During the manual debugging process of relay products, due to human uncertainty, the qualified product has a low anti-vibration qualification rate and poor quality.

Therefore, considering the impact of human uncertainty on the debugging parameters during manual debugging process is necessary. It is significant to find out the key manual debugging parameters that affect anti-vibration qualification rate, and control them to improve the vibration resistance of the product.

This article takes a relay as an object. First, it analyzes the quality characteristic parameters that affect the anti-vibration performance, and finds out its reasonable threshold through vibration experiments. Secondly, according to the fluctuations of the above debugging parameters, the virtual prototype technology is used to calculate the distribution of its quality characteristics parameters. The calculation of the anti-vibration qualification rate is completed with its threshold value. Finally, combined with the actual manual debugging process, the impact of manual debugging on the above debugging parameters is analyzed.

2. Analyze cause of relay vibration failure
The research object of this paper is a 1.5 cubic inch sealed DC power relay with a coil parameter of 28VDC/160Ω, 6 sets of transfer contacts. They are six normally open contacts (NO contact) and six normally closed contacts (NC contact). Vibration test requirements are sinusoidal vibration 10 ~ 3000Hz, 30g, random vibration 50 ~ 2000Hz, 0.4g^2/Hz. The vibration direction is shown in figure 1. At present, the vibration qualified rate of this product is only about 20%.
The matching of the relay's electromagnetic suction characteristic and reed force characteristic mainly depends on manual debugging. The debugging process is shown in figure 2. Suction force of the electromagnetic system is adjusted by manually magnetizing and demagnetizing. Reaction force of the contact spring system is adjusted by adjusting the position of the NC contact. The suction and the reaction force are continuously matched to complete the final debugging of the product. Therefore, the anti-vibration qualification rate of the product is very likely to be affected by the electromagnetic suction of the relay and the reaction force of the contact spring.

The following experiments are designed for electromagnetic suction and contact spring reaction force. The main factors affecting the contact jitter are the armature holding force and the contact pressure. The contact pressure of the original product is 600-800mN. Two relays numbered 062 and 090 are selected from the products with vibration failure in the factory. Keep the pull-in and releasing force of the 062 product unchanged. And only increases its contact pressure; Set the 090 contact pressure to be almost the same as 062. And reduce its pull-in force. The parameter settings are as follows table 1. The experimental results are shown in table 2.

![Figure 2. Manual debugging process](image)

**Table 1. Parameter settings of two products**

| Product number | 062 | 090 |
|----------------|-----|-----|
| Pull-in force/N | 5.4 | 4.3 |
| Releasing force/N | 3.6 | 3.8 |
| Contact pressure/mN | | |
| Number | NC | NO | NC | NO |
| 1 | 950 | 850 | 950 | 1000 |
| 2 | 1000 | 900 | 1000 | 1000 |
| 3 | 950 | 1000 | 1000 | 1000 |
| 4 | 950 | 1000 | 950 | 1000 |
| 5 | 1000 | 1000 | 1000 | 950 |
| 6 | 1000 | 950 | 950 | 1000 |
Table 2. Controlled test results of two products

| Product number | Test result                      |
|----------------|----------------------------------|
| 062            | No failure                       |
| 090            | Random vibration, X direction, 2,4,5,6 NO contacts shake off |

It can be known from the above results that increasing the contact pressure has a better effect on improving the anti-vibration ability. The pull-in force of the armature is an important factor affecting its anti-vibration ability. The factors that affect the anti-vibration qualification rate of the product are the pull-in force and the contact pressure.

The five products are set gradients on their contact pressure and the pull-in force in order to find their reasonable thresholds. The parameter settings are shown in the table 4. The experimental results are shown in table 3. Experimental results show that the contact pressure of the failing contacts is small (600 ~ 800mN). With the exception of No. 9 random vibration failure of all products, it was found that its pull-in force was the largest (5.6N).

From the above experimental results, it is known that the pull-in force threshold of the relay is 5.6N, the suction threshold of the electromagnetic system is 11N. The releasing force threshold of the relay is 3N, the realeasing suction threshold of the electromagnetic system is 9N. The normally open contact pressure threshold is 1000mN. And the normally closed contact pressure threshold is 850mN. The threshold of NO spring reaction force is 5.5N.

Table 3. Controlled test results of five products

| Product number | Experimental result                      |
|----------------|------------------------------------------|
| 1              | Random vibration, X direction, 6 NO contacts shake off |
| 2              | Random vibration, X direction, 5 NO contacts shake off |
| 3              | Random vibration, X direction, 2,3 NO contacts shake off |
| 4              | Random vibration, X direction, 2,3,4,5,6 NO contacts shake off |
| 5              | No failure                                |

Table 4. Parameter settings of five products

| Product number | Contact pressure/mN | Releasing force/N | Pull-in force/N |
|----------------|--------------------|------------------|-----------------|
| Number         | NC     | NO     | NC     | NO    | NC    | NO    | NC    | NO    |
| 1              | 1000   | 900    | 1000   | 900   | 950   | 900   | 750   | 700   | 750   | 750   |
| 2              | 600    | 850    | 800    | 1000  | 900   | 800   | 950   | 700   | 750   | 850   |
| 3              | 1050   | 700    | 900    | 900   | 1100  | 800   | 750   | 600   | 950   | 600   |
| 4              | 750    | 850    | 850    | 800   | 850   | 800   | 750   | 950   | 750   | 600   |
| 5              | 900    | 750    | 800    | 600   | 850   | 800   | 750   | 950   | 1000  | 600   |
| 6              | 750    | 700    | 800    | 850   | 750   | 700   | 850   | 1000  | 750   | 700   |

3. Calculation of qualified rate of anti-vibration based on quality characteristics of debugging process

The relay anti-vibration qualification rate calculation needs to considers the controlled quality characteristics of the manual debugging process. The quality characteristic threshold obtained above
is a standard. And an approximate calculation model based on a virtual prototype is established. Firstly, a three-dimensional geometric model of the product based on the measurement is built. Then use software of finite element analysis to construct a finite element electromagnetic model to simulate electromagnetic force, and use adams software to construct a reed system model to simulate spring force. Secondly, according to the fluctuation range of key parameters, sampled-data is obtained. And it is brought into the simulation model to calculate the corresponding output parameters. Quick calculation model of quality characteristics based on kring approximation method is built. Finally, according to the manufacturing process parameters, virtual product samples are generated by the Monte Carlo method. And virtual product samples are brought into quick calculation model of quality characteristics to complete the calculation of the qualification rate of vibration resistance. The calculation flowchart is as follows Figure 3.

3.1. Establish virtual prototype
First, the three-dimensional geometric model of the product is established based on the actual measured values of component parts. Then the electromagnetic system and the contact spring system are imported into the finite element software and adams software to establish the electromagnetic force model and spring force model. Finally, the obtained electromagnetic and contact spring force model is verified to obtain a virtual prototype of the product. It is shown in figure 4, figure 5.

Figure 3. Calculation process of anti-vibration qualification rate.

Figure 4. Finite element electromagnetic model.
Figure 5. Multi-flexible contact spring system model.

According to the test data in the production process, the model is revised. The comparison between the simulation results and the actual measurement results is shown in the table. The maximum error is less than 8%. They are shown in Table 5 and Figure 6.

Table 5. Simulation and test electromagnetic torque comparison

| voltage/V | 0   | 8   | 16  | 28  |
|-----------|-----|-----|-----|-----|
| Tested torque/ N • m | 0.092 | 0.081 | 0.034 | 0.022 |
| Simulated torque/ N • m | 0.091 | 0.087 | 0.033 | 0.023 |
| error     | 0.9% | 6.8% | 1.2% | 4.0% |

Figure 6. Comparison of reaction force between simulation and test.

3.2. Prepare approximate model sample points

According to the above analysis, the product suction is adjusted by magnetizing and demagnetizing in the manual debugging process. The contact pressure is adjusted to adjust the reaction force by adjusting the NC contact. And the reed is often affected during the debugging process, which affects the contact reeds. Thus, the input parameters are selected from the remanence, reed stiffness and contact pressure. Parameter fluctuation range is as follows Table 6.

Table 6. Range of approximate model parameters.

| Parameter name   | central value | Range            |
|------------------|---------------|------------------|
| pre-pressure/mN   | 750           | 600-1100         |
| young's modulus/Pa | 6.70E+10     | 5.36E+10~8.04E+10 |
| remanence/T       | 0.595         | 0.535~0.654      |
The accuracy of approximate modeling is affected by the selection of sample points. Uniformly distributed sample points can greatly improve the accuracy of the approximate model. The Latin hypercube sampling method can uniformly sample to ensure uniform sample points. This article uses this method to extract 90 sets of input parameter combination data from the above parameters. Then, they are brought into the simulation model to calculate the corresponding output parameters.

### 3.3. Establish and verify approximate models

A kriging approximate model can be established by using the kriging model toolbox of MATLAB. Then, 10 sets of test points were prepared. On the one hand, the test points were input into the model to obtain the output characteristics predicted by Kriging; on the other hand, the input parameters were simulated by the model. The comparison between the predicted value and the simulation value of the electromagnetic system is shown in figure 7. The maximum error of the model is 8.03%.

![Figure 7](image)

**Figure 7.** Precision verification of approximate model.

### 3.4. Calculate anti-vibration qualified rate

The process of establishing a batch of product virtual samples is as follows: First, according to the fluctuation range of the design parameters, Values that fit a normal distribution are randomly generated by central limit theorem for independent identically. Then the values of each design parameter are combined randomly to generate N groups of relay design solutions. The number of virtual samples of batch products N = 1000 is set. Design parameter values are only generated with 1
distribution characteristics according to the central value and fluctuation range of key design parameters. Then virtual samples are obtained by random combination. The virtual input parameters are input into the established approximate calculation model to obtain the calculation results of key output characteristics, thereby objectively and accurately obtaining the mass distribution characteristics of the relay batch products. The results are shown in table 7 and figure 8.

### Figure 8. Histogram of calculation results.

### Table 7. Results of quality characteristics.

| output parameter | threshold range/N | qualified rate/N | standard deviation/N |
|------------------|------------------|------------------|----------------------|
| Pull-in force    | [11, 13]         | 15.6%            | 2.29                 |
| Release force    | [9.0, 11.0]      | 35.8%            | 2.21                 |
| React force      | [5.5, 7.0]       | 9.20%            | 0.26                 |

4. Analyze human factor uncertainty

In the process of assembling the system, the operator's assembly reliability is affected by people themselves, assembly technology, organizational management, and production environment. The debugged quality characteristic parameters have unpredictable dispersion and randomness. Classical psychology believes that the human behavior mode is the SOR mode. It is shown in figure 9. When
the signal enters the brain, the neural center of the brain screens, combines and matches the incoming and outgoing information according to the inherent memory in the brain. The processed information is passed to the action module to form a response. In this process, it is susceptible to system limitations, external interference and its own psychological and physiological conditions. Then, errors occur. Errors are random and accidental, and cannot be accurately quantified, resulting in disqualification of quality characteristics during product commissioning. It leads to a low qualification rate of anti-vibration products.

![Block diagram of SOR mode](image)

*Figure 9. Block diagram of SOR mode*

The manual debugging process is a process in which suction and reaction forces match each other. Under the specified pull-in voltage and range of contact pressure, the manual debugging process of relay is completed by magnetization and demagnetization and contact pressure debugging. In this process, the assembly system has few restrictions on the operator. And the possibility of operator error will increase. During the debugging process, the parameters affect each other, causing further fluctuations in the quality parameters of the debugging product. It is shown in figure 10.

![Relationship between debugging parameters and quality characteristics](image)

*Figure 10. Relationship between debugging parameters and quality characteristics.*
It can be seen from the above figure that the pull-in voltage of the relay, the electromagnetic suction force and the reaction force of the contact spring are a contradiction. They often affect each other, and it is difficult to find a relatively great balance point among them. This further exacerbates the difficulty and uncertainty of manual debugging, which leads to increased dispersion of the quality characteristics of the product. As shown in Table 7, the standard deviation of 28V electromagnetic suction has reached 2.29N, and the pass rate is only 15.6%, which has become the main factor affecting the product’s vibration resistance qualified rate. The overall reaction force of the contact spring is relatively small, which is mainly due to the unreasonable matching made manually to obtain the pull-in voltage within the specified range, which is also an important reason for the low qualification rate of the product against vibration. The overall reaction force of the contact spring is small. In order to obtain the pull-in voltage within the specified range, adjustors’ unreasonable matching leads to this result. It is also an important reason for the low qualification rate of vibration resistance of the product.

According to the previous analysis, during the manual debugging process, the electromagnetic suction of the releasing and pull-in position should be strictly controlled in the magnetization/demagnetization link. In the process of debugging the contact spring system, the contact pressure and the holding force of the armature are controlled to ensure sufficient margin.

5. Conclusion
The mechanical resistance of the relay is an important indicator of the relay. The manual debugging during the manufacturing process has become an important factor affecting the mechanical resistance of the product. This article firstly finds out the quality characteristic parameters of the debugging process that affect the anti-vibration qualification rate. Then, through the approximate calculation method based on the virtual prototype, the relationship between the relay quality characteristic parameters of the debugging process and the debugging parameters is established. According to the fluctuation of the measured debugging parameters, the establishment of a virtual sample is completed, and the calculation of the anti-vibration qualification rate of the product is completed according to the above threshold. Finally, according to the above debugging parameters corresponding to the manual debugging link, the effect of adjustors on the quality characteristics that affect the anti-vibration qualification rate during the debugging process is analyzed. And the key debugging parameters that need to be controlled in the manual debugging project are given. It has reference significance for the vibration resistance analysis of relays with manual debugging. This has reference significance for the analysis of the other products’ quality influencing factors to find their key debugging parameters, which need manual debugging during their manufacturing process. In addition, the research and analysis of this article is directly connected to the debugging link of actual production, and the results of the research and analysis have an important role in improving the debugging process.

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