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Research on Coupling Vibration Mechanism Based on Contact System

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Research on Coupling Vibration Mechanism Based on Contact System

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Abstract: Aiming at the problem of vibration and bounce caused by the collision and contact of the moving and static contacts of the electrical switching device during the closing process, based on the comprehensive consideration of the nonlinear electromagnetic force and the collision contact force, the two-degree-of-freedom coupled motion differential equation of the contact system is established, and to solve and experimental analysis. The theoretical and experimental results show that the contact has not separated after the collision, and the iron core has collided, which further intensifies the contact bounce; when the iron core bounces for the second time, it does not affect the bounce of the contact; the contactor is in operation In this case, the movement of the moving iron core will cause slight jitter of the system. The research results provide a theoretical basis for further control and reduction of contact bounce.

Key words: Electrical switch • Contact bounce • Electromagnetic force • Collision contact • Two-degree-of-freedom coupled motion differential equation

1 Introduction

The contact system is an important component widely used in electrical switching devices. In fact, it is a kind of nonlinear vibration behavior, in which the collision bounce between the moving and static contacts is an important factor affecting its dynamic characteristics1-3. The small distance separation of the contact parts caused by the collision and bounce can easily lead to the generation of arcs. In severe cases, fusion bonding will occur, which directly affects the electrical contact performance and service life. Therefore, it is an urgent need to analyze the vibration mechanism accurately, grasp the dynamic characteristics change law, and obtain the theoretical method to effectively reduce and suppress the contact bounce, which is an urgent need to improve the electrical life and reliability of electrical components.

In recent years, domestic and foreign scholars have done a lot of useful work on the analysis of the dynamic process of the contact system. Regarding the establishment of the contact bounce model, JIN P6, used the equivalent magnetic circuit model to solve the coupling calculation problem of the magnetic field and mechanical motion generated by the electromagnetic and permanent magnets in the permanent magnet contactor, and deduced the coupling circuit model and the mechanical model Equation of motion. HE K H7, analyzed the bouncing of the contact when the contactor is connected, and then obtained the physical process model of the mechanical bounce of the contact, and established the energy balance equation before and after the contact collision. LIN S Y, et al8-9, used Cauchy’s stress equation to calculate the displacement after considering the collision and deformation. Through the law of conservation of momentum, the control equations of the moving parts of the AC contactor during the bounce process are obtained, and regarding the research on inhibition and reduction of contact bounce. XU Z H, et al10-12, proposed the structure of the unsynchronized contact system of the intelligent AC contactor, and studied the zero current breaking control. YANG W Y, et al13-17, based on the ANSYS finite element method, simulated the electromagnetic force during the closing process, and considered the influence of the magnetic ring and magnetic leakage. There are three main methods for measuring contact bounce. One is ZHANG D K18, designed a measuring device to record the bounce time; the other is that ZHOU L19, connected the moving and static contacts into a DC circuit to reflect the bounce of the contactor during the closing process by measuring the voltage change at both ends of the resistance in the circuit; and the last one is CHEN D W20, applied high-speed photography technology to set the first open phase and the non-first open phase on the side of the moving contact mark the point, get the contact bouncing by shooting to observe the displacement of the mark.

In summary, scholars at home and abroad have done some useful work on the research of the contact bounce characteristics, but a large amount of work is to analyze the dynamic characteristics of electromagnets through simple
coupled motion equations, circuit equation and magnetic circuit equation, and the vibration mechanism of contact bounce has not been studied\(^2\). Therefore, on the basis of the above research, this paper proposes to take the contactor as an example, take the mechanical vibration of the contact system as the entry point, establish a two-degree-of-freedom coupled motion differential equation based on the vibration characteristics, and use high-speed photography technology for experimental verification. It provides a theoretical reference for the optimal design of the contactor.

2 Working principle of AC contactor

The AC contactor is composed of three parts: contact system, electromagnetic system and contact bracket. It is shown in Figure 1.

![Figure 1](image1)

Figure 1 Configuration of the exoskeleton arm system

When the AC contactor is working, first energize the solenoid coil. When the electromagnetic force is greater than the force of the spring, the moving iron core makes the moving contact move downward through the contact bracket. Because the distance between the moving and static contacts is less than that between the moving and static cores, the moving contact will collide and bounce earlier than the moving iron core. At this time, the moving core continues to move downward until the static and moving cores collide, which makes the moving contact bounce again. Due to the collision between the moving and static iron cores, the movement process of the moving contacts that are already bouncing becomes more complicated. Therefore, how to accurately analyze the movement state and the bounce of the moving and static iron cores before and after collision is the key and difficult point in the research on the dynamic characteristics of the contactor.

3 Two-degree-of-freedom coupled motion differential equation

The nonlinearity and discontinuity of the AC contactor on and off make the dynamic characteristics of the AC contactor system appear abrupt change.

This paper assumes that: (1) The moving parts of the contactor can only move in one direction without displacement or rotation in the other direction; (2) The collision force between contactor parts is caused by local contact deformation, and is based on velocity and collision contact time are used as calculation parameters. Therefore, the piecewise model can be used to establish the piecewise linear vibration differential equation.

3.1 Model establishment

During the operation of AC contactor, it can be equivalent to a two-degree-of-freedom damped forced vibration system, as shown in Figure 2.

![Figure 2](image2)

Figure 2 Vibration model of AC contactor system

Where \( m_1 \) and \( m_2 \) are the mass of the moving iron core and moving contact; \( x_1 \) and \( x_2 \) are the length of the moving iron core and the displacement of the moving contact; \( c_1 \) and \( c_2 \) are the equivalent damping of the electromagnetic mechanism and contact system; \( k_1 \) and \( k_2 \) are the stiffness coefficients of the reaction spring and contact spring; \( F_s \) is the electromagnetic force; \( p_i \) and \( p_c \) are the contact force when the contact and core collide.

The closing motion process of the contactor can be divided into the following three stages: In the first stage, when the moving and static contacts have not yet collided and contacted; in the second stage, when the moving and static contacts have first collided and contacted, the moving and static iron cores have not yet collided, and the collision contact force between the moving and static contacts are considered; in the third stage, when the moving and static iron cores first collide, consider the moving and static iron core collision contact force. The differential equations of motion are:
3.2 Electromagnetic force

During the closing process of the AC contactor, the force of the moving contact and the moving iron core is simplified, $x_i$ and $x_c$ are the total stroke of the moving contact and the moving iron core respectively. The result is shown in Figure 3.

\[
\begin{align*}
    m_i x_i + c_i x_i + c_2 (x_i - x_2) + k_i x_i + k_2 (x_i - x_2) &= F_s, \\
    m_i x_i + c_1 x_i + c_2 (x_i - x_2) + k_i x_i + k_2 (x_i - x_2) &= F_s, \\
    m_i x_2 + c_1 x_2 + c_2 (x_2 - x_i) + k_2 (x_2 - x_i) &= -P_i \\
    m_i x_i + c_i x_i + c_1 (x_i - x_2) + k_i x_i + k_2 (x_i - x_2) &= F_s - P_i, \\
    m_i x_2 + c_2 (x_2 - x_i) + k_2 (x_2 - x_i) &= 0.
\end{align*}
\]

By combining formula (4) and formula (5), the electromagnetic force of the moving iron core can be solved.

3.3 Contact force

The contact belongs to an elastic body, so the collision will cause periodic bounce during the closing process. The physical process of the contact bounce is shown in Figure 4.

![Figure 4](image)

Figure 4 Model of contact bounce

Ignoring the mass of the spring, and $m_2$ is the mass of the moving contact. It can be seen from Figure 4 that the moving contact moves toward the static contact at the velocity of $v_1$.

If friction and medium resistance are ignored, the kinetic energy before the collision of the moving contact and the static contact is $1/2m_2v_1^2$. After the contact collision, the kinetic energy of the moving contact is converted into the potential energy of the deformation of the contact surface material (excluding friction). When the elastic deformation recovers, the contact will rebound, making the initial velocity of the moving contact's rebound become $v_{20}$, and the corresponding kinetic energy is $1/2m_2v_{20}^2$. Then the energy balance equation before and after contact collision is:

\[
\frac{1}{2}m_1v_1^2 = \frac{1}{2}m_2v_{20}^2 + K \frac{1}{2}m_2v_{10}^2.
\]

In this paper, the contact recovery coefficient is $K$.
According to the momentum theorem

\[ p_{t1} = m_2v_2 - m_1v_1, \]  

(7)

The contact time of the contact is \( t_1 \).
Similarly, the energy balance equation before and after the iron core collision is

\[ \frac{1}{2}m_1v_{12}^2 = \frac{1}{2}m_1v_{20}^2 + K^* \frac{1}{2}m_1v_1^*, \]

(8)

\[ p_{t1} = m_1v_{12}^* - m_1v_1^*, \]

(9)

The impact time of the iron core is \( t_2 \). The velocity of the moving iron core moving along the direction of the static iron core is \( v_1^* \). The initial speed of the reverse jump of the moving iron core is \( v_m^* \). The recovery coefficient of the core material is \( K^* \).

### 3.4 Two-degree-of-freedom coupled motion differential equation solution

In this paper, ABB A9-30-10 electromagnetic contactor is taken as an example, and parameter values at different stages are given in Table 1

#### Table 1 Parameter table of AC contactor

| Parameter name  | Parameter value |
|-----------------|-----------------|
| \( m_1(g) \)    | 200             |
| \( m_2(g) \)    | 2               |
| \( c_1(N\cdot s/\text{mm}) \) | 30             |
| \( c_2(N\cdot s/\text{mm}) \) | 4              |
| \( k_1(\text{N/mm}) \)    | 0.35            |
| \( k_2(\text{N/mm}) \)    | 0.25            |
| \( x_1(\text{mm}) \)     | 4.5             |
| \( x_2(\text{mm}) \)     | 6               |
| \( K \)          | 0.8             |
| \( K^* \)        | 0.5             |

Using the MATLAB command ode23 function to solve equations (1), (2 and 3) numerically, and the results are shown in Figure 5 and Table 2.

Among them: closing time refers to the time from the beginning of the AC contactor closing to the first contact of the contact; the bounce time refers to the time from the first bounce of the contact to the end of the last bounce; the contact stabilization time refers to the time from The time from the beginning of the contactor to the end of the last bounce of the contact, the same goes for the iron core.

From Figure 5 and Table 2, we can see that the contact closing time corresponds to the first stage of the equation (0ms~23.37ms), and the time from the first bounce of the contact to the first bounce of the core is the second stage of the equation (23.37ms ~23.90ms), the time from the start of the first bounce of the core to the end of the second bounce of the contact is the third stage of the equation (23.90ms~29.08ms).

![Figure 5](image_url)

**Table 2 Comparison of results**

| Category                      | Moving contact | Moving iron core |
|-------------------------------|----------------|------------------|
| Closing time (ms)             | 23.37          | 23.90            |
| The first bounce (start time) (ms) | 23.37          | 23.90            |
| The first bounce (end time) (ms) | 24.65          | 24.25            |
| The second bounce (start time) (ms) | 28.81          | 27.07            |
| The second bounce (end time) (ms) | 29.08          | 27.35            |
| Total time to bounce (first) (ms) | 1.28           | 0.35             |
| Total time to bounce (second) (ms) | 0.27           | 0.28             |
| Bounce time (ms)              | 5.71           | 3.45             |
| Contact stabilization time (ms) | 29.08          | 27.35            |
| Maximum bounce amplitude (first) (mm) | 0.241         | 0.195            |
| Maximum bounce amplitude (second) (mm) | 0.049         | 0.032            |
| Maximum bounce amplitude (mm)  | 0.241          | 0.195            |

The first bounce of the contact. It can be seen that the contact bounces earlier than the iron core, but ends after the iron core, and the bounce amplitude of the contact is greater than that of the iron core. This is because the distance between the moving and static contacts is smaller than the distance between the moving and static iron core. The iron core mass is much larger than the contact mass, so the fall cycle is short. Secondly, the contact has not been separated after the collision, and the iron core collided, which further intensified the bounce of the contact and increased its bounce displacement.

The second bounce of the contact. It can be seen that the start and end time of the second bounce of the iron core are earlier than the contact. It can be clearly observed from Figure 5 that when the second bounce of the iron core occurs, the bounce of the contact is not significantly affected. This is because the second bounce amplitude of the iron core is much smaller than the first one, which is consumed by the system itself and not transmitted to the contacts.
It can be seen from that the bounce time, contact stabilization time and maximum bounce amplitude of the contact are larger than the iron core. This is because the contact area of the iron core is larger when it hits, and it is always subjected to electromagnetic force during the bounce process, which further prevents the iron core from bouncing again.

4 Experiment and comparison

In order to get the whole dynamic process of contact bouncing intuitively, this paper adopts high-speed photography technology (EoSens-mini2 system) to take photographic measurement of a group of contacts of ABB's A9-30-10 electromagnetic contactor. Since the bounce time of the contact during the closing process of the AC contactor is very short, generally only 2-6 milliseconds, in order to ensure that the camera can accurately capture the whole process of bounce. Pixels were selected in this paper for shooting, and the shooting speed was 43540 frames per second. Figure 6 (a) and (b) are the layout of the contactor prototype and experimental equipment.

Figure 6 Shooting layout

The specific steps are as follows: first, a measuring hole is opened on one side of the contactor directly facing the position of the contact group; then, the high-speed camera is aimed at the contact head position and focused; finally, the moving contact head position is marked and monitored in the high-speed camera; meanwhile, the shooting parameters of the camera are adjusted and the camera is started for shooting.

Figure 7 (a), (b) and (c) are screenshots of the moving and static contacts that have not yet collided, the moving and static contacts have collided, and the moving and static iron cores collided during the contact bounce process. That is, it corresponds to the first stage, the second stage and the third stage in the closing process of the contactor.

Figure 7 Contact of bounce process

The processing program is applied to MATLAB software to process the above-mentioned collected images, mainly divided into the following steps (as shown in Figure 8).

Figure 8 Data processing Flowchart

(1) Image preprocessing: the collected image is processed by noise removal and enhancement to extract the geometric information of image feature points.
(2) Calibration and identification: according to the black and white pixel features in the image, the moving and static contact components are highlighted, as shown in Figure 6 and then the program is used to identify the marked points, and extract the image coordinate system after the value of the two images.
(3) Line fitting of marked center: image coordinate values are extracted from the value of the two images, and line fitting of marked center circle diameter is performed on the coordinates of marked points by using least square method.
(4) Calibration of object coordinate system and generation of displacement curve: the solution of the center circle diameter of the mark is transferred to the linear relationship between the two coordinate systems, and then the processing results of each picture are arranged according to the collected time series to obtain the experimental curve of the displacement of the mark point. The results are shown in Figure 9.
It can be seen from Figure 9 that the overall trend of the experimental curve and the theoretical curve is the same. The contacts have two obvious bounces, but the contacts in the first stage, and the experimental curve is not smooth. This is because the contactor is in actual operation, the movement of the moving iron core will cause a slight jitter of the contactor system, so the experimental curve is not smooth. Secondly, the experimental curve and the theoretical curve do not fit perfectly in the second and third stages. This is caused by the data measurement error in the process of measuring the model parameters in the establishment of the contactor model. This error will not affect the equation solution. So the result is negligible.

| Category                        | Theory   | Experiment | Error (%) |
|---------------------------------|----------|------------|-----------|
| The first bounce(start time)/ms  | 23.37    | 23.67      | 1.28      |
| The first bounce(end time)/ms   | 24.65    | 24.52      | 0.53      |
| The second bounce(start time)/ms| 28.81    | 29.09      | 0.97      |
| The second bounce(end time)/ms  | 29.08    | 29.34      | 0.89      |
| Closing time/ms                 | 23.37    | 23.67      | 1.28      |
| Bounce time/ms                  | 5.71     | 5.67       | 0.70      |
| Contact stabilization time/ms   | 29.08    | 29.34      | 0.89      |
| Maximum bounce amplitude/mm     | 0.241    | 0.252      | 4.56      |

The specific numerical values of experimental results and theoretical results are shown in Table 3. It can be seen from Table 3 that the start time and end time of the two bounces, closing time, bounce time, contact stabilization time, and maximum bounce amplitude error of the experimental and theoretical contacts are all within 5%, indicating that the experimental and theoretical results are highly consistent. The accuracy and reliability of the theory are verified.

5 Conclusions

(1) From the perspective of vibration, considering the nonlinear electromagnetic force and collision contact force, a two-degree-of-freedom coupled motion differential equation of the contact system is established.

(2) The first bounce of the contact starts earlier than the iron core and ends later than the iron core, and the bounce amplitude is greater than that of the iron core. The contact has not been separated after the collision contact, and the iron core collided, which further intensified the contact bounce. The start and end time of the second bounce of the contact is later than that of the iron core. When the second bounce of the iron core occurs, it does not affect the bounce of the contact.

(3) The bounce time, contact stabilization time and maximum bounce amplitude of the contact are all greater than the iron core. In addition, during the operation of the contactor, the movement of the moving iron core will cause a slight vibration of the contactor system.

6 Declaration

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Availability of data and materials
The datasets supporting the conclusions of this article are included within the article.

Authors’ contributions
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The authors declare no competing financial interests.

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Appendix