A Mechanical Model for Radial Inertial Impact Switch

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Abstract: The traditional inertial impact switch based on experience design often appears in the problem of early closure within the threshold. To solve this problem, a new method of inertial switch design is presented in this paper. Firstly, the force analysis of inertia switch is carried out and a mechanical model is established. Through the model, it is concluded that the closing threshold of inertia switch is related to the spring resistance, the mass and center of mass of contact pole, the spring radius of contact pole and the horizontal projection of the minimum distance between the spring and the reference point. After that, the mechanical model is verified by simulation, and the correctness of the mechanical model is proved. The experimental results show that the proposed model can effectively solve the problem of premature closing of the inertial switch within the threshold and improve the pass rate of the product.

1. Introduction
The inertial impact switch, an important component commonly used in fuzes, judges whether the warhead hits the target based on the overload effect generated when the warhead collides with the target. Inertial impact switches were first seen in Soviet and American missile electromechanical fuzes and shell radio fuzes in the 1950s. At present, the inertial impact switches used in domestic fuzes generally adopt the structure of the shell PF1 radio fuze inertial impact switch in the US military manual. In view of the contradiction between the sensitivity of the inertial impact switch and the safety of ballistic trajectory, Fang et al. designed an inertial impact switch applicable to non-rotating ammunition or low-rotating ammunition with a weight column. Through simulation analysis and test model verification, Shang and Ma carried out structural design and parameter adjustment of the axial inertial impact switch with a working overload of about 114g. Tao established a physical model between the impact switch spring and the conductive rod, and analyzed the spring influence on the switch closure characteristics. However, the works mentioned above mainly focus on the simulation analysis and experimental research of axial inertial impact switches, while the inertial impact switch is not studied. Wang analyzed the relationship between spring resistance and switch closing response using RecurDyn simulation software, and proposed that increasing the spring resistance can effectively solve the problem of early closure of radial inertial impact switches, but cannot provide theoretical method for inertial switch design. In order to solve the problem that the empirically designed inertial impact switch has a low pass rate during the screening test due to early closure within the threshold, this paper proposes a new inertial switch design method, establishes a mechanical model and verifies it.
2. Inertial impact switch and empirical design method

2.1 Inertial impact switch structure and working principle [10]

The inertial impact switch is composed of a conductive sleeve, an insulating sleeve, a contact pole, a spring and a shell. The switch structure is shown in Wang [10]. The contact pole and the shell constitute one pole of the switch, the conductive sleeve constitutes the other pole of the switch, and the metal parts constituting the two poles are separated by an insulating sleeve. Regarding the working principle of the axial inertial impact switch, after the ammunition is launched and hits the target, due to the forward momentum, the compression spring of the contact pole contacts the conductive sleeve, which makes the switch close, triggering the circuit path so that the fuze works. For the working principle of the radial inertial impact switch, after the ammunition is launched and hits the target, due to the forward momentum, the flange outer edge of the contact pole presses one side of the spring, and the top of the contact pole contacts the conductive sleeve to make switch close, triggering the circuit path so that the fuze works. The inertial impact switch in the fuze usually adopts two installation methods: the switch axis is parallel to the spring axis in the case of axial installation; the switch axis is perpendicular to the spring axis in the case of radial installation. The inertial compact switch mentioned herein adopts radial installation.

2.2 Empirical design method for inertial impact switch

The axial inertial impact switch is designed based on the classic spring mass model. According to the fuze use environment, the closing threshold of the fuze is determined to initially determine the mass, shape and stroke of the contact pole, and then the spring's pre-compression resistance and spring stiffness are designed based on the spring mass model.

Radial impact switch has complex working conditions. As a result, the flange outer edge of the contact pole extrudes one side of the spring. It is not easy to calculate the pre-tightening torque of the spring against the contact pole, and movement is not linear with force [7], so design based on simple model is difficult. For the general design method of radial impact switch spring: based on the designed axial inertial impact switch, process springs of various stiffness and lengths, perform screening and testing on the centrifuge, select the switch with closed target threshold, then pre-compression resistance and spring stiffness of the spring are the design values of the radial impact switch. However, because the weight, center of mass position and assembly size of the inertial switch are scattered, switches designed according to this method have low pass rate of generally less than 30% [10].

3. New design method for inertial impact switch

To solve the problem of low pass rate of radial inertial impact switches, this paper proposes a new method for designing inertial impact switches.

3.1 Force analysis of inertial impact switch

When the ammunition hits the target, the contact pole of the inertial impact switch will receive forward momentum, and the contact pole of the switch will rotate around the reference point O under the action of forward momentum overload \( \alpha \) and spring pre-compression resistance \( F \), as shown in Fig. 1. Newton's law of motion is used to establish the dynamic equation of the contact pole as below:

\[
M - M_0 - f = I \dot{\theta}
\]

where \( M \) is the torque of the contact pole rotating around point \( O \) under the action of the forward momentum overload \( \alpha \); \( M_0 \) is the pre-tightening torque of the contact pole rotating around point \( O \) under the action of the spring pre-compression resistance \( F \); and the direction is opposite with that of \( M \); \( f \) is the moment acting on the contact pole due to the rotation angle and spring stiffness when the contact pole rotates around point \( O \); \( I \) is the moment of inertia of the contact pole around point \( O \); and \( \theta \) is the rotation angle of the contact pole around point \( O \).
In the theoretical design, since the small moment of force $f$ and moment of inertia $I \theta$ can be ignored, Formula (1) can be expressed as:

$$M = M_0$$  \hspace{1cm} (2)

Fig. 1 Force analysis of contact pole

3.2 Calculation of main parameters

Based on the above analysis, the main parameters in the inertial impact switch design include: the torque $M$ of the contact pole rotating around point $O$ under the action of forward momentum overload $a$, and the pre-tightening torque $M_0$ of the contact pole rotating around point $O$ under the action of spring pre-compression resistance $F$.

1) Calculation of torque $M$ generated by overload

For a unit body with the mass of $dm$ on the contact pole, the distance between the unit body and the lower end of the contact pole is $x$, as shown in Fig. 2.

Fig. 2 Torque generated by overload

The torque $M$ acting on the contact pole due to overload can be calculated by Formula (3):

$$M = \iiint a \cdot x dm = \iiint a \cdot x \cdot \rho dv = m \cdot h \cdot a$$  \hspace{1cm} (3)

where $dv$ is the unit body volume, $\rho$ is the contact pole density, and $h$ is the distance between the center of mass of the contact pole and the lower end surface.

2) Calculation of pre-tightening torque $M_0$ of the spring

The contact pole of the switch has a tendency to rotate counterclockwise under the action of the forward momentum overload $a$ (Figure 1). The spring with pre-compression resistance $F$ produces a clockwise resistance moment on the contact pole. Fig. 3 shows force analysis of spring in contact with contact pole.
Fig. 3 Analysis on spring force in contact with contact pole

The spring pre-tightening torque $M_0$ can be obtained by Formula (4):

$$M_0 = \int_0^{2\pi} \frac{F}{2\pi r} \cdot r \cdot d\Phi \cdot \left[ c + r \cdot (1 + \cos \Phi) \right] = F \cdot (c + r)$$  \hspace{1cm} (4)

where, $r$ is the radius of the spring in contact with the contact pole, $F$ is the pre-compression resistance of the spring, $rd\Phi$ is the arc length of the infinitesimal element, and $c$ is the horizontal projection of the minimum distance between the spring and the reference point $O$.

From Formulae (3) and (4), it can be concluded that the torque $M$ of contact pole rotating around point $O$ under the action of forward momentum overload $a$ is related to the overload $a$, the contact pole mass $m$, and the distance $h$ between the center of mass of the contact pole and the lower end surface; the pre-tightening torque $M_0$ of the contact pole rotating around point $O$ under the action of spring pre-compression resistance $F$ is related to the spring pre-compression resistance $F$, the radius $r$ of the spring in contact with the contact pole, and the horizontal projection $c$ of the minimum distance between point $O$ and the spring.

The key to the inertial impact switch design lies in calculation of the spring pre-compression resistance $F$. According to Formulae (3) and (4) and combining Formula (2), the spring pre-compression resistance $F$ can be calculated.

4. Calculation examples and verification

4.1 Calculation examples

The model parameters selected in this paper are shown in Table 1.

| Mass of contact pole $m$/g | The distance between the center of mass of the contact pole and its bottom $h$/mm | The radius of the bottom end of the contact pole $(c+r)$/mm | Radial closing stroke/mm | Critical threshold $l$/g |
|---------------------------|--------------------------------------|-------------------|----------------------|-------------------------|
| 0.077                    | 2.9                                  | 1.5               | 0.6                  | 100                     |

By substituting the parameters in Table 1 into Formulae (2), (3) and (4), the spring pre-tightening resistance $F$ can be calculated to be 0.149N.

4.2 Simulation verification

The ADAMS software was used to simulate the inertial impact switch, with the model parameters shown in Table 1. The simulation model is shown in Fig. 4, which are simulation photos at different moments. The curve is loaded according to the screening process. The simulation results show that at the critical threshold of 100 g, the spring pre-tightening resistance $F$ is 0.16N, which is close to the theoretical calculation value in this paper.
4.3 Laboratory verification

The empirical method and the method proposed herein are used to assemble 10 inertial impact switches. Screening and testing are performed on the centrifuge, with test g value set to 100 g. The test results are shown in Table 2. The test results show that the empirically designed inertial impact switch has a pass rate of 30%, while the figure for the inertial impact switch designed by our method is 70%. It can be seen that the design method proposed herein can significantly improve the pass rate of the inertial switch. To verify the credibility of our method, we used it to assemble products in the production of multiple batches of products. A total of more than 11,000 products were assembled, including 9,135 qualified products, with a pass rate of 83%.

Table 2 Comparison of method designed in this paper and experience

| Switch number | spring resistance range/N | spring resistance/N | Comparison between the empirical design method and our method |
|---------------|---------------------------|--------------------|-------------------------------------------------------------|
| 1#            | 0.07 0.1                  | 0.093              | Closed before 100 g                                         |
| 2#            | 0.07 0.1                  | 0.085              | Closed before 100 g                                         |
| 3#            | 0.07 0.1                  | 0.098              | Not closed before 100 g                                     |
| 4#            | 0.07 0.1                  | 0.077              | Closed before 100 g                                         |
| 5#            | 0.07 0.1                  | 0.071              | Closed before 100 g                                         |
| 6#            | 0.07 0.1                  | 0.083              | Closed before 100 g                                         |
| 7#            | 0.07 0.1                  | 0.095              | Not closed before 100 g                                     |
| 8#            | 0.07 0.1                  | 0.091              | Not closed before 100 g                                     |
| 9#            | 0.07 0.1                  | 0.096              | Closed before 100 g                                         |
| 10#           | 0.07 0.1                  | 0.093              | Closed before 100 g                                         |
| 11#           | 0.1 0.19                  | 0.133              | Closed before 100 g                                         |
| 12#           | 0.1 0.19                  | 0.136              | Not closed before 100 g                                     |
| 13#           | 0.1 0.19                  | 0.139              | Not closed before 100 g                                     |
| 14#           | 0.1 0.19                  | 0.135              | Not closed before 100 g                                     |
| 15#           | 0.1 0.19                  | 0.141              | Closed before 100 g                                         |
| 16#           | 0.1 0.19                  | 0.146              | Not closed before 100 g                                     |

Fig. 4 Simulation model
5. Conclusion
This paper presents a new method for inertial switch design. This method establishes a mechanical model for the radial inertial impact switch, and directly calculates the pre-compression resistance of the spring through theoretical analysis. Theoretical calculation shows that the closing threshold of the inertial impact switch is related to the spring resistance, the mass and the center of mass position of the contact pole, the radius of the spring in contact with the contact pole, and the horizontal projection of the minimum distance between the spring and the reference point. Simulations and experiments verified that the inertial impact switch design method proposed in this paper can improve the pass rate of the switch in the screening test, and effectively solve the problem of early switch closure in the screening test.

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