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Development of a Reliable Vibration-Current Coupling-Based Foreign Matter Detection System for Electro-Explosive Devices

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Abstract

Electro-explosive devices (EEDs) are components that initiate the explosive charge through electrical current input, converting it into chemical energy or kinetic energy in the form of heat, pressure, and shock waves. These mission-critical components are extensively integrated into space launch systems, naval vessels, and spacecraft propulsion systems, where their operational reliability directly influences mission outcomes. The insulation performance of EEDs is susceptible to degradation due to foreign objects in static discharge channels, which can lead to ignition failure. Based on the particle noise method, this study proposes a reliable foreign object detection system that leverages the vibration-current coupling relationship. By integrating adjustable vibration excitation loading and real-time leakage current detection, an automated system is established to define process parameter ranges and detection criteria. The system enables automated and reliable detection of foreign objects larger than 0.05 mm in length.

Keywords

Foreign Matters Detection, Vibration Loading, Insulation Resistance, Electro-Explosive Devices

1. Introduction

Initiating explosive devices are widely applied in systems such as aerospace launch vehicles, ships, and satellite-rocket combinations, and are closely associated with key components including rocket engine ignition and shutdown, stage separation, fairing separation, satellite-rocket spin-up, attitude control, launch canister cover ejection, as well as ejection escape systems in fighter aircraft. The primary initiating elements of initiating explosive devices are mainly electro-explosive devices (EEDs), and a schematic diagram of the typical structure of an electric initiating explosive device is shown in **Figure 1**. Among these properties, insulation performance, especially between the electrode pin and the casing, is highly correlated with product quality. Tiny foreign matters present in the electrostatic discharge channel may lead to degraded insulation performance, thereby affecting the operational reliability of the electric igniter.

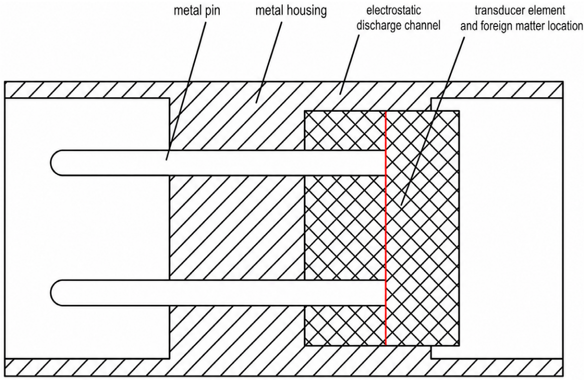

Figure 1. Schematic diagram of typical structure.

High confidentiality is maintained in the foreign initiating explosive industry, making it difficult to obtain specific testing methods adopted by various countries. However, relevant reports indicate that automated testing has been widely applied in developed industrial countries in sectors including aviation, aerospace, and transportation [1]-[4].

In China, commonly used methods for detecting tiny foreign matters in aerospace products are as follows:

1) Microscopic inspection. The interior of components is observed under a microscope before sealing, which has been widely used in the assembly of initiating explosive devices.

2) Particle Impact Noise Detection (PIND) [5] [6]. Vibration conditions are applied to components via vibration equipment, and noise signals generated by collisions between inner walls and foreign matters are detected to determine the presence of foreign matters. This method achieves high accuracy in detecting non-typical foreign matters, but requires product samples (usually fixed by potting adhesive) for testing, making it suitable for sampling and screening of electronic components.

3) Electrical performance testing. Insulation resistance testing, electrostatic discharge testing, etc., are adopted to determine the existence of metallic foreign matters inside components, but fail to accurately detect tiny and movable foreign matters.

Foreign matters in the electrostatic discharge channel of EEDs are often shielded by energy conversion elements and thus cannot be directly observed via microscopic inspection. Therefore, based on PIND and electrical performance testing [7], this project monitors the real-time variation of insulation resistance of EEDs under vibration, so as to determine the presence of internal metallic foreign matters. The development of a reliable foreign matter detection system for EEDs based on vibration current coupling is thus realized.

2. Theoretical Research and System Construction

2.1. Theoretical Analysis of Vibration Excitation Parameters

Under vibration excitation, the electrostatic discharge channel of EEDs is in a sealed state, and the movement process of foreign matters inside is invisible. It is difficult to determine the influences of parameters such as vibration direction, amplitude, vibration times, impact force and frequency on the excitation effect of foreign matters, and parameters including acceleration and frequency are especially hard to quantify. The vibration excitation process of electric initiating explosive devices is analyzed by dynamics. Vibration times, amplitude, impact force, frequency and vibration direction are all related to the vibration insulation test results of the device.

According to the theory of structural vibration, the equilibrium equation of the structure in dynamic analysis is expressed as follows:

$$[M][\ddot{u}(t)]+[C][\dot{u}(t)]+[K][u(t)]=[F(t)] \tag{1}$$

In equation (1), $[M]$ denotes the structural mass matrix, $[C]$ denotes the structural damping matrix, and $[K]$ denotes the structural stiffness matrix.

The global structural stiffness matrix $[K]$ is assembled by the element stiffness matrix $[k]$. Similarly, the global structural mass matrix $[M]$ is also assembled by the element mass matrix $[m]$.

The expression of the element mass matrix can be derived as:

$$[m]^e=\iiint[N]^{\mathrm{T}}\rho[N]\mathrm{d}v \tag{2}$$

In equation (2), ρ represents the density of the element material. The global mass matrix $[M]$ is formed by assembling all element mass matrices $[m]$ of the structure according to nodes, which is a banded symmetric square matrix identical to the global stiffness matrix.

The element damping matrix is derived in a similar manner as:

$$[C]^e=\iiint[N]^{\mathrm{T}}\gamma[N]\mathrm{d}v \tag{3}$$

In equation (3), γ is the damping coefficient.

It can be observed that the integral forms of the structural mass matrix $[M]$ and damping matrix $[C]$ are highly similar, differing only by a constant coefficient, indicating a direct proportional relationship between the two matrices.

In dynamic analysis, the calculation of structural eigenvalues and eigenvectors corresponds to the determination of natural frequencies and natural modes of vibration, which constitutes the fundamental content of dynamic analysis. In actual vibration processes, the influence of damping on the natural frequency and vibration mode of the structure is negligible, and thus damping is neglected when solving frequencies and modes.

By setting the excitation force to zero, the vibration equation of the system is obtained as follows:

$$[M]\{\ddot{u}\}+[K]\{u\}=0 \tag{4}$$

During free vibration, each node undergoes harmonic motion, and its displacement can be expressed as:

$$\{u\}=\{u_0\}\cos(\omega t+\varphi) \tag{5}$$

In equation (5), $\{u_0\}$ is the amplitude of each node; ω is the natural frequency corresponding to the vibration mode; φ is the phase angle.

Substituting the above equation into the vibration equation of the system yields:

$$\left([K]-\omega^2[M]\right)\{u_0\}=0 \tag{6}$$

Since the amplitudes $\{u_0\}$ of each node cannot all be zero, the determinant of the matrix in the brackets must be zero. Thus, the equation for the natural frequency of the structure is obtained as:

$$[K]-\omega^2[M]=0 \tag{7}$$

Assuming that the structure has n degrees of freedom after discretization, both the structural stiffness matrix $[K]$ and mass matrix $[M]$ are n order square matrices. The above equation can be solved to obtain n natural frequencies ω_1, ω_2, …, ω_n of the structure. By means of the Rayleigh method, the general solution of displacements at each node in free vibration is further derived as:

$$\begin{aligned}\{u\}=k_1\{u_0\}_1\cos(\omega_1 t+\varphi_1)+k_2\{u_0\}_2\cos(\omega_2 t+\varphi_2)+\cdots\\ +k_n\{u_0\}_n\cos(\omega_n t+\varphi_n)\end{aligned} \tag{8}$$

In equation (8), $\{u_0\}_t$ denotes the vibration mode corresponding to each natural frequency ω_t. The value of K_t is determined by the initial conditions of the structure. Spectral analysis is performed on random vibrations based on the obtained solutions to characterize the vibration behavior.

Impurities in the electrostatic discharge channel of the product are small in volume and light in weight. Metallic foreign matters in the electrostatic discharge channel are mainly spot-welding spatters or metal chips, and the gap of the electrostatic discharge channel is (0.25 - 0.3) mm. As can be seen from **Figure 1**, under the structure of the revolution body, foreign matters can only move radially into the electrostatic discharge channel. Based on this, a simulation model is established, as shown in **Figure 2**.

The dynamic simulation was carried out using Abaqus. The EED was simplified according to the electrostatic-discharge channel geometry shown in **Figure 1**, and the foreign matter was modeled as small metallic particles representing laser-cut microchips or spot-welding spatters. Contact between the particle, the channel wall and the insulating surfaces was defined with frictional interaction. The product body and fixture contact surfaces were constrained, while radial vibration excitation was applied successively in different directions. The main outputs used for parameter selection were the particle displacement trajectory, contact state and whether the particle entered the electrostatic-discharge channel. These outputs showed that 5 Hz excitation promoted sliding rather than suspension, direction changes greater than 120 degrees improved channel entry, and at least 10 vibration cycles were required for stable particle migration toward the channel.

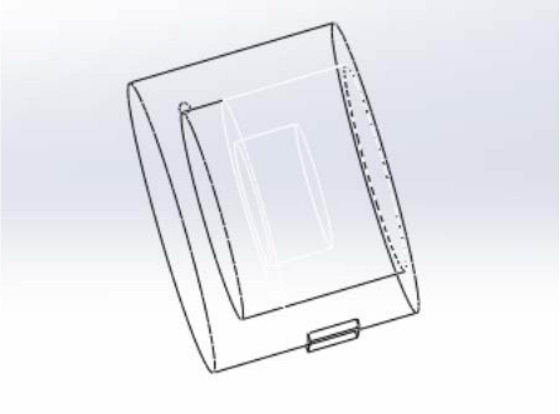

Figure 2. Vibration simulation model of foreign matters.

According to the simulation results, with regard to vibration frequency, when the simulation parameter is set to a low frequency of 5 Hz, metallic impurities (the spheres in the figure) can move back and forth under certain impacts and slide into the electrostatic discharge channel, thereby affecting the insulation resistance of the product. In the case of high-frequency vibration (above 10 Hz), metallic impurities are usually suspended and cannot enter the electrostatic discharge channel.

Regarding the vibration direction, since the product vibration is radial, the direction needs to be changed so that foreign matters are driven by vibration excitation into the electrostatic discharge channel. The simulation shows that foreign matters may get stuck when the direction is changed by 180˚, while alternate changes of more than 120˚ can ensure that foreign matters reliably fall into the electrostatic discharge channel during movement.

As for the number of vibrations, foreign matters require displacement induced by multiple vibration excitations to fall into the electrostatic discharge channel. Based on the simulation conclusions, a vibration of no less than 10 times can effectively drive foreign matters from the center to the electrostatic discharge channel.

2.2. Theoretical Analysis of Vibration Impact Loading Model

The vibration rod equipped with the product is regarded as a whole, and a certain

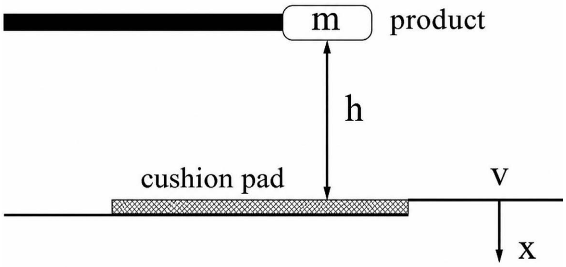

Figure 3. Simplified schematic diagram of theoretical calculation model.

mathematical relationship exists among its acceleration a, pulse width τ, height h, and stiffness c of the buffer material. The analysis is given as follows.

Let the weight be ω, the mass be m (including the product and fixture), the falling height be h, and the deformation of the cushion pad be x, as shown in **Figure 3**. The differential equation of motion is expressed as:

$$m\left(\mathrm{d}^2x\right)/\left(\mathrm{d}t^2\right)+cx=mg \quad \left(x\geq 0\right) \tag{9}$$

Let: $\omega^2=c/m$.

The differential equation is transformed into:

$$\left(\mathrm{d}^2x\right)/\left(\mathrm{d}t^2\right)+\omega^2x=g \tag{10}$$

The general solution of this equation (10) is:

$$x=\left(C_1\cos\omega t+C_2\sin\omega t\right)+g/\omega^2 \tag{11}$$

According to the initial conditions:

$$x\big|_{t=0}=0 \quad x'\big|_{t=0}=v=\sqrt{2gh} \tag{12}$$

The new solution to the equation (12) is:

$$\begin{aligned} x&=\left(-\frac{g}{\omega^2}\cos\omega t+\frac{v}{\omega}\sin\omega t\right)+\frac{g}{\omega^2}\\ &=A\sin\left(\omega t+\varphi\right)+\frac{g}{\omega^2}\\ &=A\sin\left(\omega t+\varphi\right)+x_0 \end{aligned} \tag{13}$$

In equation (13):

$$\begin{aligned} A&=\sqrt{\frac{g^2}{\omega^4}+\frac{v^2}{\omega^2}}\\ \varphi&=\mathrm{tg}^{-1}\left(-g\right)/\omega v\\ x_0&=g/\omega^2=\omega/c \end{aligned} \tag{14}$$

x_0 is the static deformation, which can be obtained from the above equation (15).

$$\begin{aligned} x'&=\omega A\cos\left(\omega t+\varphi\right)\\ x''&=-\omega^2A\sin\left(\omega t+\varphi\right) \end{aligned} \tag{15}$$

Let: $\left|x''_{\max}\right|=a$

$$a=\omega^2A=\sqrt{g^2+v^2\omega^2}=g\sqrt{1+2h/x_0} \tag{16}$$

The time during which the value of x changes from 0 to maximum then to 0 is defined as the impact pulse width τ. The solution of this equation is obtained as:

$$\begin{aligned} &\tau=\frac{2}{\omega}\left(\frac{\pi}{2}-\varphi\right)\\ &\because \varphi=\mathrm{tg}^{-1}\frac{-g}{\omega v}=-\sin^{-1}\frac{g}{a}\\ &\therefore \tau=\frac{2}{\omega}\left(\frac{\pi}{2}+\sin^{-1}\frac{g}{a}\right)=2\sqrt{\frac{m}{c}}\left(\frac{\pi}{2}+\sin^{-1}\frac{g}{a}\right) \end{aligned} \tag{17}$$

When $a \gg g$:

$$\tau \approx \pi\sqrt{\frac{m}{c}} \tag{18}$$

When a, τ and m are known, the following formula can be used:

$$\begin{cases} \tau = \pi\sqrt{\dfrac{m}{c}} \\ a = \sqrt{g^2 + 2gh\dfrac{c}{m}} \end{cases} \tag{19}$$

The c and h are obtained.

In practical applications, the drop height h of the shock table can be first calculated according to a and τ. When the shock table drops from height h, the cushion pad is adjusted so that the impact acceleration is equal to a.

2.3. Determination of Vibration Excitation Impact Magnitude

According to the impact loading model shown in **Figure 3**, a simple impact magnitude test device as illustrated in **Figure 4** is constructed, which was adopted from a previous research project [8]. The product is lifted and dropped manually to acquire a certain velocity, and impact acceleration is generated upon collision with a rubber sheet placed on the desktop. This forces the foreign matters enclosed in the electrostatic discharge channel of the electro-explosive device to undergo relative motion due to inertia, resulting in conduction between the pin and the housing of the product and thus a change in insulation resistance.

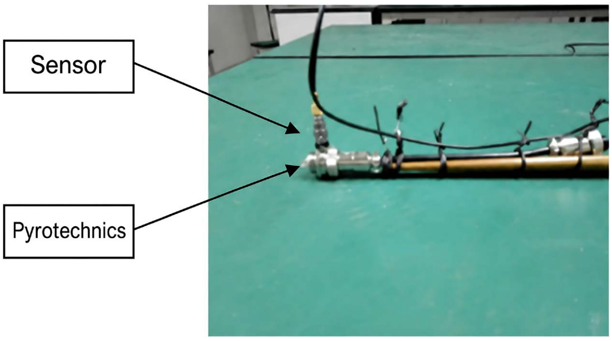

Figure 4. Simple impact magnitude test device from [8].

Based on the theoretical analysis in Section 2.1, manual application is performed in three radial directions, with (10 - 15) times per direction, vibration frequency of (1 - 2) Hz, and drop height of (20 - 50) mm. According to the research conclusions in Section 2.3, the stiffness of the cushion material is fixed, so the impact magnitude is adjusted by varying the drop height. Since the impact acceleration cannot be controlled manually, it can only be indirectly regulated through the drop height.

Meanwhile, an acceleration sensor is used to accurately quantify and test this process. During manual vibration of the product, the acceleration sensor mounted on the product collects vibration waveforms, and the impact acceleration is obtained through waveform analysis, as shown in **Figure 5**.

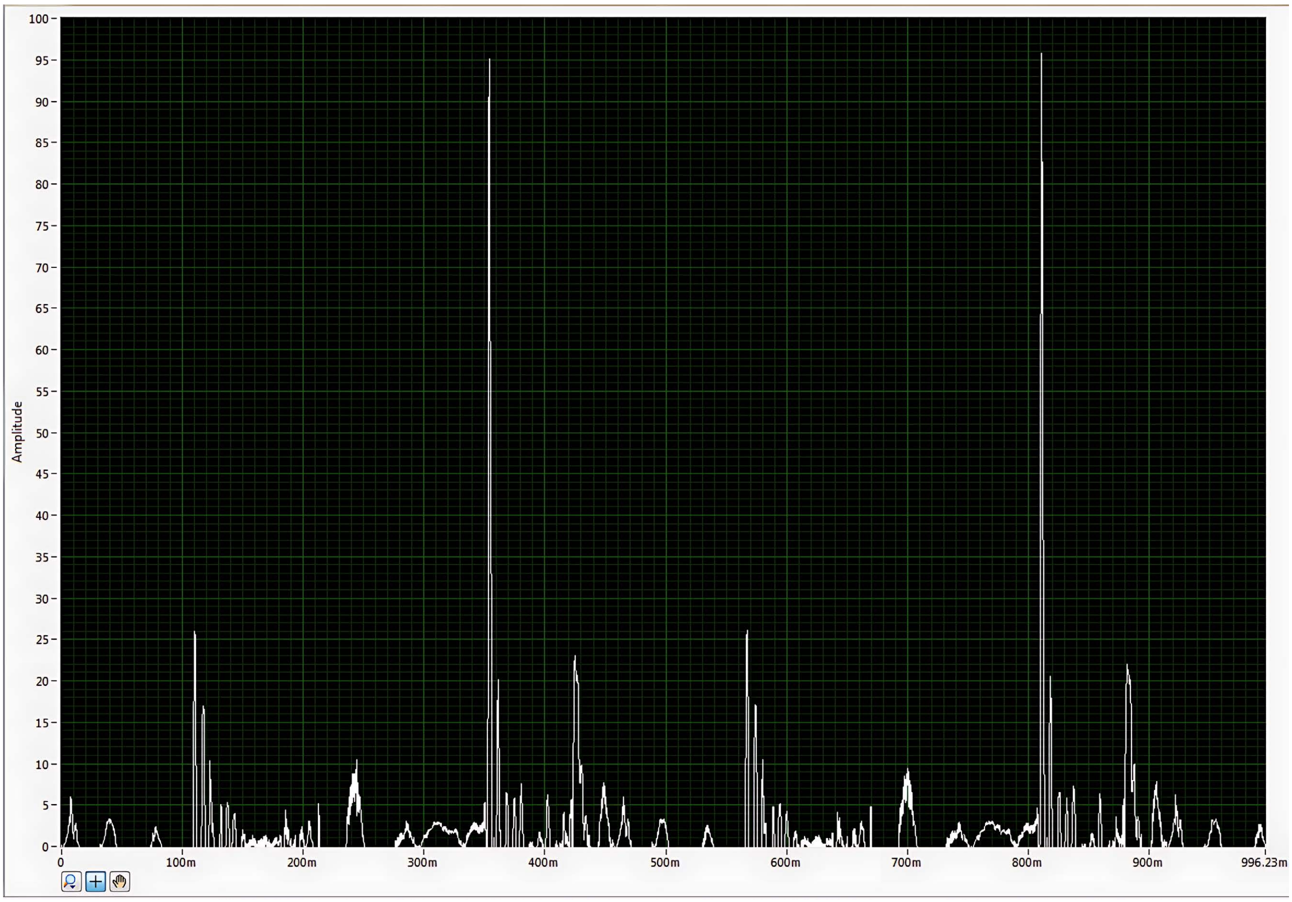

Figure 5. Waveform diagram of vibration and impact magnitude.

It can be seen from **Figure 5** that the vibration excitation adopts an impact mode, and its acceleration exhibits periodic sharp fluctuations, which is a typical shock wave. Three people were randomly selected to participate in the test and operated in accordance with the test procedures and parameters. Based on the measured change in insulation resistance of the product, valid data were obtained within the drop height range of (2 - 5) cm. The processed and statistically analyzed data are shown in **Figure 6**.

According to the statistics, the impact acceleration ranges from (66 - 160) g with a pulse width of (2 - 0.8) ms. The expected value of impact acceleration is approximately 105 g, the expected pulse width is about 1 ms, the variance of impact acceleration is 451.89, and the pulse width variance is 0.099.

According to the research conclusions in Section 2.2, the vibration effect is equivalent under consistent impact acceleration. Therefore, when the loading range of impact acceleration remains unchanged, an automatic vibration loading device can be used to achieve the same excitation effect on metallic foreign matters.

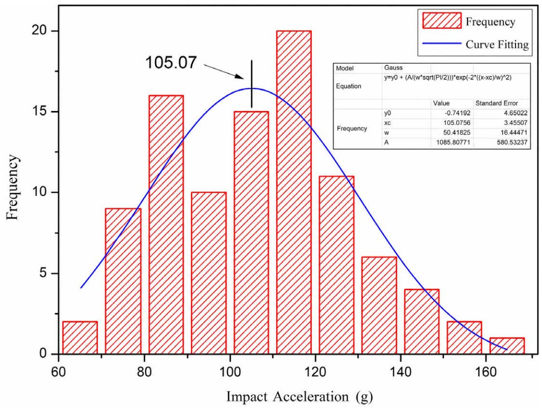

Figure 6. Frequency statistics and normal distribution fitting diagram of impact Acceleration.

2.4. Construction of the Detection System

Based on the above theoretical research, a reliable detection system for foreign matters in electro-explosive devices based on vibration-current coupling is constructed. It is mainly composed of a vibration loading module, an insulation resistance testing module and a software module. The structure of the main functional modules is shown in **Figure 7**, and the physical system is illustrated in **Figure 8**.

The working principle of the system is as follows: the vibration loading module is used to apply the impact magnitude, as shown in **Figure 9**. A cam drives the product fixture to rise, and upon reaching the set height, the fixture falls freely and collides with the cushion pad to generate the impact magnitude, which is then applied to the test product. During the vibration of the product, the insulation resistance testing module detects the leakage current of the test article, performing real-time monitoring and measurement of the in-system insulation resistance value. The value is then compared with the preset lower limit through computer software calculation, and an alarm is triggered when the lower limit is exceeded, as illustrated in **Figure 10**.

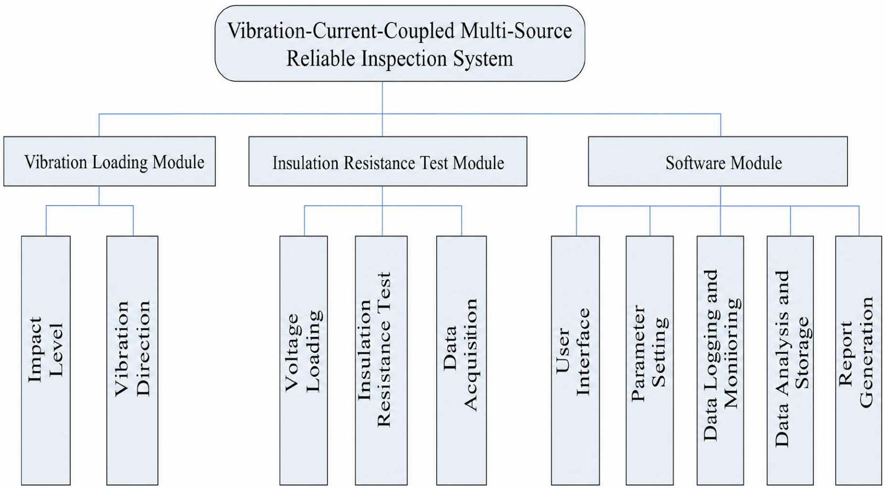

Figure 7. Framework of the reliable foreign matter detection system based on vibration-current coupling.

Figure 8. Physical diagram of the reliable foreign matter detection system based on vibration-current coupling.

The software detection criterion was defined as follows. During each test, the applied voltage was increased gradually from 0 V to 500 V. After the voltage reached a stable 500 V, the vibration excitation sequence was loaded and the insulation resistance was recorded synchronously with the test process, including the voltage-rising stage and each vibration cycle. In the validation test with 1 Hz vibration, one insulation-resistance value was recorded for each vibration cycle. A product was judged unqualified and an alarm was triggered immediately when the measured insulation resistance was lower than 20 MΩ at any sampling point; otherwise, the product was judged qualified after completing the full vibration sequence.

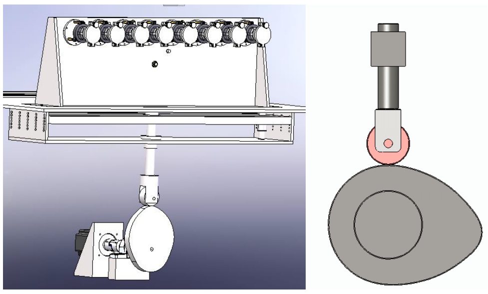

Figure 9. Schematic diagram of the vibration loading module.

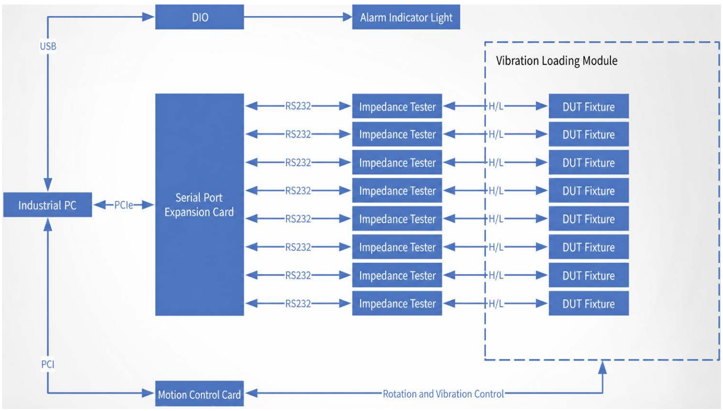

Figure 10. System coupling test framework.

3. Results and Analysis

3.1. Verification of System Impact Magnitude

The impact magnitude at the connection between the system and the electro-explosive device installation fixture is measured using an impact sensor. The specific measurement position is shown in Figure 11.

Figure 11. Impact magnitude measurement point.

The actual test data of the channel are shown in Figure 12. It can be seen that the impact acceleration, waveform, pulse width and other parameters generated by this method are similar to the vibration waveform required by the theoretical analysis in the previous chapters, with the same principle. The waveform is consistent with that of manual vibration loading, which indicates that the waveform loaded by the system is effective and can excite the foreign matters to vibrate.

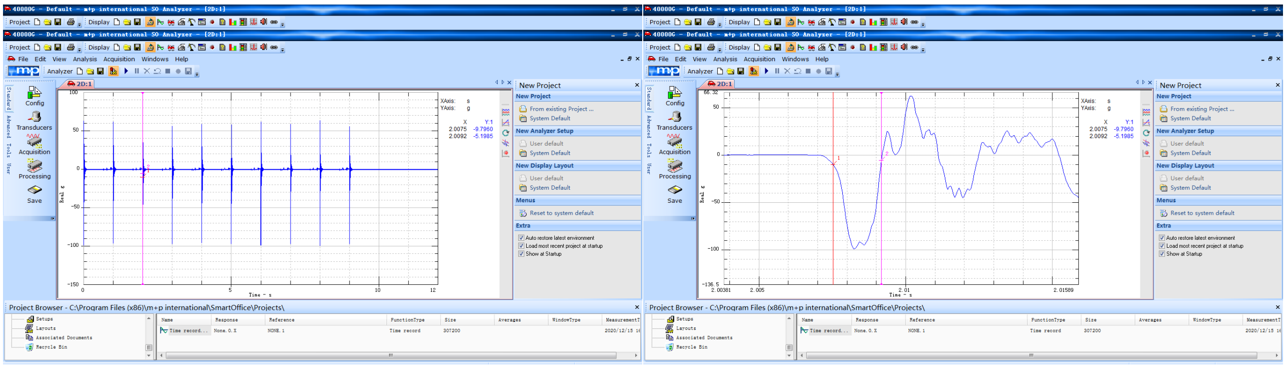

Figure 12. Test diagram of system impact acceleration and pulse width.

3.2. Validation of Effectiveness for Reliable Foreign Matter Detection

Metal filaments with a length of approximately (0.05 - 0.1) mm were artificially added to the electrostatic discharge channels of the products. These filaments are similar to the typical metallic foreign matters found in factory electric igniter products. A total of 30 such products were prepared: 15 with one metal filament added (hereinafter referred to as State 1 products), and the other 15 with two metal filaments added (hereinafter referred to as State 2 products).

The test articles were electric-igniter-type EEDs with the same representative structure as that shown in **Figure 1**. The added foreign matter was prepared as laser-cut metallic microchips rather than intentionally oriented continuous wires; therefore, a filament diameter was not used as the controlling parameter, and the characteristic size was controlled by microscopic measurement. For each contaminated unit, one or two microchips were inserted into the electrostatic-discharge channel under microscopic observation. The insertion location around the channel was randomized among products, and the particles were not deliberately placed in a preferred electrical conduction position.

A screening verification test was conducted on these 30 contaminated products, including 15 State 1 and 15 State 2 units. Radial vibration was applied in three directions: 0˚, 120˚, and −120˚, with 15 vibration cycles per direction and a vibration frequency of 1 Hz. The verification results show that the system can effectively screen all defective products. The detailed results are listed in **Table 1**.

Table 1. Validation results of effective detection for products with foreign matters.

State 1 products			State 2 products		
No.	Detected	Detection Round	No.	Detected	Detection Round
01	yes	0˚, 4 vibrations	01	yes	0˚, 2 vibrations
02	yes	120˚, 2 vibrations	02	yes	0˚, 6 vibrations
03	yes	0˚, 7 vibrations	03	yes	0˚, 3 vibrations
04	yes	0˚, 9 vibrations	04	yes	0˚, 12 vibrations
05	yes	−120˚, 3 vibrations	05	yes	120˚, 4 vibrations
06	yes	120˚, 7 vibrations	06	yes	0˚, 9 vibrations
07	yes	0˚, 6 vibrations	07	yes	−120˚, 12 vibrations
08	yes	0˚, 12 vibrations	08	yes	120˚, 3 vibrations
09	yes	120˚, 2 vibrations	09	yes	0˚, 5 vibrations
10	yes	120˚, 13 vibrations	10	yes	0˚, 7 vibrations
11	yes	−120˚, 5 vibrations	11	yes	120˚, 2 vibrations
12	yes	0˚, 4 vibrations	12	yes	120˚, 9 vibrations
13	yes	0˚, 11 vibrations	13	yes	−120˚, 8 vibrations
14	yes	120˚, 8 vibrations	14	yes	−120˚, 4 vibrations
15	yes	0˚, 1 vibrations	15	yes	120˚, 5 vibrations

Clean-product validation was also performed using 50 uncontaminated EEDs. After multiple automated screening rounds, all 50 clean products were judged qualified, and no false-positive alarm occurred. Combining the contaminated and uncontaminated groups, the present validation produced 30 true positives, 50 true negatives, 0 false positives and 0 false negatives. Under these test conditions, the calculated sensitivity was 100% and the specificity was 100%.

A short repeatability test was further conducted by repeating the automated screening three times on the same product set. In all three runs, the products containing foreign matter were detected. For some contaminated products, the insulation resistance had already decreased below 20 MΩ during the voltage-rising stage, before vibration loading was completed. For both State 1 and State 2 products, the exact alarm round showed only the expected variation associated with random particle movement, while the final qualified/unqualified judgment remained stable in repeated runs and no false-negative result was observed.

3.3. Discussion: Comparison with PIND and Static Electrical Testing

Compared with conventional PIND, the proposed vibration-current coupling system changes the judgment basis from identifying weak impact noise to identifying an insulation-resistance change caused by metallic foreign matter. This makes the detection result more direct and less dependent on acoustic coupling, sensor mounting, background noise and subjective interpretation of small signals. In this study, laser-cut metallic microchips with a characteristic size of approximately 0.05 - 0.1 mm were successfully detected, and the 30 contaminated products and 50 clean products gave 100% sensitivity and 100% specificity under the validation conditions. The test duration is also traceable: after voltage ramping and stabilization, the programmed vibration sequence uses three radial directions, 15 cycles per direction and 1 Hz excitation, corresponding to about 45 s of vibration loading per unit. Static electrical testing is faster when a foreign matter has already formed a discharge path, but it cannot reliably detect movable particles that have not yet entered the electrostatic-discharge channel; such particles may move into the channel later during storage, transportation or use. Therefore, the proposed system provides a stronger screening margin than static electrical testing and a more intuitive criterion than PIND for small metallic foreign matters in EEDs.

4. Conclusion

Through this research project, based on theoretical analysis and deduction, a method for screening and testing foreign matters in electric igniter products using mechanical automation was developed. Specifically, vibration loading is used to excite foreign matters, making them move in the electrostatic discharge channel. The change in insulation resistance of the product is monitored in real-time to confirm the existence of foreign matters. Through calculation and manual tests, the effective impact excitation parameters for driving foreign matters were determined, such as impact magnitude, frequency and vibration direction. A corresponding device was constructed to verify the feasibility of this process method. Experimental results show that under the determined process parameters, the experimental prototype can reliably screen out all foreign matters. This method can provide a new reference for the detection of foreign matters in products in industries such as electronics and aerospace, effectively promoting the improvement of industry detection capabilities.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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