Research on Test Method of Ignition Temperature of Electric Explosive Device under Electromagnetic Pulse

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Abstract. *The safety and reliability of electric explosive device, as the most sensitive initiating energy for igniting powder and explosive, directly impact those of weapon system. The safety and reliability of the electric explosion device were determined by the ignition temperature of the electric explosion device. Based on the conservation of energy and Fourier's law, a mathematical model was built for the relationship between the temperature rise of the bridge line and the amplitude of the electromagnetic pulse. In the experiment, the semiconductor bandgap temperature measurement technology was used, and the correctness of the mathematical model was verified by altering the amplitude of the pulse signal. Then, the 50% ignition excitation of the device was determined with the Bruceton method and the statistical theory. According to the built mathematical model, the ignition temperature of the electric explosion device was determined as 412°C. In this paper, the measurement method of the ignition temperature of the electric explosive device was developed, which could act as a technical means for the safety assessment of the electromagnetic environment of the weapon system. Moreover, this method is critical to improve the safety and survivability of the weapon system in the complex electromagnetic environment.*

Keywords

Electric explosive device, electromagnetic pulse, weapon, ignition temperature, electromagnetic environment

1. Introduction

With the modernization of weapon system, microelectronic technology, computer technology and electro explosive devices have been extensively used in all kinds of high-tech weapons and equipment, making them increasingly information-based and electromagnetic sensitive [1]. In the high-tech battlefield, the complex electromagnetic environment affects the performance of weapons and equipment, while threatening their survival. In the military engineering of conventional weapons (e.g., ammunition, missiles, nuclear weapons and aerospace), the position and role of the electric explosive device (the most sensitive initiating energy exploited to ignite gunpowder and detonating explosives) in the weapon system are determined by its first function and sensitivity [2–4]. The safety and reliability of the electric explosive device directly affect those of the weapon system, which are determined by the ignition temperature of the electric explosive device. Therefore, accurate ignition temperatures can technically support the electromagnetic safety evaluation of the electric explosion device.

Electric detonators refer to the electric detonators or components that use electric energy to ignite the explosives, propellants or pyrotechnic materials contained in these devices (e.g., hot bridge electric detonators, conductive explosive synthetic detonators, semiconductor bridge electric detonators, laser detonator initiators, exploding foil detonators and burning metal wires or fused fuses) [5–8]. The electric energy is used as the initial excitation energy of the electric explosive device, and the most common form is the hot bridge wire electric explosive device, which is called bridge wire electric explosive device for short. The bridge wire electric explosive device is detonated by Joule heat generated on the bridge wire. Whether a given excitation source can detonate an electric explosive device depends on the current on the bridge wire and the initiation characteristics of the powder on the bridge wire. Whether the temperature on the bridge wire reaches the initiation temperature is a problem that must be considered [9–13]. On the whole, the safety test method of electromagnetic radiation in the service life of the electric explosion device is assessed by the induced current on the electric explosion device. With the radiation frequency reaching GHz, the induced current on the lead wire of the electric explosive device tends to form a standing wave. In addition, the current amplitude at different positions on the lead wire of the electric explosion device will vary obviously. Moreover, under the skin effect, the current is difficult to accurately measure at the bridge wire position [14], [15]. Accordingly, the electromagnetic safety of the electric explosion

device is unlikely to accurately assess. However, the temperature rise of the bridge wire is insignificantly related to the radiation frequency of the electromagnetic wave. The accurate measurement of the ignition temperature of the electrical explosive device can provide an effective technical means for the electromagnetic safety evaluation of the electrical explosive device weapon equipment.

The absolute radiation intensity of the black body is measured by the passive infrared temperature measurement device of the US Navy [16], [17]. Because the temperature measurement system has no light source, it will not affect the thermal and electromagnetic characteristics of the measured object. Besides, the blackbody had a significantly weak infrared light in the low temperature range (0–100°C), so the accuracy of the chip is noticeably high, and it is greatly affected by the environment. In Canada, an optical fiber fluorescence temperature measurement method of photoluminescence physical phenomenon has been adopted to measure the temperature of the electric explosion device [18]. The detection circuit determines the temperature of the electric explosion device by detecting the fluorescence lifetime in the reflected fluorescence. However, the response time of the temperature measurement system is too long, which is about 100 milliseconds, so it cannot be used for measurement of instantaneous pulses. In China, the fluorescence temperature measurement method based on the relationship between fluorescence decay time and temperature is used to measure the temperature of the electric explosion device [19], [20]. The principle is similar to that of the optical fiber fluorescence temperature measurement method, but the device is different. The response time of the temperature measurement system is too long to be used for instantaneous pulse measurement. All the above temperature rise test methods are used to evaluate the ignition temperature of the electric explosion device under the condition of injecting DC current.

In this paper, the ignition temperature of the electric explosive device was evaluated under the action of electromagnetic pulse. On that basis, a new method was developed to evaluate the ignition temperature of the electric explosive device. Based on the conservation of energy and Fourier's law, a mathematical model of the relationship between the temperature rise of the bridge line and the amplitude of the electromagnetic pulse was established. The semiconductor bandgap temperature measurement technology is not sensitive to mechanical vibration and fiber movement, and it is completely immune to EMI. Given this, the technology was used to conduct the mathematical model test verification research on the ignition temperature rise and excitation signal of the electric explosion device. Next, under the action of the pulse excitation signal, the 50% ignition excitation of the electric explosive device was determined by using the Bruceton method test and statistical theory. According to the established mathematical model, the ignition temperature of the electric explosive device was measured, which could provide a technical means for the safety assessment of the electromagnetic environment of the weapon system. Moreover, this paper is critical to improving the safety and survivability of the weapon system in the complex electromagnetic environment.

2. Theoretical Analysis

The bridge wire material of the electric explosive device applied in the test was nickel-chromium alloy 6J20 with a significantly low-temperature coefficient of resistance, nearly $7 \times 10^{-5}°C^{-1}$[21]. Since the ignition temperature of the electric explosive device is lower than 1000°C, falling into the test error range, it could be considered that the resistance of the bridge wire does not vary with the temperature increase. Under the different characteristics exhibited by the external excitation signal, the bridge wire might heat up under two conditions, i.e., adiabatic or thermal equilibrium. Under adiabatic conditions, the heat generated by the bridge wire is expressed as:

$$Q = \int_0^{t_0} \frac{(U \cdot D)^2}{R} dt \tag{1}$$

where U denotes the peak value of the pulse signal voltage; D represents the duty cycle; R expresses the equivalent impedance of the electric explosive device; t_0 is the action time.

By complying with the law of conservation of energy, all the heat generated was employed for the temperature increase in the bridge wire of the electric explosive device. Then, it yields:

$$Q = \int_0^{t_0} \frac{(U \cdot D)^2}{R} dt = c \cdot m \cdot \Delta T \tag{2}$$

where c denotes the specific heat of the bridge wire of the electric explosion device; m represents the quantity of the bridge wire of the electric explosion device; ΔT expresses the temperature increase in the bridge wire of the electric explosion device.

Under the heat balance, the heat generated by the bridge wire of the electric explosive device was used for the temperature increase in the bridge wire, and part of it was conducted to the external medium. Based on Fourier's law, the heat lost by the bridge wire is proportional to the temperature gradient dT/dr in the direction perpendicular to the cross-section and the cross-sectional area S. Then, it yields:

$$Q' = k \cdot \frac{dT}{dr} \cdot S \tag{3}$$

where k denotes the heat transfer coefficient of the medium.

The temperature increase ΔT on the bridge wire of the electric explosive device satisfies an integral relationship with dT/dr. On that basis, the relationship between ΔT and Q' is also proportional to be given for idealized conditions.

$$Q' = k' \cdot \Delta T \tag{4}$$

where k' represents the proportional coefficient.

As indicated from (2) and (4), U^2 is proportional to T under thermal equilibrium conditions. This conclusion underpins the determination of the ignition temperature of electric explosive devices under electromagnetic pulses.

3. Test Method

3.1 Test Method for Temperature Increase of Bridge Wire under Electromagnetic Pulse

As impacted by electromagnetic pulse, to measure the ignition temperature of the electric explosive device, the relationship between the temperature increase in the bridge wire of the electric explosive device and the amplitude of the electromagnetic pulse should be determined. By regulating the electromagnetic pulse amplitude, the temperature increase in the bridge wire of the electric explosive device under different pulses was determined, as an attempt to develop the relationship between the two.

Under electromagnetic pulse, to analyze the change law of bridge wire temperature increase and pulse amplitude, this paper developed the test method of the relationship between bridge wire temperature increase and electromagnetic pulse amplitude of the electric explosive device. Figure 1 presents the test principle diagram. The test system primarily consisted of electromagnetic pulse source INS 4040, optical fiber temperature measurement system, and bridge wire for removing explosives.

After the explosive of the electric explosive device was removed clean, the exposed bridge wire for a temperature increase test was obtained. Next, the exposed bridge wire to remove the explosive was fixed after contacting the optical fiber temperature sensor (Fig. 2). The corresponding bridge wire temperature increase could be determined by injecting the excitation signal into the exposed bridge wire.

The optical fiber temperature sensor consisted of tiny crystals of gallium arsenide (GaAs) glued to the top of the optical fiber. The principle diagram is shown in Fig. 3. Light from the signal demodulator was injected into the fiber, which was directed to a GaAs crystal. Subsequently, light waves below the bandgap spectrum were absorbed, while those above the bandgap were reflected to the signal demodulator. The light reflected back from the signal demodulator went into a small spectrometric analyzer, thereby breaking the light space down into its wavelength components. In addition, an optical detector's linear Charge Coupled Device (CCD) array measured light intensity at the mentioned wavelengths, and each pixel of the Charge-Coupled Device array represented a particular calibrated wavelength. Thus, the entire detector array provided the spectral intensity distribution reflected to the GaAs crystals, which was translated into an absolute temperature reading.
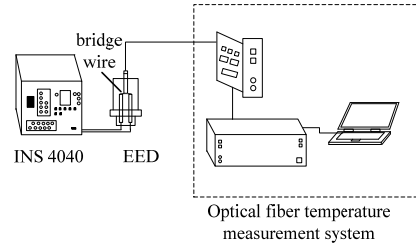

Fig. 1. Schematic diagram of testing the relationship between bridge wire temperature increase and electromagnetic pulse amplitude.
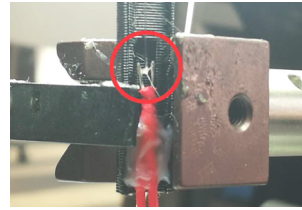

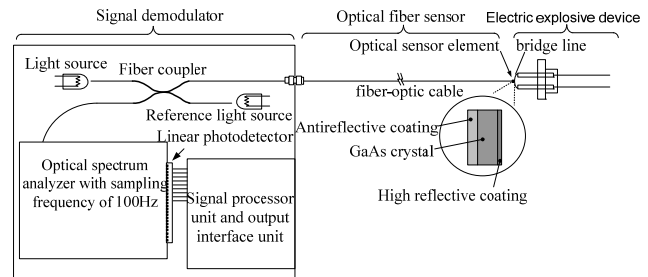**Fig. 2.** The fixed structure of the exposed bridge and the optical fiber temperature sensor.

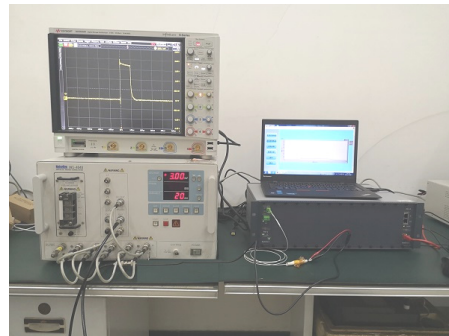**Fig. 3.** Principle diagram of optical fiber temperature measurement system.

Fig. 4. Bridge wire temperature increase and electromagnetic pulse parameter test system.

According to the principle diagram of the test system for the relationship between the temperature increase in the bridge wire and the electromagnetic pulse amplitude, the test system was built (Fig. 4). After removing the explosive on the bridge wire of the electric blasting device, the electromagnetic pulse source directly employed the pulse signal to both ends of the bridge wire of the electric blasting device, and then the temperature increase on the bridge wire was measured with the optical fiber temperature measuring system. Under the electromagnetic pulse width (PW) of 150 ns and the pulse frequency of 50 Hz, by regu-

lating the electromagnetic pulse amplitude, the temperature increase in the bridge wire under different electromagnetic pulse amplitudes was determined. The test result is presented in Fig. 5. The curve of different colors in the diagram indicates the bridge filament of the corresponding pulse amplitude.

When the temperature on the bridge wire of the electric explosive device reached equilibrium, the test data of the temperature increase in the bridge wire and the pulse amplitude were acquired based on the test results (Tab. 1).

According to the test results listed in Tab. 1, the relationship was drawn between the temperature increase in the bridge wire and the pulse amplitude under the equilibrium state of the bridge wire temperature increase of the electric explosive device (Fig. 6). Moreover, the relationship model was built between the temperature increase in the bridge wire and the pulse amplitude in the equilibrium state, as written in (5).

$$T_2 - T_0 = 2.49 \times 10^{-4} \times U^2 \tag{5}$$

where T_2 denotes the temperature of the bridge wire; T_0 is the temperature of the outside environment; U expresses the amplitude of the electromagnetic pulse.
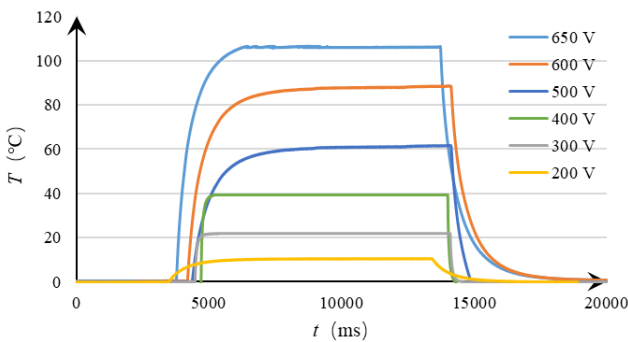

Fig. 5. Test results of pulse amplitude and temperature increase of bridge wire, $f = 50$ Hz, PW = 150 ns.

Pulse amplitude (V)	200	300	400	500	600	650
Temperature increase of bridge wire (°C)	10.0	22.1	39.3	62.4	89.3	106.5

Tab. 1. Test data of pulse amplitude and temperature increase of bridge wire, $f = 50$ Hz, PW = 150 ns.
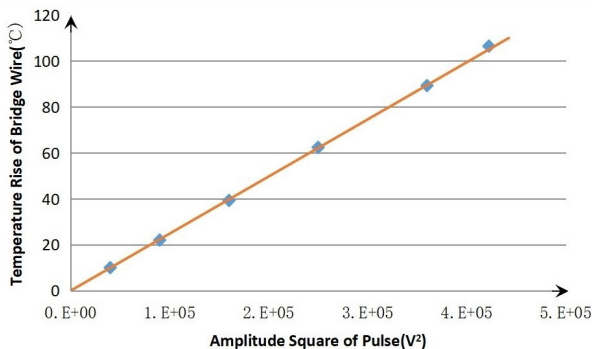

Fig. 6. The relationship curve between bridge wire temperature increase and pulse amplitude square.

3.2 Test Method for Ignition Excitation of Electric Explosive Device under Electromagnetic Pulse

To determine the amplitude of the electromagnetic pulse signal under the ignition of the electric explosive device, the ignition excitation of the electric explosive device as impacted by electromagnetic pulse should be tested. Figure 7 illustrates the ignition test system of the electric explosive device. The test system comprised an electromagnetic pulse source INS 4040, an electric explosion device, as well as a test box. Furthermore, the INS 4040 output was connected to an electric explosion device and then placed in a test chamber to be tested.

When the pulse width and pulse frequency were unchanged, the electric explosive device ignition excitation test was performed by regulating the amplitude of the electromagnetic pulse signal. The test steps are elucidated below [22], [23]:

Step 1: Put the electric explosive device into the ignition test box, and then connect it with the INS-4040 via a wire to build a test system for the electric explosive device ignition excitation as impacted by the electromagnetic pulse.

Step 2: Set the pulse width of the electromagnetic pulse signal to 50 ns, the pulse frequency to 12.5 Hz, and the initial pulse amplitude to 1230 V, and perform the ignition test of the electric explosive device. When $i = 0$, the pulse amplitude acted as the first effective stimulus. The test results were recorded, the response was 1, and the nonresponse was 0. The pulse amplitude used in the second and subsequent tests is presented as follows: if the previous test used the pulse amplitude corresponding to i, under the test result of 1, the test would use the pulse amplitude corresponding to $i - 1$. Under the trial result of 0, it would be the pulse amplitude corresponding to $i + 1$. Observe whether the electric explosive device is ignited by regulating the pulse amplitude based on the Bruceton method. If the electric explosive device is not ignited, increase the pulse amplitude of the fixed step till the electric explosive device is ignited, and then down-regulate the pulse amplitude of the fixed step until the electric explosive device is not ignited. The test was performed with the Bruceton method, and the test data are listed in Tab. 2.

Fig. 7. The ignition excitation test system of the electric explosive device as impacted by the electromagnetic pulse.

Pulse Amplitude	i	del	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1290 V	2						1									
1270 V	1			1		0		1		1						
1250 V	0		0		0				0		1		1		1	
1230 V	−1	0										0		0		0
1210 V	−2															

Pulse Amplitude	i	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1290 V	2								1		1		1			
1270 V	1	1				1		0		0		0		1		1
1250 V	0		1		0		0								0	
1230 V	−1			0												
1210 V	−2															

Tab. 2. Test data of ignition excitation of electric explosive device under electromagnetic pulses. Explanations: *i* is weight coefficient; 'del' represents 'delete'.

To improve the reliability of the test data, the test data should be processed:

(1) The test results were not calculated from the first test, but from the previous time when the reaction result was opposite to the first reaction result, as an attempt to reduce the effect exerted by the probing stimulus on the test result.

(2) At the end of the test, the reaction result between ignition and non-ignition should be altered to avoid the sampling test data from deviating in a certain direction.

(3) The number of ignitions in the test should be maximally the same, or there should be only one difference from the number of no ignitions to improve the test accuracy of 50% of the critical stimulus.

The test was initiated at 1230 V, and 20 V was selected as the step voltage test. The test data are listed in Tab. 1.

Referencing to Bruceton method [23], [24],

$$\sum n_{i1} = 15 \qquad (6)$$

where n_{i1} denotes the ignition number of the sample.

$$\sum n_{i0} = 14 \qquad (7)$$

where n_{i0} represents the misfired number of the sample.

$$n = \sum n_i = \sum n_{i0} = 14 \qquad (8)$$

where n expresses the number of valid probes.

$$A = \sum (i \cdot n_i) = -7, \qquad (9)$$

$$B = \sum (i^2 \cdot n_i) = 11, \qquad (10)$$

$$M = \frac{n \cdot B - A^2}{n^2} = \frac{14 \times 11 - (-7)^2}{14^2} \approx 0.54, \qquad (11)$$

$$b' = \left| \frac{A}{n} - \frac{1}{2} \right| = \left| \frac{-7}{15} - \frac{1}{2} \right| \approx 1.0. \qquad (12)$$

When $b' > 0.5$, $b = 1 - b' = 0$. Here A, B, M, b' and b are the median values adopted to calculate 50% ignition electrical excitation and assess the standard deviation.

Based on the calculating results of n, M and b, from the appendix of GJB/Z 377A-94, it yields,

$$\rho = \rho(n, M, b) = \rho(14, 0.54, 0) = 1.049, \qquad (13)$$

$$G = 0.998, \qquad (14)$$

$$H = 1.403 \qquad (15)$$

where ρ, G and H are the median values.

The 50% igniting voltage estimate value μ of the tested sample is expressed as:

$$\mu = y_0 + \left(\frac{A}{n} \pm \frac{1}{2} \right) \cdot d = 1250 + \left(\frac{-7}{14} + \frac{1}{2} \right) \times 20 = 1250 \qquad (16)$$

where y_0 denotes the pulse signal voltage of the first test stimulation; d represents the variation in the amplitude of the excitation signal. Explanations: n from (7), adopting '+'.

Standard deviation estimate value σ:

$$\sigma = \rho \cdot d = 1.049 \times 20 = 20.98. \qquad (17)$$

According to the pulse amplitude at 50% ignition of the electric explosive device, combined with the relationship model (5) between the temperature increase in the bridge wire and the pulse amplitude in the equilibrium state, the ignition temperature of the electric explosive device was calculated as 412°C.

4. Conclusion

This paper aimed to examine the temperature of the bridge wire during the ignition of the electric explosive device. For this end, based on the law of conservation of energy and Fourier law, a theoretical model was built to describe the relationship between the temperature increase in the bridge wire and the amplitude of the electromagnetic pulse under the adiabatic and thermal equilibrium. To verify whether this relationship is correct, a test system impacted by the electromagnetic pulse was developed to analyze the relationship between bridge wire temperature increase and pulse amplitude. Besides, the correctness of the relationship model between bridge wire temperature increase and pulse amplitude was verified experimentally. With the Bruceton method, the pulse amplitude at 50%

ignition of the electric explosive device was determined experimentally. Based on the relationship model between the temperature increase in the bridge wire and the amplitude of the electromagnetic pulse in the equilibrium state, the ignition temperature of the electric explosive device was measured as 412°C.

In this paper, the 50% ignition excitation of the electric explosive device was determined with the Bruceton method and the statistical theory under the action of electromagnetic pulse. By performing the electromagnetic pulse injection test, the equivalent test under the high amplitude of electromagnetic pulse was achieved, and the measurement of the ignition temperature of the electric explosion device was realized. On that basis, a new method was proposed to evaluate the ignition temperature of the electric explosion device. This method is capable of technically supporting electromagnetic radiation effect test of weapon system, and helps ensure the survivability of weapon system in the complex electromagnetic environment.

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