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Article

Research on Electromagnetic Radiation Characteristics of Energetic Materials

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Abstract: During the explosion of energetic materials, obvious electromagnetic interference will be generated, which will affect the normal operation of surrounding electronic equipment. Experiments are still an important means to study this issue. A set of electromagnetic radiation measurement device based on short-wave omnidirectional antenna and ultra-wideband omnidirectional antenna is designed to measure the electromagnetic radiation generated by the explosion of energetic materials of different masses, and the electromagnetic radiation characteristics are obtained through data processing. The results show that the mass of the energetic material has a significant effect on the time-domain characteristics of the electromagnetic radiation generated by the explosion: the higher the mass of the energetic material, the shorter the delay response of the electromagnetic signal, the longer the duration, and the earlier the peak appears. The frequency of electromagnetic radiation signals generated by the explosion of energetic materials is mainly concentrated below 100 MHz, and the energy is most concentrated in the frequency band of 0~50 MHz. The composition of energetic materials has the greatest influence on the spectral distribution, and the spectral distribution of electromagnetic radiation produced by the explosion of explosives with different compositions has obvious specificity. The electromagnetic radiation intensity generated by the explosion of energetic materials has a strong correlation with the distance from the explosion center, and it decreases with the increase of the distance, and the decreasing range is large. The structure and detonation method of energetic materials can change the geometrical motion mode during the explosion, resulting in the non-uniformity of electromagnetic radiation propagation.

Keywords: explosion; energetic material; electromagnetic radiation; characteristic

1. Introduction

It produces strong electromagnetic radiation during explosion of energetic materials. Electromagnetic radiation of different intensities or frequencies can cause electromagnetic interference on nearby electronic equipment such as unmanned aerial vehicle or communication device, and in severe cases, the equipment cannot be started or even damaged, causing an accident. In order to improve the anti-electromagnetic interference performance of electronic equipment, it is necessary to measure and study the electromagnetic radiation generated by the explosion of energetic materials[1].

In 1954 Kolsky published an article in Nature on measurements of electromagnetic waves emitted from the detonation of high-explosives charges[2]. Boronin studied the physical mechanism of the electromagnetic wave generated by the explosion of condensed explosives. Boronin believed that at the initial moment of metal deformation and destruction, gaseous and solid potential energy flowed out of the formed cracks. Due to the electrokinetic effect and the friction of the potential energy on the failed shell, the shell is charged and the charged polarity of the gas and the solid are opposite. Because of the asymmetric scattering of the potential energy, the space charge of the potential energy of the gas and the solid forms an effective dipole. Boronin proposed that the mechanism of electromagnetic radiation produced by explosion is related to the acceleration or deceleration of certain electronic genes in the ionized air layer at the front of shock wave, which is later called the "Boronin effect"[3-4]. Boronin elaborated firstly the mechanism of electromagnetic radiation generated during the explosion of energetic materials, and guided the direction of related research in the future, which is of great significance. A.L.Kuhl explained the mechanism of electromagnetic waves generated by TNT, he believed that the movement of ionized atoms, ions, and electrons was the cause of explosive electromagnetic waves. The expansion of detonation products caused strong vibration in the surrounding air and formed a strong heat wave lasting about 20 μs. Temperatures as high as 11000 K cause significant ionization in the air, and the movement of ion plaques generates electric currents that generate electric and magnetic fields. Kuhl studied the effects of these motions through numerical simulations of TNT explosions, using high-order Godunov Equations to integrate the conservation laws of one-dimensional aerodynamics, and using a very fine grid (minimum unit as 10 μm) to obtain the convergent temperature and the conductivity profile, which is used to predict the three-dimensional electromagnetic waves generated by TNT explosion[5-7]. Li Jianqiao conducted theoretical and numerical simulation studies on the natural magnetic field disturbance caused by the explosion of energetic materials, obtained the temporal and spatial distribution of the electrical conductivity and the magnetic field diffusion rate of the explosive field, and found that the explosive initiation parameters have a great influence on the magnetic field disturbance. Li Jianqiao developed a more reliable method for numerical simulation of magnetic field disturbances in explosive fields, and pointed out that when explosives are geometrically asymmetric, different magnetic field disturbances will be generated in different directions of the natural magnetic field through numerical simulations. Different types of energetic materials have different magnetic field disturbance amplitudes, but the disturbance mode is the same, and this research has not been paid attention to in related fields and has high innovative value[8-9]. Ren Huilan and Chen Hong carried out electromagnetic radiation measurement experiments on B explosive and RDX-based aluminum-containing explosive respectively. The research results showed that the electromagnetic radiation signal spectrum generated by the explosion of 4.5~7.5 kg B explosive was mainly distributed in the range of 0~50 kHz, and the amplitude of the first pulse was basically linear to 1/3 equivalent power, its arrival time is not sensitive to the amount of explosives. The intensity of electromagnetic radiation signal generated by the explosion of 160~188g RDX-based aluminum-containing explosive is in the range of 1.87~15.20 V/m, and the spectrum distribution of electromagnetic radiation is mainly concentrated in the range of 500 MHz, while the content of aluminum in the explosive has an obvious effect on the spectrum distribution of 100~500 MHz[10-11].

In this article we use dual-frequency antenna to measure electromagnetic wave and high-speed acquisition card to record data. The electromagnetic signal is analyzed in detail using methods of noise reduction, Fourier transform, and attenuation compensation. The time-domain and frequency-domain variation characteristics of electromagnetic radiation produced by explosions are discussed, and a more comprehensive and accurate law of electromagnetic radiation has been obtained.

2. Experimental Principle and Method

2.1. Experimental Principle

Measuring electromagnetic radiation generated by explosive needs to consider factors such as electromagnetic radiation intensity, propagation law and direction, equivalent test and antenna device protection in the explosive field. According to the theory of explosion mechanics and electromagnetics, assuming f is the characteristic time, $\mathrm{f} = \mathrm{t}/m^{1/3}$, m is the quality of explosive, the relationship between the velocity of the gas explosion product $u(f)$, the velocity of the solid particles in the explosion product $v(f)$, and the shell fragment velocity u can be expressed as:

$$u(f) = \frac{dR(f)}{df} \tag{1}$$

$$v(f) = u(0)\exp(-Bf) + B \cdot \exp[-Bf \int_0^f u(f) e^{Bf} df] \tag{2}$$

$$u = \frac{D}{2}\left\{\frac{1}{2U+1}[1 - (\frac{r_0}{r})^4]\right\}^{1/2} \tag{3}$$

$$B = \frac{9}{5}\frac{Z}{a^2} m^{1/3}, \quad U = \frac{M_c}{m} \tag{4}$$

Where *R*(*f*) is the radius of the contact surface between the gas explosion product and the shell, $R(f) = 1 + 4.6 \times 10^4 f - 0.57 \times 10^8 f^2 + 3.3 \times 10^{10} f^3 - 10^{13} f^4 + 1.2 \times 10^{15} f^5$, *u*(*0*) is the velocity of the gas explosion product at the initial moment. In Equation (4), *a* is the radius of solid particle, *d* is the particle density, and *Z* is the viscosity coefficient. According to the characteristics of the condensed explosive, 2 μm≤a≤5 μm, d≈2 g/cm^3, η≈1.0×10^3 g/(cm·s), when the quality of working condition is constant, *B* can be considered as a constant. In Equation (3), r_0 is the charging radius, *r* is the limit expansion radius of the charging shell during explosion, Equation (3) becomes $u \approx \frac{D}{2}(\frac{1}{2U+1})^{1/2}$ with ignoring $(r_0/r)^4$. Therefore, when studying the electromagnetic radiation of energetic materials, as long as the parameters of *m*, *Mc*, *f*, *B* and *D* are considered, *u*(*f*), *v*(*f*) and *u* are considered equivalently. In electromagnetism, $E = \frac{q}{4\pi X r^2}$, when measuring the electromagnetic radiation of energetic materials, it just needs to consider the electric field intensity *E*, the dielectric constant of air *X* and the distance between antenna and explosion center *r*[12-16].

2.2. Experimental method

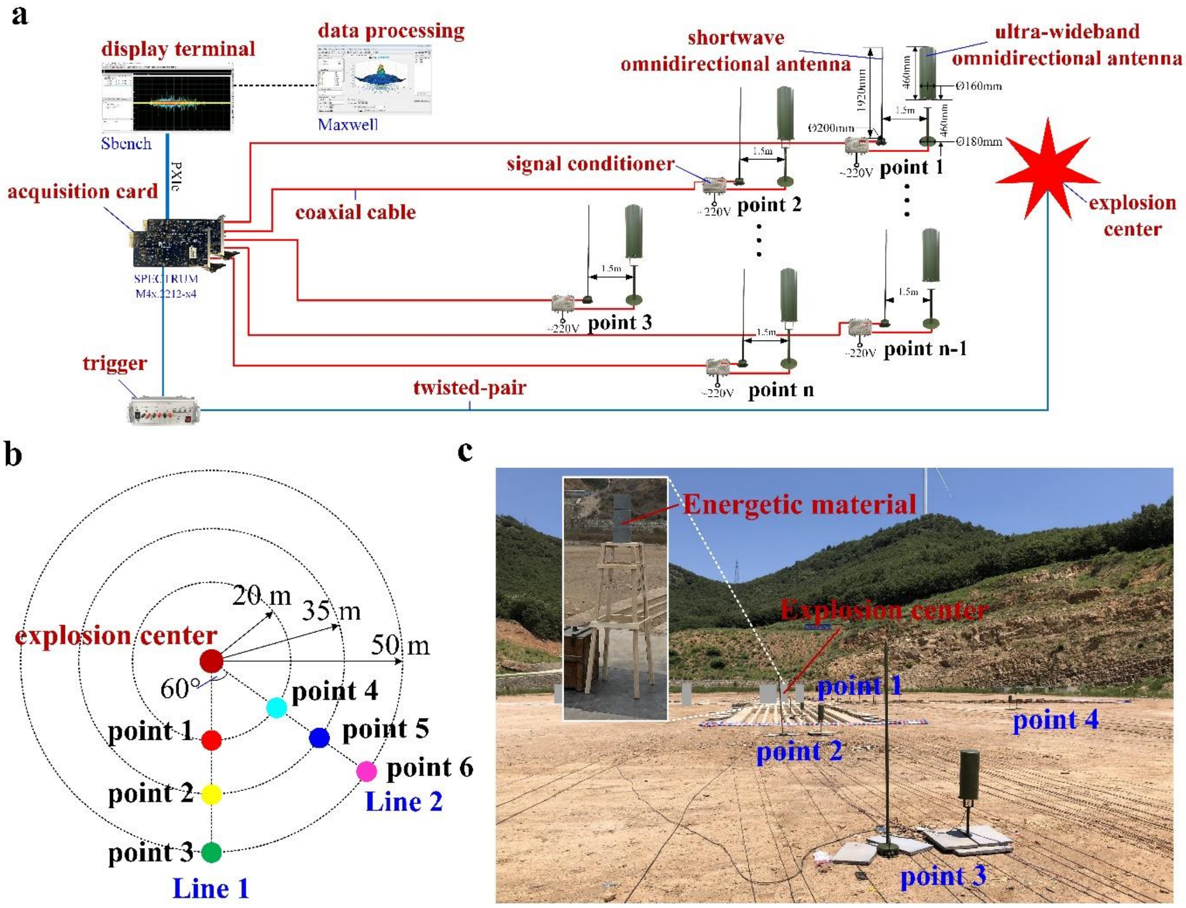

Figure 1. (a) electromagnetic radiation experimental device; (b) test points distribution; (c) experiment field.

According to the theoretical analysis of blasting mechanics, combined with the quality of explosives used in the experiment, an electromagnetic radiation measuring device is designed, which is shown as Figure 1(a). The test point consists of a short-wave passive omnidirectional antenna, an ultra-wideband passive omnidirectional antenna, a signal amplifier and a limiter. The short-wave passive omnidirectional antenna is a monopole antenna with the height of 2000 mm, the sampling frequency of which is 1 MHz~30 MHz and the output impedance is 50 Ω. The ultra-wideband omnidirectional antenna is a dipole antenna with the height of 450 mm, the sampling frequency of which is 30 MHz~1.5 GHz and the output impedance is 50 Ω. The signal conditioner possesses multiple functions, including a combiner, signal amplifier and limiter, which can combine two electromagnetic signals of different frequencies and amplify the signal at the same time with a range of amplification factors of 10 dB~30 dB. The function of the limiter with limiting power greater than 10 W is to prevent the signal power from being excessively high and damaging acquisition card. The test point is connected to the data acquisition card through the radio frequency line, and the high-speed acquisition card is used to record data. The maximum sampling rate is set to 3 GSa/s, the electromagnetic signal with the highest frequency of 1.5 GHz can be collected on basis of Nyquist sampling law, which matches the frequency bandwidth of antenna. The sampling duration is set to 810 ms, in which the sampling duration before the trigger is 10 ms, and the sampling duration after the trigger is 800 ms[17-21]. As shown in Figure 1(b), there are six test points in the test points distribution diagram. The point 1, point 2 and point 3 form line 1, which are respectively 20, 35 and 50 meters away from the explosion center. The point 4, point 5 and point 6 form line 2, the distance from the explosion center is 20, 35 and 50 meters respectively. The angle between Line 1 and Line 2 is 60 degrees. The measuring equipment is placed on basis of the distribution shown in Figure 1(b), and the electromagnetic radiation measurement experiment field is shown in Figure 1(c).

3. Experimental Results and Analysis

This paper mainly studies the electromagnetic radiation of 30 kg TNT and 60 kg TNT explosions, and the explosion experiment process of energetic material is shown in Figure 2. Before the start of the experiment, the electromagnetic background noise of the experimental site was first tested. The maximum voltage of the background electromagnetic signal measured was 62.5 mV, and the average voltage was 12.531 mV. The electromagnetic signal waveform was stable without fluctuation. It can be considered that the electromagnetic noise interference of the experimental site is extremely weak, and the explosion electromagnetic radiation experiment can be carried out.

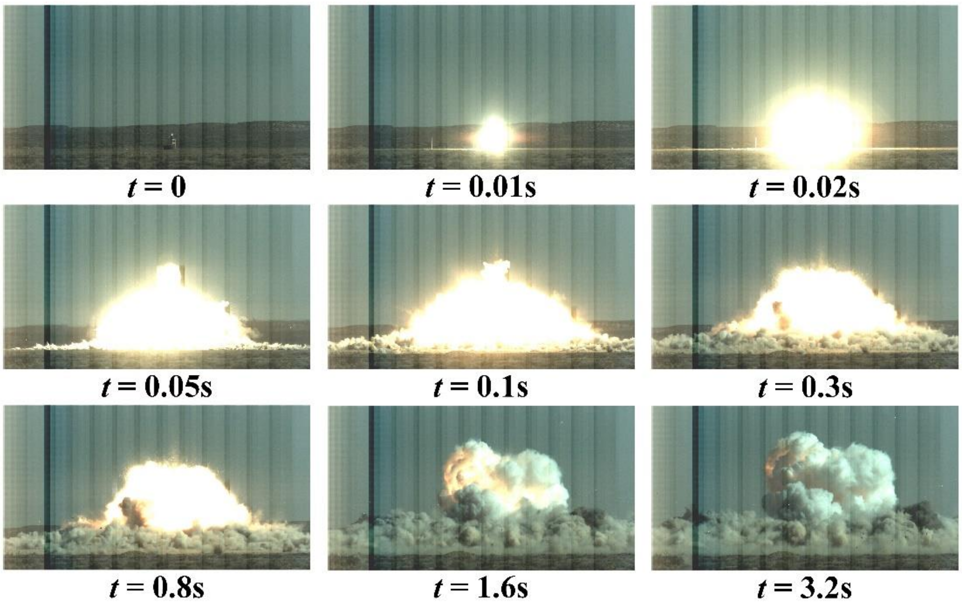

Figure 2. Explosion experiment process of energetic material

3.1. Analysis of the Time-Domain Characteristics of Electromagnetic Radiation

The time-domain characteristics of electromagnetic radiation mainly include main parameters such as the duration in the sampling period, the delay response time, and the peak arrival time[22]. In this paper, a total of two effective experiments were carried out, and the electromagnetic signals of 30 kg TNT and 60 kg TNT explosives were measured respectively. Each group of experiments included the signals of six channels, and each channel corresponds to the test points 1~6. The electromagnetic radiation signal generated by the explosion of 60 kg TNT is shown in Figure 3(a), and the time-domain distribution of the electromagnetic signal of each adopted channel is shown in Figure 3(b). It can be seen from Figure 3 that the time domain distribution of the 60 kg TNT electromagnetic pulse is also denser, which proves that the mass of the energetic material has an important influence on the duration of the electromagnetic radiation generated by the explosion. The greater the mass, the longer the duration of the electromagnetic signal. The time-domain distribution of the electromagnetic signals measured by each test point is regular, the electromagnetic signal measured by the test points far from the explosion center has a shorter duration, and the time domain distribution of the electromagnetic pulse is also scattered.

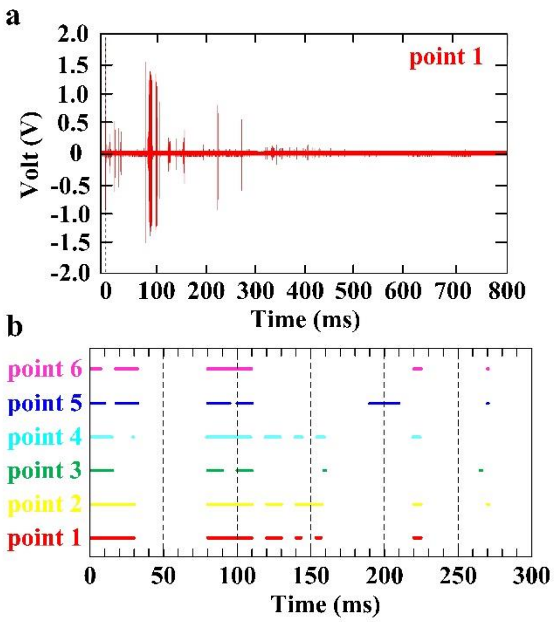

Figure 3. Electromagnetic radiation signal of TNT explosion. **(a)** Full-time electromagnetic radiation signal of 60 kg TNT explosion; **(b)** Time-domain distribution of electromagnetic radiation of 60 kg TNT explosion

The delay of the electromagnetic radiation signal generated by the explosion of 30 kg TNT is shown in Figure 4(a) and (b), and the delay of the electromagnetic radiation signal generated by the explosion of 60 kg TNT is shown in Figure 4(c) and (d). It can be seen from Figure 4 that the electromagnetic signal of 60 kg TNT appears significantly earlier than that of 30 kg TNT, the duration of the electromagnetic signal generated by the explosion of 60 kg TNT is also significantly longer than that of 30 kg TNT, and the peak time of the electromagnetic signal generated by the explosion of 60 kg TNT is significantly earlier than that of 30 kg TNT.

The electromagnetic radiation signal produced by the explosion of 30 kg TNT appeared 1.5~2.7 ms before the trigger, and a large-amplitude electromagnetic pulse appeared around 9.8 ms. The signal delay response time of each test point is not much different, and the test point far from the explosion center has a slightly later signal appearance time. The arrival time of the electromagnetic radiation signal generated by the 60 kg TNT explosion is concentrated between 46 μs and 62 μs after the trigger time. At the same distance, the electromagnetic signal appearance time of the test point on the testing line 2 is 5~10 μs delayed than that of the test point on the testing line 1, and the peak appearance time of the electromagnetic signal measured by most of the test points is between 0.31~0.39 ms. The mass of energetic materials has a significant impact on the time-domain characteristics of the electromagnetic radiation produced by the explosion. For energetic materials of the same quality, the type and composition of explosives have no significant effect on the time-domain characteristics of electromagnetic radiation generated by the explosion.

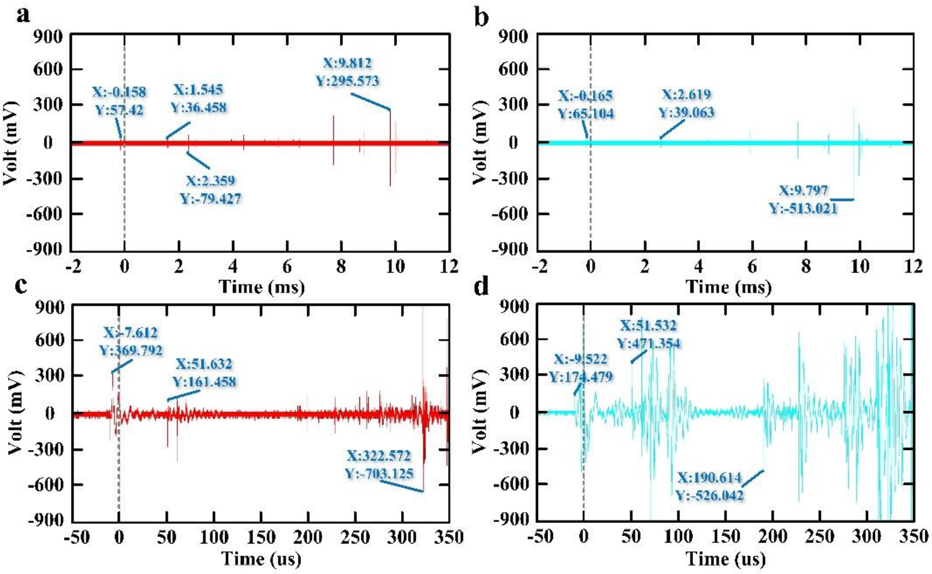

Figure 4. Delay response time of electromagnetic radiation signal of TNT explosion

3.2. Analysis of the Frequency-Domain Characteristics of Electromagnetic Radiation

Due to the large mass of energetic materials, the electromagnetic radiation signal lasts for a long time, and an obvious phenomenon of electromagnetic wave reflection and superposition occurs after 50 ms. In order to facilitate comparison with previous literature data and explore the law of electromagnetic radiation of explosion, this paper extracts the electromagnetic signal within the initial 2.5 ms, and combines the experimental results of small-equivalent energetic materials to summarize and study the law. Electromagnetic radiation signal of 60 kg TNT is shown in Figure 5.

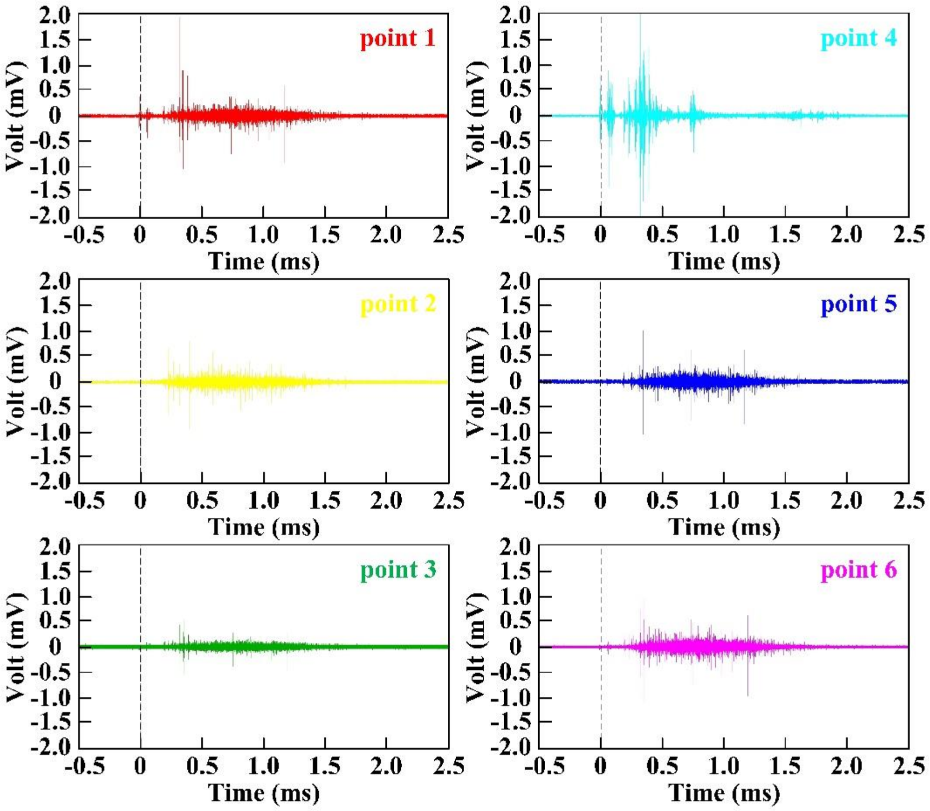

Figure 5. Electromagnetic radiation signal of 60 kg TNT

The spectral distribution of electromagnetic radiation is an important parameter in electromagnetic signal analysis, and the electromagnetic radiation signal is processed by means of Fourier transform with Hanning window. The electromagnetic radiation frequency distribution of 60 kg TNT is shown in Figure 6. The electromagnetic signal frequencies measured at test points 1~3 are mainly concentrated in 0~60 MHz and 90~105 MHz, and the amplitude in the 0~30 MHz frequency band is larger. The electromagnetic signal frequencies measured at test point 4 are mainly concentrated in 0~100 MHz, and the amplitude is larger in the 0~40 MHz frequency band. The frequency of electromagnetic signals measured at test point 5 is mainly concentrated in 0~40 MHz, of which the amplitude is larger in the 0~20 MHz frequency band, and there is a small amount of signal distribution in the 90~100 MHz frequency band. The electromagnetic signal frequencies measured at test point 6 are mainly concentrated in 0~20 MHz and 80~100 MHz, and the amplitude is larger in the 0~10 MHz frequency band.

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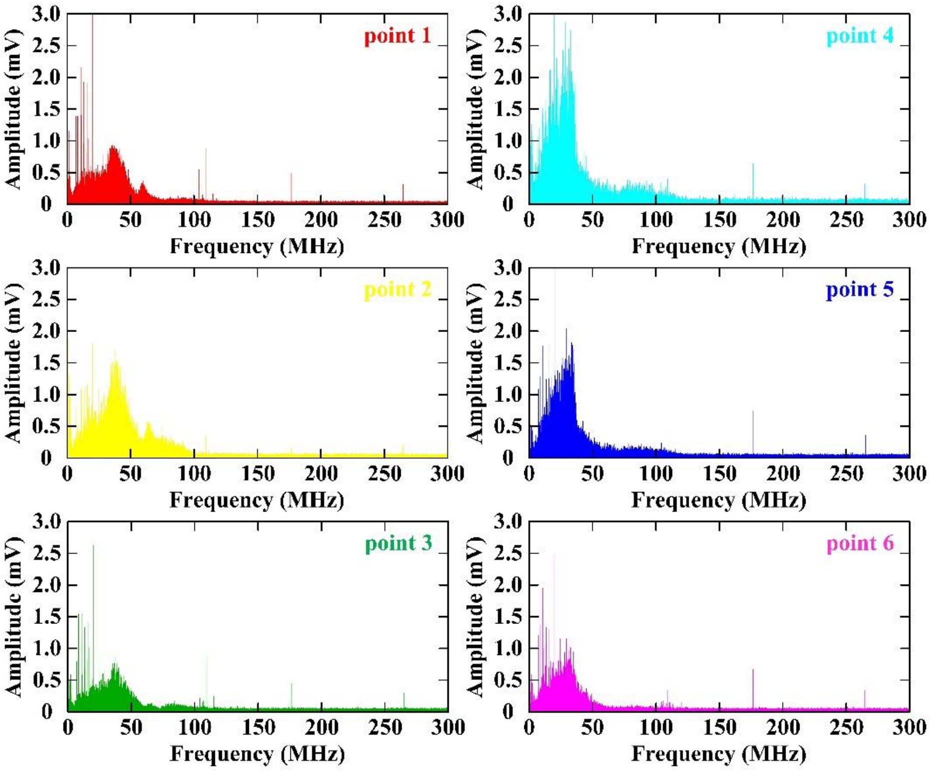

Figure 6. Spectrum of electromagnetic radiation signal of 60 kg TNT

According to the experimental data in the references, it can be concluded that the larger the mass of the energetic material, the larger the frequency distribution range of the electromagnetic radiation signal generated by the explosion, and the more concentrated the energy. The composition of energetic materials has the greatest influence on the spectrum distribution, and the electromagnetic radiation spectrum distribution produced by the explosion of energetic materials with different compositions has obvious specificity. This conclusion can be applied to the identification and identification of explosive composition. The closer the distance to the explosion center, the larger the frequency distribution range of the electromagnetic signal, and the electromagnetic frequency distribution in different directions is obviously different[23-25].

3.3. Analysis of the Energy-Domain Characteristics of Electromagnetic Radiation

Electromagnetic radio frequency radiation hazards mainly include protection location, spectrum characteristics, power intensity, signal time domain characteristics, and protection requirements. The environmental analysis of transient electromagnetic hazards mainly includes protection location, frequency band, and intensity. Electromagnetic strength is the most important reference value for electromagnetic hazard protection[26]. The energetic materials used in this experiment are of relatively high quality, and the energy produced by the explosion is relatively strong. The data acquisition equipment is placed in a shelter for protection, and the distance between the data acquisition equipment and the front-end sensor (antenna) is relatively long. In the experiment, the SYV50-5-1 coaxial cable is used for incoming signal transmission. The total length of the coaxial cable is 100 m. As the signal frequency increases, the attenuation rate of the electromagnetic signal will gradually increase. Therefore, it is necessary to perform attenuation compensation and gain correction in the experimental data processing, and also consider factors such as antenna coefficient, antenna gain, signal conditioner gain and adapter loss. The correction parameters of this experimental device are shown in Figure 7.

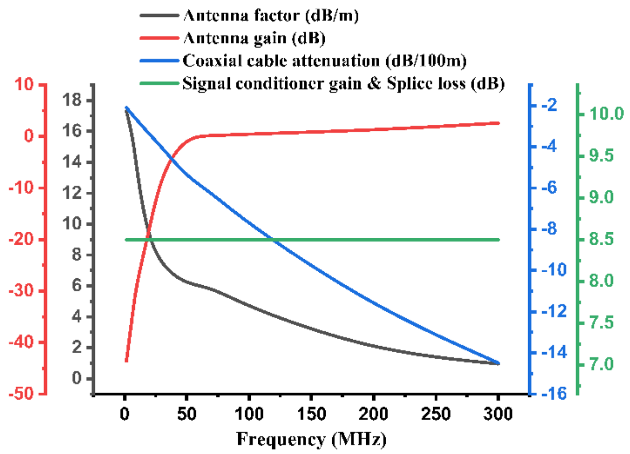

Figure 7. Experimental data correction parameters

The output of the electromagnetic sensor (antenna) of the electromagnetic measurement system is the voltage value, and the voltage value can be converted into the electric field intensity E (*V/m*) by using the antenna coefficient and the equivalent power value. The output voltage of the measuring antenna is U (*V*), the antenna gain after calibration is G (*dB*), and the antenna coefficient is AF (*dB/m*). The space energy flux density is shown in Equation 5, the effective area of the antenna is shown in Equation 6, and the antenna received power is shown in Equation 7.

$$S = (\frac{1}{2}E^2)/120\pi \tag{5}$$

$$A = G\lambda^2/4\pi \tag{6}$$

$$P = S \cdot A = U^2/2Z_0 \tag{7}$$

In the formulas, Z_0 is the system impedance (Z_0=50 Ω), the propagation speed of electromagnetic wave in vacuum is the speed of light (c=3.0×10^8 m/s). The relationship between electromagnetic frequency f (*Hz*) and wavelength λ (*m*) is $f\lambda = c$. According to these formulas, Equation 8 can be obtained, where the unit of f_M is *MHz*. The antenna factor *AF* is as in Equation 9. Substituting *AF* (*dB*) into Equation 9 yields Equation 10. Finally, the conversion relationship between signal power *P* (*dBm*) and electromagnetic strength *E* (*dBμV/m*) is obtained as Equation 11.

$$U = \frac{96.82}{\pi} E\sqrt{G}\frac{1}{f_M} \tag{8}$$

$$AF = \frac{E}{U} = \frac{\pi f_M}{96.82\sqrt{G}} \tag{9}$$

$$AF = 20\log f_M - 10logG - 29.78 \tag{10}$$

$$P = E - AF - 107 \tag{11}$$

The experimental results after data correction are shown in Table 1. The maximum value of electromagnetic radiation intensity produced by 30 kg TNT explosion is 85.56 V/m, and the maximum value of electromagnetic radiation intensity produced by 60 kg TNT explosion is 168.86 V/m. The electromagnetic radiation intensity of 60 kg TNT measured at the same test point is 96.2%~304.3% higher than that of 30 kg TNT. The electromagnetic radiation intensity produced by the explosion of explosives with different masses differs by more than one time. For the electromagnetic radiation intensity produced by the explosion of explosives of the same quality, the electromagnetic intensity decreases with the increase of the distance from the detonation center. For test points at the same distance and in different directions, there are also differences in the measured electromagnetic radiation intensity. The electromagnetic radiation intensity measured at the test points of 30 kg TNT in different directions is quite different, and the difference range is 17.35%~102.17%. The electromagnetic radiation intensity measured by 60 kg TNT in different directions has a small difference, and the difference range is 11.1%~17.7%.

Table 1. Experimental data of electromagnetic radiation of TNT explosion

Test point	Peak voltage / V		Effective voltage / V		Signal power / dBm		Electromagnetic intensity / V•m^{-1}	
	30 kg	60 kg	30 kg	60 kg	30 kg	60 kg	30 kg	60 kg
Point 1	1.426	1.914	11.408	20.468	34.154	39.231	85.56	168.86
Point 2	0.644	1.563	7.187	15.841	30.141	37.005	57.49	130.68
Point 3	0.703	0.898	2.371	9.181	20.508	32.268	18.73	75.74
Point 4	0.507	2.500	5.161	18.881	27.264	38.530	42.32	151.99
Point 5	0.683	1.875	3.829	14.168	24.672	36.036	29.29	114.05
Point 6	0.332	0.585	2.152	4.214	19.667	25.504	15.96	64.33

Conclusion

Aiming at the phenomenon of electromagnetic radiation generated by the explosion of energetic materials, this paper carried out the electromagnetic radiation measurement experiment of energetic materials explosion. According to the analysis of relevant literature, the following main conclusions were obtained:

(1) The time-domain characteristics of the electromagnetic radiation generated by the explosion of energetic materials are most affected by the quality of the explosive. For energetic materials of the same mass, the time-domain distribution of electromagnetic radiation measured at different test points is roughly the same, but the farther away from the explosion center, the shorter the duration of electromagnetic radiation. Additionally, there are some differences in the time-domain distribution of electromagnetic radiation measured at test points in different directions.

(2) The frequency of electromagnetic radiation signals generated by the explosion of energetic materials is mainly concentrated below 100 MHz. The greater the quality of energetic materials, the wider the frequency distribution of electromagnetic radiation and the more concentrated the energy. The composition of energetic materials has a great influence on the spectrum distribution. The electromagnetic radiation spectrum distribution produced by the explosion of energetic materials with different compositions has obvious specificity, which can be applied to the identification and identification of explosive components.

(3) The electromagnetic radiation generated by the explosion of energetic materials can last until 600 ms after the explosion, the electromagnetic pulse is mainly concentrated in 0~300 ms, and the energy is most concentrated in the period of 80~110 ms. During the explosion of energetic materials with different masses, the first electromagnetic radiation signals appear at different times, but they are all concentrated within 100 μs.

(4) For the electromagnetic radiation intensity produced by the explosion of energetic materials of the same mass, the intensity decreases greatly with the increase of distance. There is a large difference in the intensity of electromagnetic radiation at the same distance but in different directions. The configuration of the charge and the way of detonation make the geometric movement pattern of the explosive change during the explosion process, resulting in non-uniformity in the propagation of electromagnetic radiation.

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