Simulation study on radio frequency safety of electric explosive device

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Abstract. Radio frequency (RF) is a great danger to the electric explosive device (EED) of typical ordnance. This paper introduced the RF firing mechanism of the EED and the measuring method of its RF impedance. Through the professional antenna simulation software CST, a dipole antenna model of the EED was set up, the gain coefficient of the antenna model was obtained, and the RF power penetrating into the EED was calculated. The multi-frequency analysis of the emulation indicates that in the certain frequency range of 0.5-2 GHz, the gain coefficient of the antenna model increases as the frequency does.

1. Introduction
Along with the rapid development of radio technology, RF electromagnetic field has widely spread among both human living space and cosmic space. The EED in ammunition can be affected by the broadcast on the ground, transmitter on the aircraft, and communication radars on the warship easily [1-2]. As a result, researches have been massively done around the world to study the RF safety of EED since 1950s. Although there are various EED, the most common one used in the weapon equipment is the bridge-wire EED. Statistics from the 213\(^{th}\) Research Institute of China Ordnance Industry indicate that some 90\% of EED are bridge-wire ones. The electrode leads of the bridge-wire EED, when put in particular environment, can be used as receiving antennas to absorb RF energy, which will result in malfunctions of the EED. Consequently, the bridge-wire EED can be taken as antenna model, the electrical parameter of which can be obtained through the professional simulation software. Then the RF power penetrating into the EED can be calculated and the coupling law of its electromagnetic energy will be summarized.

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2. Basic Theory and the Antenna Model of EED
The basic structure of any bridge-wire EED is similar, mainly composed of electrode leads, bridge wire, explosive and shell, as shown in figure 1.

![Figure 1. Structure diagram of bridge wire EED.](image1)

The EED in ammunition along with its connecting circuit and related parts can be used as a receiving antenna of radio waves to lead RF energy into the EED. This type of energy is generally too weak to induce accidental firing or ineffectiveness of the EED, but under certain conditions, an unexpected action of ammunition may be caused if RF energy gives birth to an earlier ignition of the EED. On the other hand, the reliability of the EED may be lowered due to its chronic exposure to RF energy insufficient for ignition. The RF energy it receives is mainly seen from the functions of electric current and voltage: the electric current, when transmitting from the feet of circuit to the bridge wire, will heat the bridge wire to ignition point, leading to an earlier action or ineffectiveness of the product; while the voltage can cause a breakdown between the feet and shell, the result of which will be a explosive detonation, similar to the static detonation.

![Figure 2. Equivalent circuit of the antenna model.](image2)
As for two-wire EED, the short-circulated EED lead functions as a loop antenna, while the one that is not short-circulated acts as a dipole antenna. Put the receiving antenna in external electromagnetic field, it will induce current and generate electromotive force (EMF) in the output terminal of antenna [3]. The EMF in the electric firing system will transmit electronic current to bridge-wire load through the firing circuit. The equivalent electrical circuit of antenna model has been shown in figure 2.

Where $V_a$ is the EMF produced by the electromagnetic field in the antenna, $Z_a$ is the equivalent impedance of antenna, $Z_{EED}$ is the RF impedance of the EED.

The EMF produced by the electromagnetic field in the antenna $V_a$, can be expressed as follows:

$$V_a = \frac{E\lambda}{\pi} \left( \frac{R G}{120} \right)^{1/2}$$

Where $E$ is the electromagnetic field intensity, $\lambda$ is the wavelength of the radio wave, $G$ is the gain of the equivalent antenna, $R_a$ is the resistive component of the antenna equivalent impedance.

The RF power ($P_{EED}$) into the EED can be calculated by the following formula:

$$P_{EED} = I^2 R_{EED}$$

$$= \frac{V_a^2 R_{EED}}{(R_a + R_{EED})^2 + (X_a + X_{EED})^2}$$

Where $I$ represents for Induced current in the load, $V_a$ represents for the Induced EMF in Ignition circuit, $X_a$ represents for reactance component of the antenna equivalent impedance, $R_{EED}$ represents for resistive component of the EED. $X_{EED}$ represents for reactance component of the EED.

### 3. The RF Impedance of EED and Its Measurement

The RF impedance of EED is a vital parameter in analyzing the electromagnetic hazard of the weapon system [4]. It can be used to analyze and calculate the RF power into the EED, which is of importance to evaluate the safety of the EED and to the design the EED. The value of RF impedance is a function of the frequency. We can measure it under the help of RF impedance analyzer. The theory of measuring system is shown in figure 3.

![Figure 3. The RF impedance measurement principle diagram.](image-url)
Connect the extended cables with three standard terminals. First, conduct automatic calibration with short circuit (0 Ω), circuit breaker (0 S) and 50 Ω in the frequency range from 1 MHz to 1300 MHz. Second, measure the RF impedance of the EED on the calibrated frequency point. The formula (3) will show the resistive value and reactance value of the RF impedance strictly.

\[ Z_{EED} = R_{EED} + jX_{EED} \]  

When the antenna is in a direction in which it can absorb radio wave by the largest margin, also, there is not power loss and the impedance between antenna and load is matching, the load can receive RF power by the largest margin, that is to say when \( R_a = R_{EED} \) and \( X_a = -X_{EED} \), the EED can absorb RF power by the largest margin.

4. The Establishment of Simulation Model and Results Analysis

CST MICROWAVE STUDIO is one of the software packages of CST studio product in CST Company and it is the flagship product of CST that is widely used in simulations of middle or high frequency passive devices. Another characteristic is that the CST MICROWAVE STUDIO is suitable for the whole electromagnetic wave, the electromagnet of the light wave band and the electromagnetic compatibility simulations. It can be used to conduct simulations in various types of antenna and antenna arrays, antenna layout, RCS, FSS, planar passive device. There exist lots of algorithmic methods such as integrated time-domain finite integral method, time domain transmission line matrix, finite integral, domain finite element [5]. So the writer has chosen this software to conduct the simulation research on dipole antenna model of EED and calculate the antenna model gain.

4.1 The Establishment of Simulation Model

The dipole antenna model is established for a type of EED of a particular artillery missile’s off-engine, based on some relevant references. The arms of antenna dipole are solid cylinder, made of silver-plated copper wire which can be taken as an ideal conductor. The length is 100 mm and the diameter is 0.3 mm. The distance of the two arms is 0.6 mm which is used for antenna to feed. Only considering the characteristic of far field, set the feeding way as discrete ports feed. Regard the center of the cylinder as the origin of coordinates and regard the positive direction of the axis z as the upward direction. According to relevant regulations in GJB1389A – 2005 [6], set up the simulation frequency from 0.5 GHz to 2 GHz. It has been shown in figure 4.
4.2 Analysis of the Simulation Results

Figure 5 is a dipole antenna far-field parameters on the condition that \( l = 100 \text{ mm} \) and the frequency is 0.75 GHz, from which we can get the gain of the radiating antenna as 2.235 dBi. According to reciprocity principle, the functioning process of the receiving antenna and the radiating antenna is reversible, that is there is only physical meaning difference when the same antenna used as a receiving and a radiating antenna respectively, but the gain will not change. Therefore, when used as a receiving antenna, its gain is also 2.235 dBi, provided that the frequency is the same.

| Type          | Farfield Approximation     | Component Monitor | Output Frequency | Rad. effic. | Tot. effic. | Dir. | Abs Directivity |
|---------------|----------------------------|-------------------|------------------|-------------|-------------|------|-----------------|
|               | enabled \((kR \gg 1)\)     | Farfield \(f=0.75\) | 0.75             | 0.09679 dB  | -0.7951 dB  | 2.235 dBi |

**Figure 5.** Dipole antenna far field parameters.

Take reference [4] as an example: The EED, its lead length being 10cm and the RF impedance being \( 1+j75 \) \((\Omega)\), when exposed to an electromagnetic environment of which test frequency is 0.75GHz and the field strength is 195 V m\(^{-1}\), what will be the RF power the EED obtains?

The test frequency in the electromagnetic field is 750 MHz, so the wavelength is 0.4 m. At this moment, \( 2l = \lambda/2 \). The antenna consisted of the lead line of EED is in a resonance condition. The equivalent impedance of antenna is pure resistance that is 73.1 \( \Omega \). From the simulated result, we can know the gain of dipole antenna is 2.235 dBi \((G = 2.235 \text{ dBi})\). Put it into formula (2), then we can obtain the largest induced electromotive force the antenna may receive \( V_a = 25.06 \text{ V} \).

If the RF impedance of EED is matched with the antenna impedance, i.e. when \( R_a = R_{\text{EED}} = 73.1 \) \( \Omega \), \( X_a = -X_{\text{EED}} \), the maximum RF power penetrating into the EED can be got by formula (2) as \( P_{\text{max}} = 2.147 \text{ W} \).

In fact, the RF impedance of EED is not matched with the antenna’s impedance. In this example, the RF impedance of EED is \( 1+j75 \) \((\Omega)\). Put it into formula (2), we can obtain that the RF power into the EED is 0.056 W \((P_{\text{EED}} = 0.056 \text{ W})\) in the unmatched condition.

Considering that there exist some errors caused by the parameter setting in the process of establishing the model and software algorithm. The error has so little influence on simulation that we consider it reasonable. Compare the result of the simulation about CST with that of reference [4]. Under the matched condition, the simulated calculation concludes that the largest RF power into the EED is 2.147 W; the reference’s is 2.10 W. Under the unmatched condition, the simulated calculation concludes that the maximum RF power into the EED is 0.056 W; the reference’s is 0.055 W. The fact mentioned above indicates that the result in the simulated calculation is almost the same.
In order to study the different effects that different frequencies have on the gain of the antenna, a far-field monitor is defined to calculate the gain of the antenna under different frequencies. When \( l = 100 \text{ mm} \), and the frequency is set as 0.5 GHz, 0.75 GHz, 1 GHz, 1.25 GHz, 1.5 GHz, 1.75 GHz and 2 GHz respectively, the simulation gains of the radiating antenna are shown in table 1.

**Table 1.** Relationship between dipole antenna gain and frequency.

| Frequency/GHz | 0.50  | 0.75  | 1.00  | 1.25  | 1.50  | 1.75  | 2.00  |
|---------------|-------|-------|-------|-------|-------|-------|-------|
| Gain/dBi      | 1.817 | 2.235 | 2.618 | 3.210 | 4.137 | 4.542 | 5.012 |

It can be seen from Table 1 that the gain of the antenna increases as the frequency does in the frequency range of 0.5 - 2 GHz. And changes of the gain will induce changes to the EMF of the antenna generated by RF waves, and further affect the RF power penetrating into the EED.

5. Conclusion
Through the professional antenna simulation software CST, a dipole antenna model of the EED was set up, the far-field characteristics of the radiation of the antenna model was analyzed, the gain coefficient of the antenna model was got, and then the RF powers penetrating into the EED was calculated when the impedance matches and does not match respectively. The simulating calculation results are basically consistent with the practical results. So it can be concluded that it is feasible to analyze the RF security of the EED with the assist of CST software. And the multi-frequency analysis of the emulation indicates that in certain frequency range, the gain of the antenna model will increase with the frequency.

**References**
[1] Li G M 1992 *Explosive Device* (China: East China Engineering Academy)
[2] Liu S H 2005 *Journal of the Academy of Equipment Command* **16** 1
[3] Zhang W X 2011 *Antennas (Third Edition)* (Beijing: Publishing House of Electronics Industry)
[4] Li J R 1995 *Initiators & Pyrotechnics* **1** 11
[5] Zhang M 2004 *CST Microwave Studio* (Chengdu: Press of Electronic Science and Technology University)
[6] GJB1389A–2005. *System Compatibility Requirements*