Hindawi
International Journal of Antennas and Propagation
Volume 2024, Article ID 9317622, 6 pages
https://doi.org/10.1155/2024/9317622

*Research Article*

# Analysis of the Electromagnetic Effect Mechanism of EED under Continuous Wave Radiation

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Received 2 March 2023; Revised 17 July 2023; Accepted 20 March 2024; Published 31 March 2024

Academic Editor: Francesco D'Agostino



The electromagnetic radiation sensitivity of the electric explosive device (EED) and its installed use state is closely related to the size of the equipment and radiation field strength constraints. The use of the traditional all-level electromagnetic radiation method for the effect of the actual installed EED test in the electromagnetic environment simulation encountered a technical bottleneck. The microwave band is difficult to effectively assess through the current standing wave distribution and skin effect. The temperature rise of the EED bridge wire has no relationship with the frequency of the electromagnetic wave. In this paper, through the analysis of the electromagnetic effect mechanism of the EED, the coupled power model of electromagnetic irradiation of the EED is obtained, and the relationship between the temperature rise of the bridge wire of the EED and the electric field strength model is established. Under the action of high-frequency continuous waves, the electromagnetic effect of the device is tested to verify the correctness of the mechanism analysis of the electromagnetic effect of the device under the action of continuous waves. The results provide crucial technical support for the electromagnetic protection of the device under the harsh electromagnetic environment of the battlefield.

## 1. Introduction

EED refers to the electric detonator or the component that adopts electric energy to initiate and ignite the explosives, propellants, or pyrotechnic materials inside. It has vital characteristics such as a large energy-mass ratio, controllable input/output energy, small size and compact structure, and good long-term storage performance [1, 2]. In the weapon system, the EED is mainly employed to ignite and detonate explosives or to complete the work, start, and other key operational tasks. It is not only the control device in the process of the device but also the work component [3]. The functional primacy and sensitivity of EED determine their position and role in the weapon system; their safety and reliability directly affect the safety and reliability of the weapon system, as well as the play of the combat effectiveness of the weapon system and the safety of combatants [4–6]. The EED in the weapon equipment is primarily used to assure the safe and reliable operation of the launching system and delivery system of the weapon for the ignition, fire transmission, delay, and control system of the weapon equipment to achieve accurate strikes on enemy targets for the initiation, transmission, and control system of weapons and equipment, as well as the role of the control warhead. It is employed for pulling, pushing, cutting, separating, throwing, attitude control, and other work sequences and control systems in weapons and equipment to guarantee that weapons and equipment can adjust themselves, change states, and control safety [7, 8].

With the rapid development of electronic technology, the combat system and electromagnetic weapons and equipment based on electromagnetic technology are accelerating the change of the combat system and attack and defense style of modern war, making the electromagnetic environment on the battlefield increasingly harsh and thus leading to more severe electromagnetic environment threats faced by weapons and equipment in military operations [9–15]. EED, as a miniaturized electromagnetic sensitive element, is not only the "source" for weapon systems to complete the predetermined functions but also the "root" for these systems to have possible accidental ignition, explosion, and other accidents [16–18]. Accurate analysis of battlefield electromagnetic environment, scientific protection and reinforcement measures, and enhancement of battlefield survivability of weapon systems are critical to improving combat effectiveness [19–22]. Therefore, the electromagnetic effect mechanism of the EED should be analyzed to ensure that the weapon system has good combat effectiveness.

Given the mechanism of the electromagnetic effect of EED, Pantoja et al. proposed an input impedance model of bride-wire EED based on differential mode measurement [3]. They studied the influence of different coupling conditions on the hot bride-wire EED by measuring the input impedance and gain of the transmitting circuit of the EED. The correctness of the equivalent antenna theoretical model and Monte Carlo simulation theoretical model to analyze the electromagnetic response of the transmitting circuit of bridge wire EED is verified. With EED as the research object, Galuga J and Bray J R evaluated the feasibility of induced current detonation in EED by analyzing the magnetic susceptibility of EED under the irradiation of continuous wave and linearly polarized plane wave so as to investigate the electromagnetic effect mechanism of EED [23]. Wang et al. from the Beijing Institute of Technology designed an analytical method following the field line coupling theory to explore the damage mechanism of EED under electromagnetic irradiation, obtained the mathematical model of the transmission line of EED through theoretical analysis, and determined the relationship between the absorbed power and radiation frequency of EED [24].

Although some researchers have studied the electromagnetic damage mechanism of EED, there is little research on the electromagnetic damage mechanism of EED from the aspects of bridge wire temperature rise and radiation field strength, only involving the induced current, impedance model, and radiation frequency of EED. In this paper, the bridge wire type EED is taken as the research object. The structural characteristics of the EED and the RF environment are combined to determine the effective aperture of the equivalent antenna of the EED. Besides, the power coupling model of the electromagnetic irradiation of the EED is established, and the relationship between the temperature rise of the bridge wire and the electric field strength of the EED is demonstrated. Furthermore, the authenticity of the analysis of the electromagnetic effect mechanism of the EED is verified under the action of high-frequency continuous waves. This study provides a new idea for the electromagnetic safety assessment of the EED.

## 2. Mechanism Analysis

In a complex battlefield electromagnetic environment, electromagnetic radiation forms a certain antenna structure on the two-foot leads of the EED and then the electromagnetic energy is coupled [25]. The effective aperture of the antenna is a parameter representing the ability of the antenna to receive electromagnetic waves. The equivalent antenna constituted by the foot line of the EED also has an effective aperture. According to the reciprocity theorem of the antenna, the effective aperture of the antenna is the same in the transmitting state and the receiving state [26–30]. Therefore, the total power received by the receiving antenna can be calculated by the sum of the power density radiated to the effective aperture of the receiving antenna. Since a typical bridge wire EED is sensitive to electromagnetic radiation in equilibrium mode, the equivalent antenna of EED in the equilibrium mode is analyzed. The equivalent antenna and equivalent circuit of EED in the equilibrium mode are exhibited in Figure 1. $R_{\mathrm{EED}}$ denotes the bridge wire resistance of the EED, $R_r$ expresses the radiation resistance of the equivalent antenna, $R_L$ represents the loss resistance of the equivalent antenna, $X_{\mathrm{EED}}$ indicates the bridge wire reactance of the EED, and $X_r$ signifies the reactance of the equivalent antenna.

Under the condition of far field, the electromagnetic radiation field is made up of right angles to each other and spread their direction of the electric field and magnetic field of two components, and the power density of the incident wave (Poynting vector) is the product of the two [31].

$$\overline{P} = E \times H, \tag{1}$$

where $\overline{P}$ denotes the power density of the incident wave, $E$ expresses the electric field strength of the incident wave, and $H$ represents the magnetic field strength of the incident wave.

The available power is calculated using the maximum effective aperture (the receiving area of the antenna). The incident wave power received by the receiving antenna is directly proportional to the maximum effective aperture of the antenna.

$$P_A = \overline{P} \cdot A_e, \tag{2}$$

where $P_A$ indicates the received power of the incident wave, and $A_e$ signifies the maximum effective aperture of the antenna.

The induced voltage of the equivalent ring antenna of EED is

$$U = 2\pi f \mu_0 \mathrm{SH}, \tag{3}$$

where $U$ represents the induced voltage of the antenna, $S$ denotes the loop area of the equivalent antenna of the EED, and $\mu_0$ expresses the permeability with the size of $4\pi \times 10^{-7}$.

The effective aperture of the equivalent antenna of the EED is

$$A_e = \frac{U^2 R_{\mathrm{EED}}}{\overline{P}\left[\left(R_r + R_L + R_{\mathrm{EED}}\right)^2 + \left(X_r + X_{\mathrm{EED}}\right)^2\right]}. \tag{4}$$

From equations (2) to (4), the effective aperture of the equivalent antenna of the EED can be obtained as

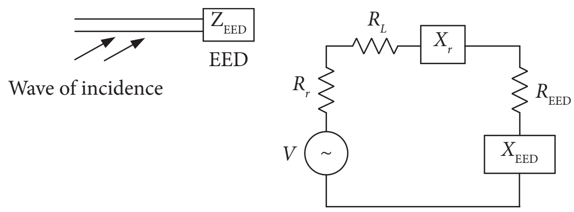


Figure 1: Equivalent circuit equivalent antenna and equivalent circuit of EED in the equilibrium mode. (a) Equivalent receiving antenna of EED in the equilibrium mode. (b) Equivalent circuit.

$$A_e = \frac{64\pi^4 f^2 S^2 \times 10^{-4}}{120\pi (R_r + R_{\text{EED}})^2} R_{\text{EED}}. \quad (5)$$

Generally, $R_r \ll R_{\text{EED}}$. Equation (5) can be simplified as

$$A_e = \frac{4.67 \times 10^4 S^2}{\pi \lambda^2 R_{\text{EED}}}. \quad (6)$$

The ratio of the electric field to the magnetic field represents the characteristic impedance of free space, namely,

$$Z_0 = \frac{E}{H} = 120\pi\,\Omega, \quad (7)$$

where $Z_0$ expresses the characteristic impedance of free space.

The electromagnetic radiation field's average power density $\overline{P}$ with $E$ or $H$ can be represented as

$$\overline{P} = \frac{E^2}{120\pi} = 120\,\pi H^2. \quad (8)$$

Following (2) and (8), the electromagnetic radiation power received by the equivalent antenna of the EED can be expressed as

$$P = \frac{E^2 A_e}{120\pi}. \quad (9)$$

When the pin structure state of the EED is determined to be a half-wave dipole antenna mode [25], the electromagnetic wave radiation power received by the foot line of the EED can be obtained by (9) as follows:

$$P = \frac{E^2 \lambda^2}{292.7\pi^2}. \quad (10)$$

The abovementioned analysis suggests that the accepted power on the EED is proportional to the square of the electric field intensity when the electromagnetic wave frequency is constant.

The combustion of EED is a law of conservation of energy, comprising the heat required by the heating of the bridge wire of EED, the heat released by the chemical reaction of the pyrochemical, the heat lost by the bridge wire, and the coupled radiation power. Therefore, the heat balance equation of the EED can be obtained [32] as

$$\rho_1 c_1 \frac{\partial T}{\partial t} = \rho_2 q Z e^{-E_a/\text{RT}} - \lambda \nabla^2 T + P, \quad (11)$$

where $\rho_1$ denotes the material density of bridge wire; $c_1$ expresses the heat capacity of the bridge wire; $T$ represents the temperature of the bridge wire; $P$ stands for the coupling radiated power of the bridge wire; $\rho_2$ indicates the material density of the pyrotechnic reagent; $q$ signifies the heat of reaction of the chemical reagent; $Z$ refers to the frequency factor; $e$ expresses the base of natural logarithm; $E_a$ reflects the activation energy of the pyrotechnic reagent; $R$ is the gas constant; $\lambda$ means the heat conductivity coefficient; and $\nabla^2$ terms the Laplace operator.

According to (11), the ignition condition of the EED is

$$\rho_1 c_1 \frac{\partial T}{\partial t} \geq 0. \quad (12)$$

The first item on the right of (11) is the heat energy released by the chemical reaction of the pyrochemical agent. It indicates the product of the drug dose consumed by the reaction and the heat release of the explosive per unit mass. The consumption of chemical agents in the EED before ignition is very small and thus neglected in the analysis of the electromagnetic effect mechanism of the EED. The second item on the right of (11) is the heat lost by the bridge wire. Since the EED is placed in an electromagnetic field environment, the temperature of the bridge wire rises rapidly. It can be assumed that all the coupled energy is adopted for the temperature rise of the bridge wire. Hence,

$$\frac{\partial T}{\partial t} = \frac{E^2 \lambda^2}{292.7 \rho_1 c_1 \pi^2}. \quad (13)$$

In other words, the temperature rise on the bridge wire of the EED is directly proportional to the square of the electric field when the frequency of the electric radiation is constant.

## 3. Experimental Verification

The electromagnetic effect test of the EED was performed under the action of the continuous wave to verify the authenticity of the analysis of the electromagnetic effect mechanism of the EED. The RF signal emitted by the RF signal generator was amplified by the broadband power amplifier, and the amplified RF signal was converted into RF continuous wave by the antenna to irradiate the EED under

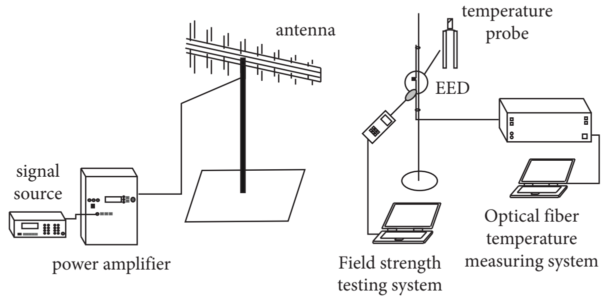


Figure 2: Test principle of electromagnetic effect of EED under continuous wave action.

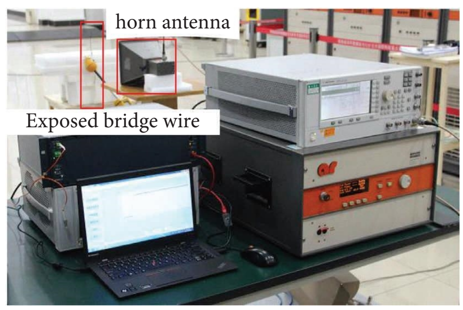


Figure 3: Test system of electromagnetic effect of EED under continuous wave.

Table 1: Test results of electromagnetic effect of EED under continuous wave.

| | | | | | | |
|---|---|---|---|---|---|---|
| Electric intensity (V/m) | 108 | 123 | 138 | 157 | 212 | 232 |
| Temperature increase of bridge wire (°C) | 2.82 | 3.53 | 4.02 | 5.33 | 8.11 | 10.05 |

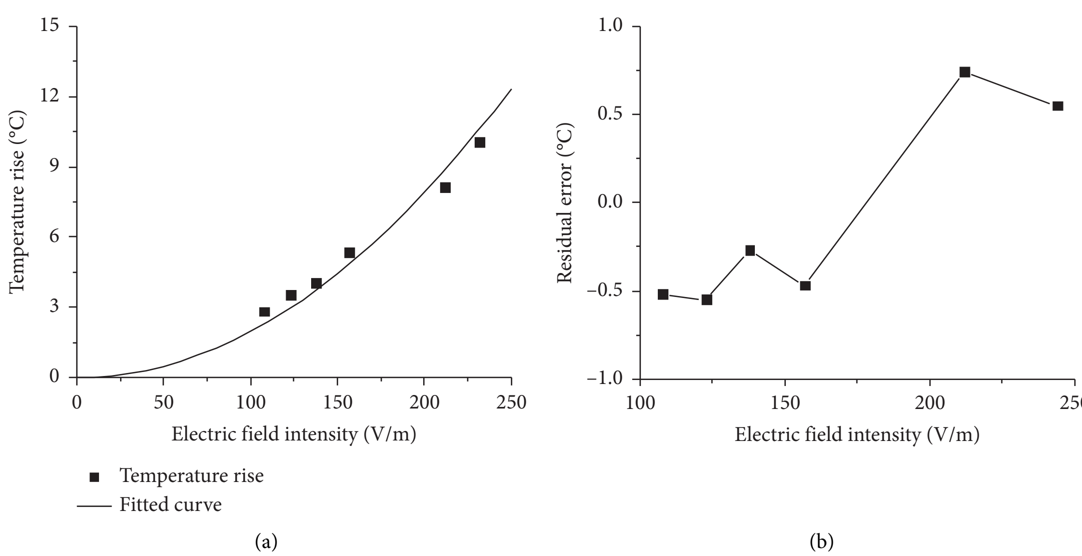


Figure 4: Bridge wire temperature rise fitting curve and fitting residual under RF continuous wave. (a) Fitting curve of bridge wire temperature rise. (b) Residual temperature rise error of bridge wire.

test. The temperature rise on the bridge wire of the EED was tested using the optical fiber temperature measurement system. During the test, the temperature rise test of the bridge wire under different field strengths was realized by adjusting the output signal of the RF signal generator. The field strength near the fixed platform of the EED under test was measured with the electromagnetic field strength tester. The test schematic diagram is illustrated in Figure 2.

Considering spatial electromagnetic field distribution and effective aperture of the equivalent antenna of EED in conducting electromagnetic effect test of EED under RF continuous wave, the transmitting frequency of RF continuous wave was selected as 5 GHz; the corresponding half wavelength was 3 cm and the length of foot line of EED was transformed into 3 cm. During the test, the electromagnetic field used vertical polarization to irradiate the EED, and the foot line of the EED was perpendicular to the ground. The electromagnetic effect testing system of the EED under the action of the continuous wave is displayed in Figure 3.

The researcher turned on the RF signal generator, broadband power amplifier, optical fiber temperature measurement system, and electromagnetic field strength tester. Then, the output of the signal source was adjusted, and the electric field intensity near the EED was tested with the field intensity tester. The radiant electric field intensity was adjusted successively to 108 V/m, 123 V/m, 138 V/m, 157 V/m, 212 V/m, and 232 V/m and the temperature rise of the bridge wire under the corresponding field intensity was examined using the optical fiber temperature measurement system. The test results are listed in Table 1.

With respect to the relationship between the temperature rise of the bridge wire of the EED and the intensity of the continuous wave irradiation field, curve fitting and residual error calculation were conducted on the test results. The results are presented in Figure 4.

Under the irradiation of 5 GHz RF continuous wave, the mathematical relationship between the temperature rise and the electric field intensity of the bridge wire of the EED was obtained through the test as

$$\Delta T = 1.97E^2 \times 10^{-4}. \quad (14)$$

## 4. Conclusions

Through the analysis of the electromagnetic damage mechanism of the EED, the effective aperture of the equivalent antenna of the EED was determined, the radiation power model accepted by the EED under the action of an electromagnetic field was established, and the relationship between the temperature rise of the bridge wire of the EED and the electric field strength was demonstrated by combining the thermal equilibrium equation of the EED. In addition, the correctness of the proportional relationship between the temperature rise of the bridge wire and the square of the electric field strength of the EED was verified by the electromagnetic effect tests on the bridge wire of the EED under a 5 GHz RF continuous wave. The fitted curve of the temperature rise of the bridge wire and the electric field strength was obtained, with the maximum residual error and root mean square error of the curve of 0.74°C and 0.54°C, respectively.

By analyzing the electromagnetic effect mechanism of EED, the relationship between the irradiation power of EED and the electric field intensity was studied, and a mathematical model for bridge line temperature rise and electric field intensity was established. The establishment of this model lays a theoretical foundation for the electromagnetic safety margin analysis of EED and guides the anti-electromagnetic interference transformation of EED in weapon equipment and the development of new EEDs. It has vital military benefits and practical value for improving the survival ability of EED in weapon equipment and enhancing the combat effectiveness of weapon equipment.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Authors' Contributions

Biao Wang was responsible for the planning, design, and implementation of the entire research paper, ensuring the completeness and accuracy of the research. He also wrote and revised the thesis. Yongwei Sun directed the planning, design, and implementation of the entire dissertation study, had oversight and coordination responsibility for the study as a whole, and provided financial and technical support. Shuai Zhou participated in the theoretical analysis of electromagnetic effects throughout the entire paper. Xiaojian Li participated in the experimental data collection, processing, and analysis of the entire paper. Nan Li and Zhiyou Fan participated in the planning, design, and implementation of the entire research paper. Ying Xiong and Tiannan Wang participated in the experimental work and data processing of the paper.

## Acknowledgments

The authors would like to acknowledge the National Defense Equipment Advance Research Program of China for providing fund for conducting experiments.

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