Modeling of the electromagnetic coupling to electro-explosive devices

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Abstract

In this work, we present a general methodology for modeling the coupling of electromagnetic fields with electro-explosive devices (EEDs). We discuss the assumptions and the necessary conditions to achieve the maximization of electromagnetic response of a canonical EED. The $E^2\tau$ product of the EED (E being the electric field and τ the duration) is presented as a means for determining the electromagnetic environment that could lead to its activation from an external impinging electromagnetic field.

1. Introduction

In the maximization of electromagnetic response of systems, one is interested in identifying the energy transfer function in the frequency domain for all the subsystems that are involved in the energy transfer from the source to the port of interest [1]. Figure 1 shows the principal subsystems identified by Baum in [1] for decomposing the electromagnetic response of any port of interest.

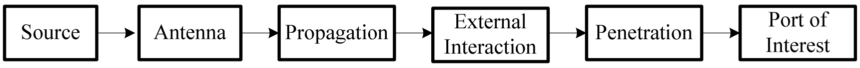

Fig. 1 Energy transfer function for the calculation of the EM response of a port of interest. (adapted from [1])

In this work we calculate the necessary electromagnetic environment to achieve the maximization of electromagnetic response of a canonical EED. For this purpose, only the transfer function from the external interaction block until the port of interest needs to be considered. For the EED case, the port of interest describes the conversion of RF power into heat for increasing the temperature of the bridge and activating the primary explosive. The penetration transfer function relates the power at the bridge to the power at the output terminals of the EED. In the external interaction block, the induced current in the cables connected to the lead-in wires of the EED is calculated from the coupled impinging field. In this work we will assume that the coupling will take place across the lead-in wires, inducing a differential mode current at the bridge.

2. Generic geometrical model of an EED

A generic geometrical model of an EED was proposed in [2] for studying the electromagnetic propagation from the lead-in wires of an EED to its bridge. Fig. 2 presents the geometry and the relevant dielectric properties. It is composed by an aluminum case that encloses two explosives and a protecting seal. A platinum alloy bridge wire is immersed in a sensitive explosive (e.g. lead-azide). Two parallel copper lead-in wires are connected to the bridge, and they cross through the seal. The seal is typically made of Diallyl Phthalate (DAP), or rubber dielectrics. The sensitive explosive is usually regarded as the primary explosive, and the other is known as secondary explosive [3-5]. PETN or RDX are generally found as secondary explosives in EEDs.

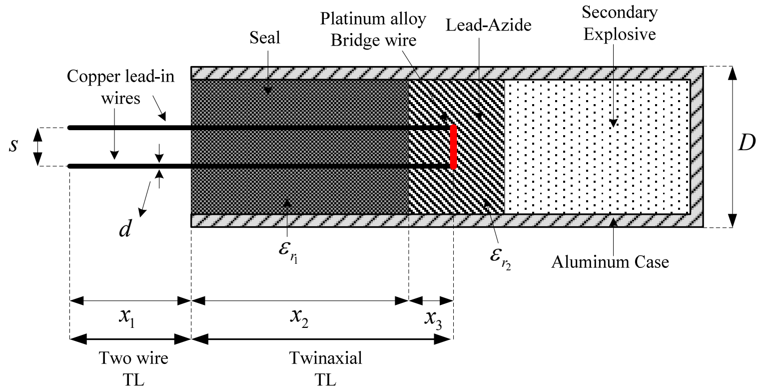

Fig. 2 Generic geometrical model of an EED. Image modified from [2].

3. Port of interest

The bridge of an EED is a resistive wire with high resistivity value that converts rapidly electrical energy into heat [6-7]. In terms of energy conversion, the port of interest of the problem under study in this work is the temperature at the bridge of the EED. The goal is to increase the temperature of the bridge until the ignition temperature of the primary explosive is reached [6-7]. In order to describe the temperature increase at the bridge in terms of the electrical energy applied to the bridge, the heat transfer equation with an electrical energy source needs to be solved over the bridge surface [8].

Some assumptions can be done in order to simplify the solution of the thermal equation [8]. If thermal diffusion is neglected, and no temperature gradient is considered over the surface of the bridge, the electro-thermal transfer can be described with the following first order ordinary differential equation [6], where *U* is the stored energy at the bridge, τ_T is the thermal time constant of the bridge [7, 9-10], and *p(t)* is the power source function:

$$\frac{dU}{dt}+\frac{1}{\tau_T}U = p(t) \text{ [W]} \tag{1}$$

The final goal of the bridge heating is to achieve the ignition temperature or critical temperature of the primary explosive θ_c. There is a critical energy U_c associated with the critical temperature and any stored energy in the bridge above this level will lead to the complete explosion process [3, 7, 11]. In order to correctly predict the ignition of an EED, the thermal time constant of the EED τ_T and the critical energy U_c need to be known.

If a constant average power $p(t)=\overline{P}_L$ during a period τ is applied to the bridge, the solution of (1) gives the stored energy with an exponential increasing profile in time:

$$U(t)=\overline{P}_L\tau_T(1-e^{-\frac{t}{\tau_T}})\text{[J]} \tag{2}$$

If the duration of the power excitation τ is much smaller than the thermal time constant of the EED (i.e. $\tau << \tau_T$), (2) can be approximated as a linear function of time:

$$U(t)=\overline{P}_L\tau_T t \text{ [J]} \tag{3}$$

and the energy stored after the excitation U can be calculated as

$$U(\tau)=\overline{P}_L\tau_T\tau \text{ [J]} \tag{4}$$

4. Penetration

Starting from the generic geometrical model in Fig. 1, the differential-mode propagation of the electromagnetic energy through the lead-in wires can be modeled as a cascade of three transmission lines. The first line is a two-wire transmission line outside the aluminum case (see Fig. 2), the second line is a twinaxial transmission line filled with the seal, and finally a small twinaxial transmission line filled with the lead-azide [2]. With this representation, the geometric and dielectric properties of the EED can be used along with the transmission line equations to determine the input impedance at the lead-in wires of the blasting cap, as well as the propagation transfer function in Fig. 1.

Consider the| terminated lossy cascaded transmission lines representing the transmission line model of the EED, shown in Fig. 3. The transmission lines are characterized by their length x_n, their characteristic impedance Z_{0n}, and their complex propagation constant γ_n where $n=1,2,3$. The cascaded line is terminated on a lumped load Z_L representing the bridge wire. The reflection coefficient at the end of each line is defined as Γ_n . The impedance at the beginning of line 1 is denoted as Z_{in} , and its current is denoted as I_{in}.

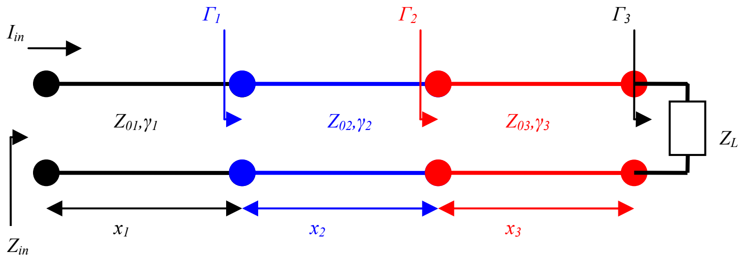

Fig. 3 Terminated lossy cascaded transmission line

The input impedance $Z_{in}(\omega)$ of the EED can be calculated as a function of frequency by translating the bridge wire impedance Z_L to the input of the three cascaded lines successively by using [12]:

$$Z_{in_n}(\omega) = Z_{0_n}\frac{Z_{in_{n+1}} + Z_{0_n}\tanh(\Gamma_n(x_n - x_{n-1}))}{Z_{0_n} + Z_{in_{n+1}}\tanh(\Gamma_n(x_n - x_{n-1}))}\ [\Omega] \qquad (5)$$

where n varies from 3 to 1. When calculating the first term Z_{in_3} the value of $Z_{in_4} = Z_L$.

The average power transfer function $T(\omega)$, between the input of the EED and the bridge can be calculated in a straightforward way as:

$$T(\omega) = \frac{\overline{P}_L}{\overline{P}_{in}} = \frac{|(1+\Gamma_1)|^2|(1+\Gamma_2)|^2|(1+\Gamma_3)|^2}{|e^{\gamma_1 x_1} + \Gamma_1 e^{-\gamma_1 x_1}|^2 |e^{\gamma_2 x_2} + \Gamma_2 e^{-\gamma_2 x_2}|^2 |e^{\gamma_3 x_3} + \Gamma_3 e^{-\gamma_3 x_3}|^2} \frac{|Z_{in}|^2}{R_{in} Z_L} \qquad (6)$$

where R_{in} is the real part of the input impedance Z_{in} of the EED.

5. External Interaction

Depending on the application, different cable configurations may be connected to the lead-in wires of the EED. A full-wave simulation tool may be used to estimate the coupling of an impinging field to the cable arrangement, loaded with the input impedance $Z_{in}(\omega)$ of the EED. Since in the EED problem we are only interested in the differential mode current at the input impedance of the blasting cap for estimating the input power, the coupling problem can be further simplified because the antenna mode currents can be neglected. For example, if transmission line hypotheses are satisfied, the BLT equation [13] can be used to solve the current at the input of the EED.

Once the current at the input of the EED is estimated, the current/field transfer function $H(\omega)$ can be estimated, and with it, the average power at the input of the EED as a function of frequency:

$$\begin{aligned} H(\omega) &= \frac{I_{in}(\omega)}{E(\omega)}\ [\frac{\mathrm{m}}{\Omega}] \\ \overline{P}_{in}(\omega) &= \frac{1}{2}|I_{in}(\omega)|^2 R_{in} = \frac{1}{2}|H(\omega)|^2 |E(\omega)|^2 R_{in}\ [\mathrm{W}] \end{aligned} \qquad (7)$$

If the duration of the field excitation τ is shorter than the thermal time constant of the EED (i.e. $\tau << \tau_T$), the stored energy at the bridge can be estimated with (4),(6), and (7) as:

$$U(\omega,\tau) = \frac{1}{2}|T(\omega)||H(\omega)|^2 R_{in} |E(\omega)|^2 \tau\ [\mathrm{J}] \qquad (8)$$

Setting the stored energy equal to the threshold energy, the $E^2\tau$ product of the EED can be estimated as:

$$|E|^2 \tau = \frac{2U_{th}}{|T(\omega)||H(\omega)|^2 R_{in}}\ [\frac{\mathrm{V}^2}{\mathrm{m}^2\mathrm{Hz}}] \qquad (9)$$

This product defines the key parameters for specifying the electromagnetic environment that could lead to the ignition of an EED due to the coupling of an impinging electromagnetic field. If the duration τ of the field source is known, the required field amplitude as a function of the frequency can be calculated as:

$$|E| = \sqrt{\frac{2U_{th}}{|T(\omega)||H(\omega)|^2 R_{in}\tau}}\ [\frac{\mathrm{V}}{\mathrm{m}}] \qquad (10)$$

6. Conclusions

In this work, we presented a general methodology for modeling the coupling of electromagnetic fields with EEDs. We presented the assumptions and the necessary conditions to achieve the maximization of electromagnetic response of a canonical EED, starting from the external interaction of the fields with the wires until the thermal response of the bridge wire. The $E^2\tau$ product of the EED is presented as a means for specifying the electromagnetic environment that could lead to its activation from an external impinging electromagnetic field. With the use of the $E^2\tau$ product the required field amplitude or the source duration can be calculated and the thresholds for security surveys in hostile electromagnetic environments can be determined in for compatibility compliances.

7. Acknowledgements

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