The Distance Property of Fields Radiated by ESD Above a Ground Plane

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Summary: Electrostatic Discharge(ESD) has commonly been potential threat to the normal operation of high-tech information equipment. It is well known that the electromagnetic interference radiated by ESD is not always proportional to the spark voltage and also that the lower voltage ESD sometimes causes the more serious demage. In this study, the impulsive electromagnetic wave will be analyzed experimently and theoretically with respect to the distance from the ESD point when the ESD occurs above a ground plane. From the result of the calculation, it will be verified that the electromagnetic interference level is not always proportional to the inverse of the distance.

1. Introduction

An advanced electronic system or digital control equipment is affectted easily by the radiated field due to electrostatic discharge(ESD) of a metallic body or a person, which can penetrate into high-tech equipment directly or excite apertures, seams, vents, and input-output cable or couple to susceptible internal circuitary. Those transient fields often reach field strength $150\,V/m$ at a distance $1.5m$, having rising time of less than $500ps$[1]. For the electromagnetic interference of this kind, the following strange cases[2],[3] are well known as a peculiar phenomenon of unknown origin. Indirect ESD occuring at the location distant from an equipment causes the stronger electromagnetic interference than direct ESD does. The interference level is not always proportional to the ESD voltage. Concerning ESD current, most reports analyzed the occurance electromagnetic fields, using the measured ESD current or the model current wave. We have derived the ESD current in a closed form by using the spark resistance given by the Rompe-Weizel' formula[4], thereby calculating the occurance electromagnetic fields. It had been conformed for the experiment data given by Wilson & Ma[5]. In this study, the ESD current above an infinite, perfectly conducting ground is regarded as a source model. The radiated impulsive wave will be analyzed with respect to the distance from the ESD point.

2. Theory

2.1 ESD source model and ESD current

Figure. 1 shows a dipole model for ESD. The portion right after the ESD has occurred can be modeled as a current dipole with the length of ℓ through which the ESD current $i(t)$ flows. Consider an ESD current as a single shot impulsive current. The current peak value is denoted by I_m, and the nominal duration period τ. It follows that $q=I_m \times \tau$.

Then the ESD current $i(t)$ can be expressed as follows:

$$i(t)=I_m \cdot F(t/\tau) \tag{1}$$

where $F(t/\tau)$ is a dimensionless function representing the ESD current waveform and the following relation holds:

$$\int_0^{\infty} F(x)dx=1 \tag{2}$$

Figure.2 shows the current waveform $i(t)$. For the function $F(x)$, considering the dipole as a spark channel, we can drive it in a closed form from solving the equation for the electrical behavior of a capacitance discharge circuit through a spark gap. For spark resistance, Rompe-Weizel resistance formula expresses the developing process of the spark discharge very well[6]. Under the assumption that the conductivity of a spark channel is proportional directly to the internal energy injected, Rompe-Weizel proposed the following formula for the spark resistance[4].

$$r(t)=\frac{\ell}{\sqrt{(2a/p)\int_0^t i(t')^2 dt'}} \tag{3}$$

where $r(t)$ is the spark resistance at time t, ℓ is the spark length, a is a spark coefficient determined by the gas pressure, nature and temperature, p is the pressure and $i(t)$ is the spark current flowing through the gap. The stray capacitance across the gap before ESD occurs is denoted by C_o, and the spark V_s.

The voltage across the gap is denoted by $v(t)$:

$$v(t)=V_s-\frac{1}{C_o}\int_0^t i(t')\,dt' \tag{4}$$

The following equations can be determined with eq.(4) and $v(t)=i(t)r(t)$ [7].

$$I_m=\frac{C_oV_s}{\tau}=\frac{C_oV_s(a/p)(V_s/\ell)^2}{3\sqrt{3}} \tag{5}$$

$$F(t/\tau)=\frac{3\sqrt{3}}{2}\exp\left\{3\sqrt{3}\left(\frac{t}{\tau}-x_o\right)\right. \cdot\left[1+\exp\left\{3\sqrt{3}\left(\frac{t}{\tau}-x_o\right)\right\}\right]^{-1.5} \tag{6}$$

$$\frac{\partial F(t/\tau)}{\partial(t/\tau)}=\frac{27}{4}\exp\left\{3\sqrt{3}\left(\frac{t}{\tau}-x_o\right)\right\}\cdot\left[1+\exp\left\{3\sqrt{3}\left(\frac{t}{\tau}-x_o\right)\right\}\right]^{-2.5} \cdot\left[2-\exp\left\{3\sqrt{3}\left(\frac{t}{\tau}-x_o\right)\right\}\right] \tag{7}$$

where x_o is an integral constant. Equation (7) and (8) show that the ESD current can be calculated from the stray capacitance C_o, the spark length ℓ and the spark voltage V_s.

Figure.3 shows the waveforms of dimensionless current $F(t/\tau)$ and its derivative $dF(x)/dx$

2.2 The ESD parallel to the ground plane

The dipole model of ESD parallel to the perfect ground is showed at Figure.4. The dipole is horizontally oriented and aligned in parallel to the ground plane. The height of dipole is z'. The perfect ground screen creates an image dipole at $-z'$. The time-dependent fields radiated by source dipole may be readily analyzed. The electric field caused by ESD at a point $P(r,\theta,\Phi)$ is as follows:

$$E_r(t)=\frac{1}{4\pi}\left(\frac{\ell}{c\tau}\right)^2\frac{Z_o I_m}{\ell}\sin\theta\left\{\frac{1}{(R_r/c\tau)^3}\left[1-\int_0^{t/\tau}F(x'-\frac{R_r}{c\tau})dx'\right]\right.$$
$$+\frac{1}{(R_r/c\tau)^2}F(\frac{t}{\tau}-\frac{R_r}{c\tau}) \qquad (8)$$
$$\left.+\frac{1}{(R_r/c\tau)}\frac{d}{d(t/c\tau)}F(\frac{t}{\tau}-\frac{R_r}{c\tau})\right\}$$

where R_r is the distance from the real source to the field point. The first term on the right-hand side of Eq.(8) is electrostatic field component. At the time($t=0$) just right before the ESD occurs, it corresponds to the electric field level produced by the electric dipole moment of $\pm q$. The second and third terms on the right-hand side of Eq.(8) represent the inductive and the radiative fields respectively. As seen in this equation, the inductive field is proportional to $F(t/\tau)$ or $i(t)$. Meanwhile, the radiated field is proportional to the derivative of $F(t/\tau)$ with respect to t/τ, or $\partial i/\partial t$. The electric field due to the image dipole is given by

$$E_i(t)=\frac{1}{4\pi}\left(\frac{\ell}{c\tau}\right)^2\frac{Z_o I_m}{\ell}\sin\theta\left\{\frac{1}{(R_i/c\tau)^3}\left[1-\int_0^{t/\tau}F(x'-\frac{R_i}{c\tau})dx'\right]\right.$$
$$+\frac{1}{(R_i/c\tau)^2}F(\frac{t}{\tau}-\frac{R_i}{c\tau}) \qquad (9)$$
$$\left.+\frac{1}{(R_i/c\tau)}\frac{d}{d(t/c\tau)}F(\frac{t}{\tau}-\frac{R_i}{c\tau})\right\}$$

where R_i is the distance from the image source to the field point. The polarity of image dipole is reverse to one of the source dipole because the dipole is located in parallel to the perfect ground screen. According to the CENELEC ESD standard [8], the rising time is very fast($\leq 1ns$) and the nominal duration period τ may be about 2ns. The radiative field dominates the inductive field or the region of $r \geq 0.54 \times c\tau$[4]. If the distance from the ESD point is larger than 0.324(m), the radiative field can be dominant. Then, the field radiated by two dipole is expressed as follows:

$$E = E_r - E_i = \frac{I_m \mu_o \ell}{4\pi} \cdot \frac{1}{\tau R_r} \cdot \frac{\partial F(t/\tau - R_r/c\tau)}{\partial (t/\tau - R_r/c\tau)} - \frac{I_m \mu_o \ell}{4\pi} \cdot \frac{1}{\tau R_i} \cdot \frac{\partial F(t/\tau - R_i/c\tau)}{\partial (t/\tau - R_i/c\tau)} \qquad (10)$$

3. Experiment and result.

Figure.5 shows the configuration of experimantal setup and ESD detection, including top view. At first, the pulse signal is generated from the pulse generator. The ignition coil controlled by an electonic circuit can generate a high voltage. In order to produce a spark, it is applied through carbon string($250\Omega/m$, $70cm \times 2$) to sphere electrodes(radius: $a = 1.5cm$). The waveform of spark voltage can be measured by oscilloscope when ESD event occurs. The height of ESD event is 1(m), that of the observation point is also 1(m). The ESD was happened parallel to the ground plane. These conditions can satisfy the radiative region mentioned above. The impulsive electromagnetic wave radiated by ESD can simply be detected with a commercially available ESD detector. ESD detector sounds a buzzer when the peak level of electric field exceeds a threshold level. The measurement experiment of ESD is performed as follows. The ESD detector is located at the constant distance from the spark point. The spark was generated at a two-seconds interval and then simultaneous measurements of ESD detection frequency and spark voltage were made for fifty-sparks. The spark length is fixed by 1.4(mm) and then the spark voltage was measured at 9.7 kV. Figure.6 shows the dependence of ESD detection rate $\eta(r)$ on observation distance r. It can be estimated from occurance probability where the radiated electric field exceeds a threshold level.

From Figure.6, there is a case that detection rate η at far distance is higher than in close proximity. It can be considered the strange phenomenon of ESD.
From the eq.(10), the normalized phase difference between the source dipole and the image dipole is given by

$$\frac{1}{c\tau}(R_r - R_i) = \frac{1}{c\tau}\{\sqrt{\rho^2 + (z-z')^2} - \sqrt{\rho^2 + (z+z')^2}\}$$

Above equation means that the longer the distance from ESD point is, the smaller the phase difference is. Figure.7, 8 express the electric fields in the time domain concerning each distance. Figure.9 shows the peak radiated electric field calculated with respect to the distance from ESD point. Due to such phase property of electric field explained above the peak value of the wave decreases very slowly in the region $r=7\sim 9(m)$. It can be thought that the overlapped field owing to shortened phase difference makes up the peculiar distance characteristic of the ESD appeared with experiment.

4. Conclusion

An ESD event has been modeled using a simple elementary dipole above a ground plane. It has been verified that radiated field is not always proportional to the inverse of observation distance. The cause is based upon the fact that the phase difference between the directly propagating wave and the reflected wave change the field waveform according to the variation of the observation distance. The agreement between model and experiment can explain the strange distance phenomenon of ESD. Future subject is to confirm experimently the electric field calculated from the ESD model on the perfect plane presented here. Then the antenna used to measure the electric field has to have a flat response until the broadband frequency.

References

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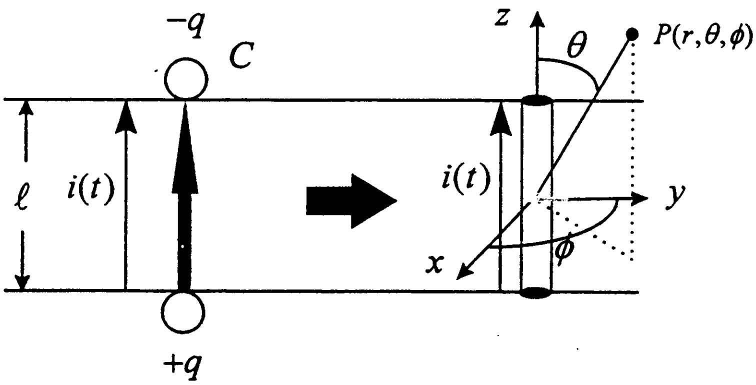

Figure.1 Electric dipole moment and dipole model

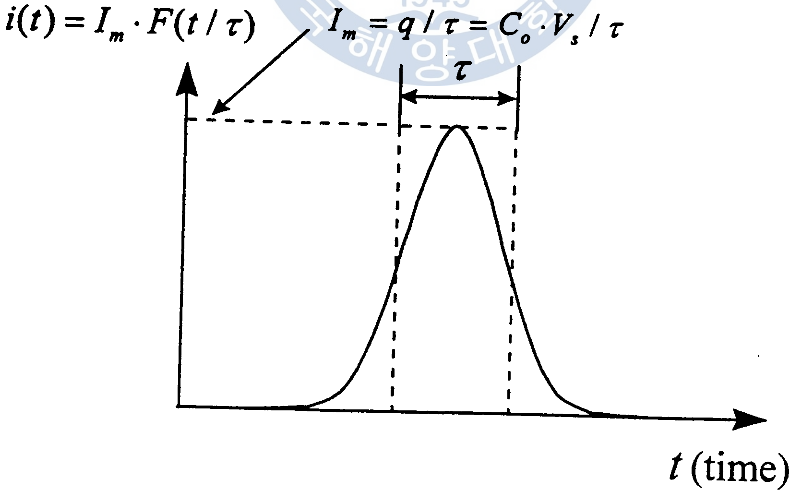

Figure.2 Impulsive spark current

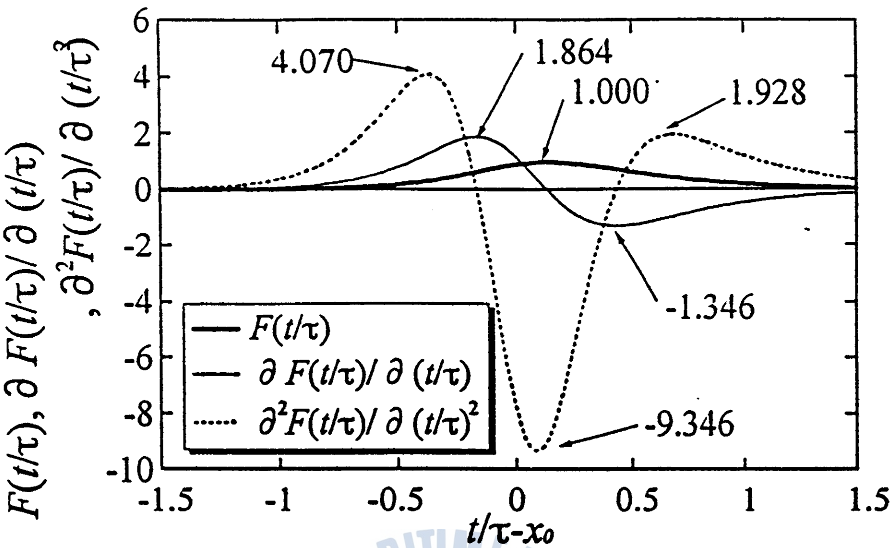

Figure.3 Waveforms of dimensionless $F(t/\tau)$, its derivatives $\partial F(t/\tau)/\partial(t/\tau)$, and $\partial^2 F(t/\tau)/\partial(t/\tau)^2$

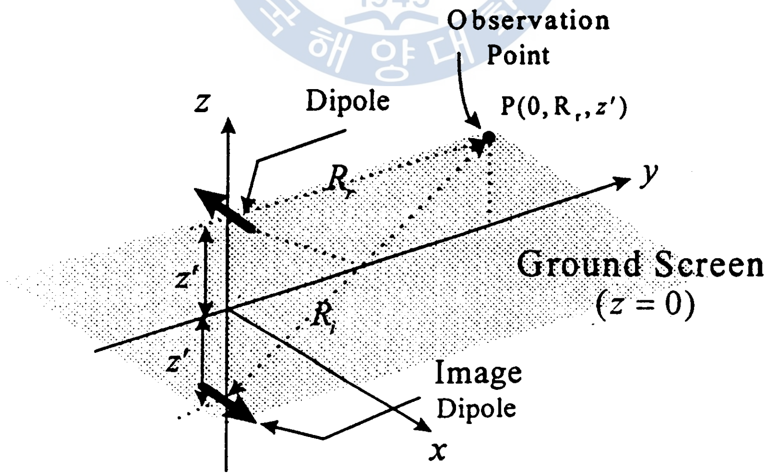

Figure.4 Dipole model of ESD on the perfect ground

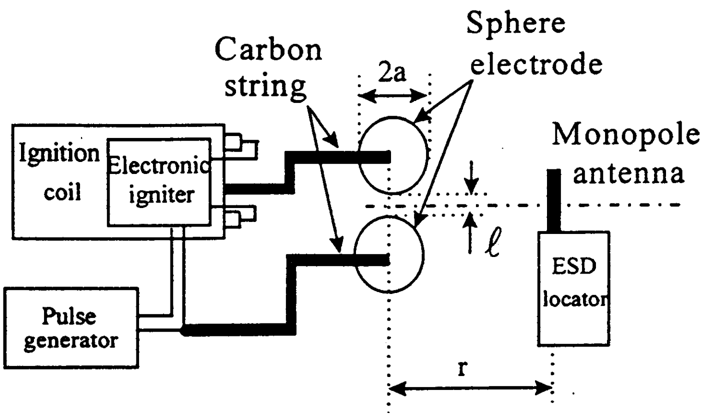

Figure.5 The configuration of experiment setup and ESD detection

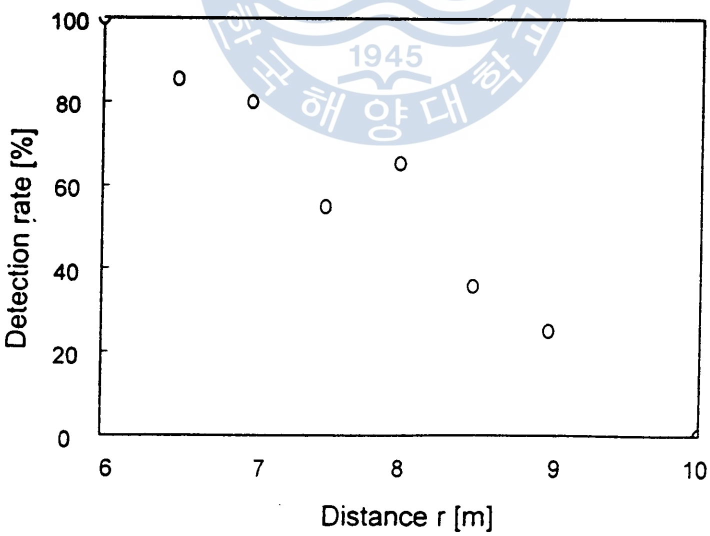

Figure.6 The detection rate at observation distance r

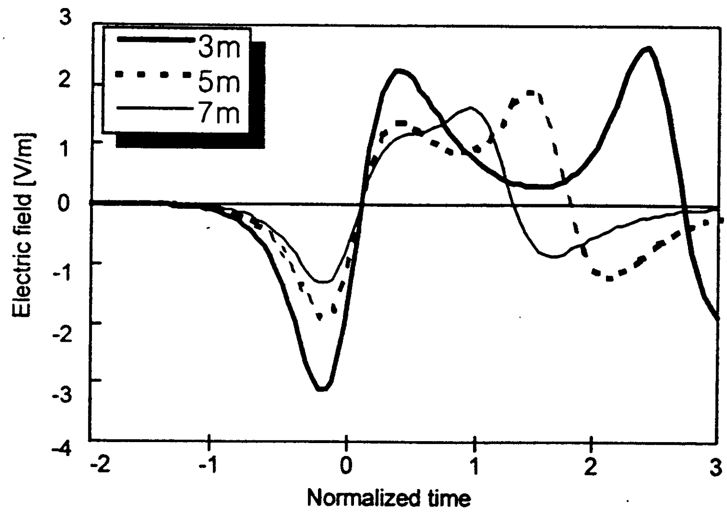

Figure.7 The waveforms of the summed electric fields(r=3,5,7(m))

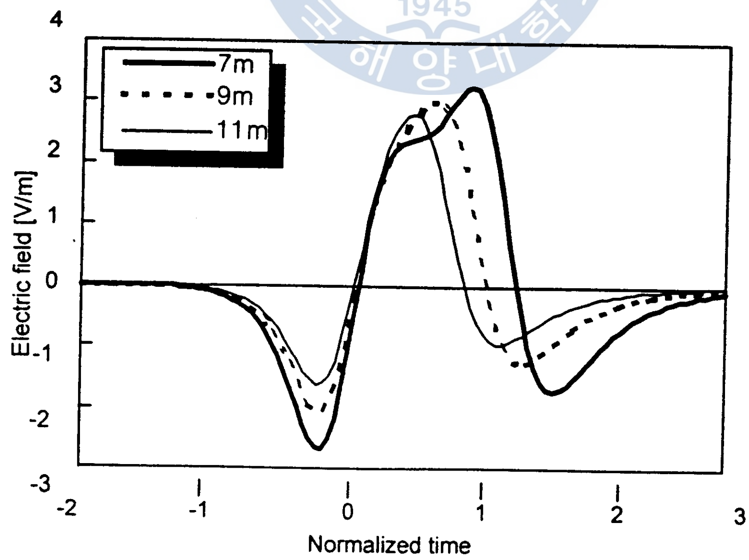

Figure.8 The waveforms of the summed electric fields(r=7,9,11(mm))

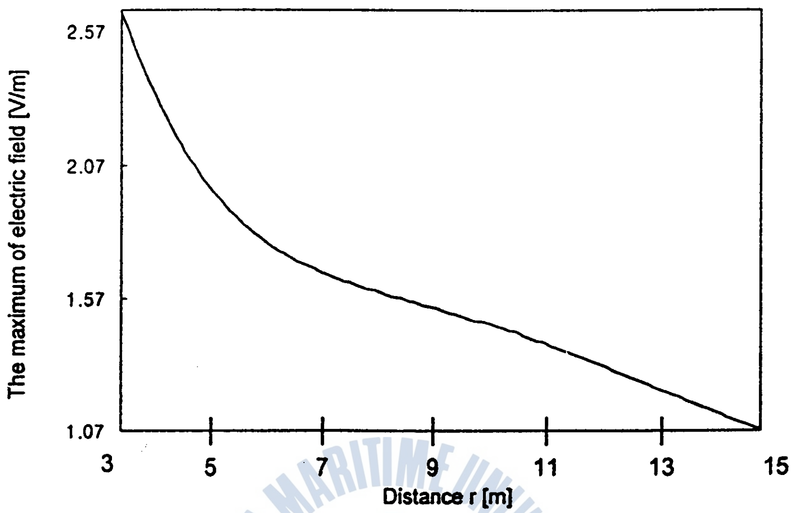

Figure.9 The peak radiated electric field calculated with respect to the distance r.