Application of TEM horn antenna in radiating NEMP simulator

Yun Wang 1*, Yongguang Chen 2, Qingguo Wang 2
1. Department of Postgraduate, the Academy of Equipment, Beijing 101416, China;
2. Institute of Electrostatic and Electromagnetic Protection, Mechanical Engineering College, Shijiazhuang, 050003, China

Email: wangyunjunxie@163.com

Abstract. In order to design a small radiating nuclear electromagnetic pulse simulator with fast rise time, we have investigated the application of TEM horn antenna in this kind of simulator. The TEM horn antenna is excited by the integral double exponential pulse. Farfield response in time domain is analyzed based on the step response formula which is derived from the equivalent transmission line model of TEM horn antenna. Principle of antenna parameters selection is determined. The results of numerical calculation give a show of the radiation waveform and some problems. Then experiments are implemented and results are compared with the radiation waveforms generated by double exponential pulse excitation. It suggests that the TEM horn antenna can be used as radiating antenna in the NEMP simulator, which can radiate double-exponent-like pulse with the integral double exponential pulse as excitation. Meanwhile, impedance loading can improve farfield waveforms and enhance the low-frequency radiating ability of antenna.

1. Introduction

Nuclear electromagnetic pulse simulators (NEMPS) are usually used to produce nuclear electromagnetic pulse (NEMP) environment by generating double exponential pulse approximately when testing NEMP’s electromagnetic effect. At present, international and domestic waveform standards have been made for electromagnetic pulse (EMP) simulators. In 1999, the U.S. standard “MIL-STD-461E” [1]. specified following standards: EMP waveform peak value is 50 kV m⁻¹, rise time is 1.8-2.8 ns, and half peak pulse width is 23±5 ns. Our country has released similar waveform standard “GJB1389A-2005” [2]. All these standards have shorter rise time and narrower pulse width than old standards (such as the 1986 U.S. standard “MIL-STD-461C” [3], 1993 U.S. standard “MIL-STD-461D” [4] etc.). Rise time of pulse generated by traditional NEMPS (such as bounded wave simulator, static simulator, etc. [5]) is not fast enough because of the transmission line structure. However, the radiating EMP simulators using antenna structure can get faster rise time and larger test space without special requirements, which benefit to the EMP effect experiments for large equipment.

Nowadays cage-like dipole antennas are commonly used [6] with the features of constant impedance, broad band and good field uniformity parallel to the axis. However, the volume of this kind of antenna is generally very huge, rise time is longer, directionality is poor, and the effective test area is small. In this paper, TEM horn antenna is tried for NEMPS, which has been widely adopted in ultra wideband fields [7] as a pulse radiating antenna with a certain directivity, wide bandwidth and

* To whom any correspondence should be addressed.
the phase centre of radiation invariance. Theoretic analysis and numerical simulation as well as experiment are implemented. Results show that TEM horn antenna can be used as the radiating antenna in EMP simulator if its low frequency radiation performance can be improved.

2. Basic theory of TEM horn antenna

As shown in figure 1, TEM horn antenna is composed of two triangular metallic plates. The intersection angle is $\beta$. Each plate’s flare angle is $\alpha$. Antenna length is expressed by $l$, height by $h$, width by $w$. The characteristic impedance of antenna is $Z_c$. For TEM horn antenna with small flare angle, current distribution on plates is mainly composed of the longitudinal component along with $Z$ direction. Therefore, in literature [8], TEM horn antenna can be described by a transmission line circuit model with terminal open. Based on this equivalent model, a formula of step response for radiation on the antenna’s axis is given:

$$
\tilde{E}_{y}^{TOT}(r,t)=\frac{V_0}{r} \frac{l}{h} E_y^{\text{norm}} \left[ e^{-\omega r/c} u(t_r) \frac{c}{2l} \left( (1-e^{-\omega r/c})u(t_r)-(1-e^{-\omega r/c})u(t_r-\frac{2l}{c}) \right) \right]
$$

(1)

where $u(t)$ is the step pulse; $t_r = t - \frac{r+1}{c}$; $c$ is light velocity; $r$ is the far-field distance shift from the antenna aperture; $w_2 = 2\pi f_2$, which means high frequency cut-off point in antenna frequency response; $V_0$ is the input voltage peak, $E_y^{\text{norm}} = E_y / (V_0 / h)$; for TEM horn antenna with small flare angle, $E_y^{\text{norm}} \approx 1$. From the frequency response asymptotes of the TEM horn with step excitation shown in figure 7 of literature [8], we get that:

$$
f_1 = \frac{c}{2\pi l}
$$

(2)

$$
f_2 = \frac{2lcw_2 E_y^{\text{norm}}}{h^2}
$$

(3)

This frequency response can be viewed as the band pass filter. In the pass band, the curve is smoothing, which means that radiation waveforms keep up with the differential form of pulse excitation. So in order to get double-exponent-like pulse radiation field, we need to use the integral double exponential pulse excitation.

![Figure 1. Diagram of the TEM horn antenna.](image)
3. Farfield in time domain with integral double exponent pulse excitation.

The actual systemic response is the convolution of step response and the differential form of actual input voltage. Using formula (1), the formula of radiation farfield response in time domain can be deduced for TEM horn antenna excited by arbitrary pulse:

\[
\tilde{E}_y^{\text{TOT}}(r,t) = \text{formula(1)} \otimes \frac{dV(t)}{dt}
\]

\[
= -\frac{v_0}{r} E_y^\text{norm} y \left[ A - \frac{c}{2l} \frac{1}{\omega_z} [B - C] \right] = -\frac{v_0}{r} E_y^\text{norm} \left[ A(t_r) - \frac{c}{2l} \frac{1}{\omega_z} B(t_r) \right] \quad t_r < 0
\]

\[
= -\frac{v_0}{r} E_y^\text{norm} \left[ A(t_r) - \frac{c}{2l} \frac{1}{\omega_z} [B(t_r) - B(t_r - \frac{2l}{c})] \right] \quad t_r > \frac{2l}{c}
\]

Where \( \frac{dV(t)}{dt} = V'_1(t) u(t) \) indicates that \( V'_1(t) \) only has meaning at \( t \geq 0 \), and

\[
A = e^{-\omega_z t} u(t_r) \otimes V'_1(t) u(t) = A(t_r) u(t_r);
\]

\[
A(t_r) = e^{-\omega_z t} u(t) \otimes V'_1(t) u(t);
\]

\[
B = (1 - e^{-\omega_z t}) u(t_r) \otimes V'_1(t) u(t) = B(t_r) u(t_r);
\]

\[
B(t_r) = (1 - e^{-\omega_z t}) u(t) \otimes V'_1(t) u(t);
\]

\[
C = (1 - e^{-\omega_z t} \frac{2l}{c}) u(t_r - \frac{2l}{c}) \otimes V'_1(t) u(t) = B(t_r - \frac{2l}{c}) u(t_r - \frac{2l}{c})
\]

According to IEC 61000-2-9 [1], we can get the integral double exponential pulse,

\[
V(t) = \begin{cases} 
0 & \text{for } t \leq 0 \\
\frac{k E_0}{\tau_1 \tau_2} \left( \tau_1 e^{-\tau_1 t} - \tau_2 e^{-\tau_2 t} \right) & \text{for } t > 0 \end{cases}
\]

Where \( E_0 = 50 \text{ kV m}^{-1}, \tau_1 = 4.0 \times 10^7 \text{ s}^{-1}, \tau_2 = 6.0 \times 10^8 \text{ s}^{-1}, k = 1.3 \), pulse duration time \( T = 100 \text{ ns} \).

Figure 2. Radiated waveforms for different antenna length.
Figure 3. Comparison of farfield waveforms.

Set the antenna length as 1.6 m, 7 m, 16 m, respectively, the corresponding antenna height are 1.55 m, 3.24 m, 4.90 m, using integral double exponential pulse excitation, the far field radiation waveforms on the antenna’s axis are shown in figure 2, which indicate that the amplitude of radiation field becomes large, the pulse width is broadening, and the pulse form is gradually close to double exponential pulse with the antenna length and height increasing. However, the zero-crossing phenomenon becomes serious, the negative peak value is larger and the waveform after zero comes to be poor.

4. Simulations and experiments

Now we execute some simulations and experiments to have a farther analysis for the TEM horn antenna.

4.1. Principle of antenna parameters selection

There are 5 parameters which are $l$, $h$, $w$, $\alpha$, and $\beta$. According to the geometric features, the relationship between them is shown as follows:

$$\begin{cases}
\beta = 2 \tan \left( \frac{h}{2l} \right) \\
\alpha = 2 \tan \left( \frac{w}{h} \sin \left( \frac{\beta}{2} \right) \right)
\end{cases} \quad (6)$$

In this formula, the ratio of $\frac{w}{h}$ is determined by characteristic impedance $Z_c$, which can be calculated by the formula (21) and (22) in literature [9].

According to the above analysis, the principle of TEM horn antenna parameters selection can be summarized as: with $Z_c$ known, $E_{\text{norm}}$ is generally taken as one, we need firstly to determine the antenna length $l$ and height $h$ according to frequency range $f_1 \sim f_2$ by formula (2) and (3); and then get the values of aperture width $w$ and structure angle ($\alpha, \beta$) by the formulas in literature [10].
4.2. Numerical modeling and simulation results
According to the above principle, let \( f_1 = 3 \) MHz, \( f_2 = 400 \) MHz, \( Z_c = Z_0 = 377\Omega \), then we can get that: \( l \approx 16 \) m, \( h \approx 4.89 \) m, \( w \approx 0.85 \) m, \( \alpha \approx 3^\circ \), \( \beta \approx 17^\circ \). With integral double exponential pulse as excitation, based on the finite integral in time domain (FITD) method [11], the farfield waveform of 50 m away from the antenna aperture, compared with the theoretical value (because of the difference between norm antenna and equivalent transmission line model, the farfield amplitudes are not comparable, so both the simulation and theoretical results are normalized by max values), is shown in figure 3.

It can be seen that there are negative peak in both numerical and theoretical calculations. Coincident front waveforms demonstrate that the high frequency radiation performance of actual antenna is good, so we can have lower requirement for antenna height in view of antenna parameter selection principle. However, the farfield pulse width calculated by simulation is far narrower than theoretical calculation. This is because that the actual antenna length is limited and then most of the low frequency components of the pulse excitation is not radiated out but returned from antenna terminal. Therefore, we have to consider methods of impedance loading, antenna deformation, filling medium, and low frequency compensation loop and antenna array and so on to improve low-frequency radiation performance for TEM horn antenna.

4.3. The experimental design and results analysis
TEM horn antenna for experiments has length 1.5 m and height 1 m, aperture width 2 m, two 180 ohms water resistances are placed at the antenna end. High voltage source is used for charging the capacitor, and then the spark gap switch breaks over, capacitor discharges to produce an integral double exponential pulse approximately. Electric field is measured by optical field tester, and displayed in a shielded room through the oscilloscope.

Do gradually increase the output voltage value to make switch breakdown. Because of the functional limitations of field tester, waveforms but not the field strength values are observed. E-field waveform at 5 meters shift from the aperture is shown in figure 4. In order to compare with radiation waveform generated by double exponential pulse excitation, we can use Marx generator to replace voltage source and capacitor, for which far field is shown in figure 5.

![Figure 4. Farfield waveform with resistors at the antenna end.](image1)

![Figure 5. Farfield waveform with Mark generator excitation.](image2)

From experimental results it can be seen that when using integral double exponential pulse excitation, far field is approximately close to double exponential pulse form, and low frequency radiation performance can be improved through the method of resistance loading; but when using Marx generator as excitation, TEM horn antenna actually radiate the differential form of double...
exponential pulse, and pulse width is smaller, furthermore, radiation waveform is generally in some serious oscillation as the Marx generator itself output dithering double exponential pulse. Experiments indicate that TEM horn antenna can be used for radiating NEMPS, but the low frequency radiation ability needs to be enhanced through the way of resistance loading.

5. Conclusions
This paper tries to apply TEM horn antenna for NEMPS and get the following conclusions:

a) Radiation theory in time domain is analyzed based on the equivalent transmission line model of TEM horn antenna with small flare angle, which deduces far field response for the integral exponential pulse excitation, and indicates that with the antenna length and height increasing, amplitude of radiation field becomes larger, pulse width is broaden and waveform is gradually close to double exponential pulse form, and low frequency radiation performance is improved, but the zero-crossing phenomena becomes serious, the part of waveform after zero goes into poor;

b) Principle for antenna parameters selection is given as that: firstly, choose the proper antenna length and height with taking the frequency range into account; and then set the structure angles based on the characteristic impedance of antenna;

c) Numerical results and experimental results show that: the high frequency radiation performance of actual antenna is good; but the narrow half peak pulse width cannot satisfy the requirements. Therefore, when using TEM horn antenna as the radiating antenna of simulator, low frequency radiation performance need to be improved.

As limited by experimental conditions, the strength values of far field and field uniformity have not been analyzed. Further work will be concentrated on EMP waveform, field strength, field distribution and field uniformity and many other aspects. More importantly, we have to improve the low frequency radiation performance of antenna through antenna optimization design in depth.

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