Time-domain simulation and waveform reconstruction for shielding effectiveness of materials against electromagnetic pulse

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Abstract. Shielding effectiveness (SE) of materials of current testing standards is often carried out by using continuous-wave measurement and amplitude-frequency characteristics curve is used to characterize the results. However, with in-depth study of high-power electromagnetic pulse (EMP) interference, it was discovered that only by frequency-domain SE of materials cannot be completely characterized by shielding performance of time-domain pulsed-field. And there is no uniform testing methods and standards of SE of materials against EMP. In this paper, the method of minimum phase transfer function is used to reconstruct shielded time-domain waveform based on the analysis of the waveform reconstruction method. Pulse of plane waves through an infinite planar material is simulated by using CST simulation software. The reconstructed waveform and simulation waveform is compared. The results show that the waveform reconstruction method based on the minimum phase can be well estimated EMP waveform through the infinite planar materials.

1. Introduction
Electromagnetic pulse (EMP) is a phenomena of transient electromagnetic, with a characteristics of transient, wideband, high field strength, wide effective scope and so on, the coupling path through the antenna through an aperture, cable and other electronic equipment system to cause a serious threat. EMP is an important part of electromagnetic environment, which is described in time-domain. EMP includes electrostatic discharge (ESD), lightning electromagnetic pulse (LEMP), nuclear electromagnetic pulse (NEMP), high power microwave (HPM), intends to electromagnetic interference (IEMI) and ultra-wide band (UWB). With the extensive application of microelectronic devices, the sensitivity and vulnerability of electronic device or system against EMP are gradually increasing. It seriously limits the electromagnetic viability of electronic device or system. Therefore, research and analysis of anti-jamming capability of electronic equipment or system in complex electromagnetic environment has an important theoretical and practical significance.

Shielding effectiveness (SE) of materials of existing testing standards is usually described by continuous-wave measurement in frequency domain. Amplitude-frequency characteristic curve is used to characterize SE by measuring the response amplitude at each frequency point one by one in a system. It can be more comprehensive understanding shielding ability of materials to the measured

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spectrum of electromagnetic waves based on the SE in frequency-domain. But with the discovery of high-power EMP interference, only by the SE of materials in frequency-domain cannot be completely characterized by time-domain pulsed-field shielding effect [1-4]. The method of minimum-phase transfer function and flow chart of reconstruction waveform is proposed to reconstruct shielding time-domain waveform based on the analysis of the waveform reconstruction method. Pulse of plane waves through the infinite planar materials is simulated by using CST simulation software. In order to verify the applicability of minimum-phase method, the reconstructed waveform is compared with the simulation waveform.

2. Analysis of the waveform reconstruction method
There is no phase information in continuous-wave test. Researchers want to estimate time-domain response from the actual measurement of amplitude-frequency characteristics, and establish relationship between time-domain SE and frequency-domain SE. M. H. Hayes and other researchers have made a detailed discussion that reconstruct the phase information using amplitude-frequency characteristics. It is generally believed that the phase-frequency characteristics can be uniquely determined by its amplitude frequency characteristics when the system meets the minimum phase condition. Assumed that the system is linear and satisfy the minimum phase condition, the relationship between the real and imaginary parts of transfer function is established by Hilbert transform, and then shielding time-domain waveform of EMP is reconstructed.

For a stable, causal real sequence \( x[n] \), the complex cepstrum \( \hat{x}[n] \) is defined as the Fourier transform of \( x[n] \) to take the logarithm after the inverse Fourier transform.

\[
\hat{x}[n] = \frac{1}{2\pi} \int_{-\pi}^{\pi} \ln|X(e^{j\omega})| e^{j\omega n} d\omega
\]

\( X(e^{j\omega}) \) will be written in polar form

\[
X(e^{j\omega}) = |X(e^{j\omega})| e^{j\arg[X(e^{j\omega})]}
\]

Real inverted spectrum \( x_r[n] \) is defined as the Fourier transform \( x[n] \) of taking the logarithm after inverse Fourier transform.

\[
x_r[n] = \frac{1}{2\pi} \int_{-\pi}^{\pi} \ln|X(e^{j\omega})| e^{j\omega n} d\omega
\]

Obviously, \( x_r[n] \) is the Fourier transform of the real part of the inverse Fourier transform of \( \hat{x}(e^{j\omega}) \), and \( x_r[n] \) is the even part of \( \hat{x}[n] \). Transfer function to meet amplitude-frequency characteristics of the system has infinitely many, because the phase-frequency characteristics can be arbitrarily chosen, but only one of which is the minimum-phase system. Minimum-phase system is the discrete transfer function of the system of poles and zeros outside the unit circle.

The complex cepstrum \( \hat{x}[n] \) is causal discrete, so \( x[n] \) is transfer function of minimum-phase system. Log and its phase function of frequency-domain amplitude spectrum of minimum phase system discrete transfer function is a mutual Hilbert Transform, which \( \ln|X(e^{j\omega})| \) and \( \arg[X(e^{j\omega})] \) satisfy the following relationship:

\[
\arg[X(e^{j\omega})] = -\frac{1}{2\pi} \int_{-\pi}^{\pi} \ln|X(e^{j\omega})| \cot\left(\frac{\omega - \theta}{2}\right) d\theta
\]

\[
\ln|X(e^{j\omega})| = \frac{1}{2\pi} \int_{-\pi}^{\pi} \arg[X(e^{j\omega})] \cot\left(\frac{\omega - \theta}{2}\right) d\theta + \hat{x}[0]
\]

Where \( \hat{x}[0] = \frac{1}{2\pi} \int_{-\pi}^{\pi} \ln|X(e^{j\omega})| d\omega \)

If \( |X(e^{j\omega})| \) is known, the phase spectrum can be got by the equation (4). The processing of singular point should be noticed in the same.
The real cepstrum $x_c[n]$ can be got by logarithmic from frequency-domain amplitude spectrum $|X(e^{j\omega})|$. And $\hat{x}[n]$ can be recovered by adding window function form the real cepstrum $x_c[n]$.

$$\hat{x}[n] = x_c[n] \cdot \min[n]$$  
(6)

Where $l_{\min}[n] = 2u[n] - \delta[n]$.

If the frequency-domain SE of materials is known, unshielded EMP is looked as the input excitation of system and response of EMP penetrating the materials is looked as output of system, then frequency-domain transfer function $H(\omega)$ can be calculated using the equation (8). Assuming minimum-phase system, the time-domain transfer function is calculated based on the frequency-domain transfer function, then it convolution with unshielded EMP time-domain waveform. Shielded time-domain waveform $E_m(t)$ is got, it can be estimate the time-domain SE of materials. The calculation flow chart is shown in figure 1.

$$SE = 20 \log_{10} \frac{E_{\text{unshielded}}(\omega)}{E_{\text{shielded}}(\omega)}$$  
(7)

$$H(\omega) = \frac{E_{\text{shielded}}(\omega)}{E_{\text{unshielded}}(\omega)} = 10^{-\frac{SE}{20}}$$  
(8)

**Figure 1.** Modelling flow chart of SE of materials against EMP.

3. **Simulation of SE of infinite planar materials against EMP**

The waveform of plane wave through the infinite planar materials is calculated with the CST simulation software, the model shown in figure 2, the polarization direction of the plane wave $+y$, incident direction-$z$. Simulation with a uniform thickness of the material to take the 0.1 mm thick, the relative permittivity and relative permeability are 1, the conductivity of the material taken $10^3$ s m$^{-1}$. Square wave EMP and IEC61000-4-4 standard EMP is used for excitation source signal. And the parameters of square wave EMP is rising edge 1ns, the falling edge 4 ns, flat top keeping 47 ns.

4. **Comparison of reconstructed waveform and simulation waveform**

The time-domain waveform of pulse through the shielding materials is calculated by the minimum-phase method, which was compared to simulation results. The results are shown in figure 4, in good agreement with the simulation results. It is known that waveform reconstruction method based on the minimum-phase can be well estimate the time-domain waveform of EMP through the planar materials.
Frequency-domain SE can provide a more comprehensive understanding of shielding ability of materials against each frequency band. But with the strong EMP interference research, it cannot fully characterize the SE of materials against EMP based on frequency-domain SE. Peak ratio SE is often used to characterize the SE of materials against EMP, and it cannot directly determine the peak ratio SE by frequency-domain SE. In addition, it cannot meet the needs of EMP protection design only by the time-domain peak ratio SE. Rise time, pulse width and other information of EMP is also important, except for the time-domain peak ratio SE. The use of minimum-phase method, you can get the materials to shield the pulse before and after the time-domain parameters change. Then, it can estimate the time-domain SE of materials, the results are listed in table 1.

| Table 1. Time-domain parameter changes of EMP penetrate the planar materials. |
|---------------------------------|----------------|----------------|----------------|
|                                | unshielded | Peak of EMP(V m⁻¹) | SE(dB) | Rise time of EMP(s) | unshielded | shielded | shielded |
| Square EMP                      | 1.0040     | 0.0053             | 45.5   | 7.8615e-010        | 8.2258e-010 |
| IEC61000-4-4 EMP                | 1.0166     | 0.0053             | 45.7   | 4.9848e-009        | 4.9841e-009 |

5. Conclusions
In this paper, the method of minimum-phase transfer function is suggested to reconstruct shielding time-domain waveform based on the analysis of the waveform reconstruction method. Pulse of plane waves through the infinite planar material is simulated by using CST simulation software. And the reconstructed waveform is compared with the simulation waveform. The results show that the waveform reconstruction method can be well estimate the waveform of EMP through the infinite planar materials.

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