Time-domain modeling for shielding effectiveness of materials against electromagnetic pulse based on system identification

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Abstract. Shielding effectiveness (SE) of materials against electromagnetic pulse (EMP) cannot be well estimated by traditional test method of SE of materials which only consider the amplitude-frequency characteristic of materials, but ignore the phase-frequency ones. In order to solve this problem, the model of SE of materials against EMP was established based on system identification (SI) method with time-domain linear cosine frequency sweep signal. The feasibility of the method in this paper was examined depending on infinite planar material and the simulation research of coaxial test method and windowed semi-anechoic box of materials. The results show that the amplitude-frequency and phase-frequency information of each frequency can be fully extracted with this method. SE of materials against strong EMP can be evaluated with time-domain low field strength (voltage) of cosine frequency sweep signal. And SE of materials against a variety EMP will be predicted by the model.

1. Introduction
Testing standards of shielding effectiveness (SE) of materials are carried out through one by one measurement in frequency-domain by far. Then, the shielding performance of materials can be characterized by the amplitude-frequency curve. With in-depth study of high-power electromagnetic pulse (EMP) interference, it was discovered that only by frequency-domain SE of materials research cannot be completely characterized by shielding performance of time-domain pulsed-field [1, 2]. The results of frequency-domain measurement cannot directly determine time-domain shielding effectiveness of EMP mentioned in [3, 4]. And measurement equipment for EMP-field is not as continuous-wave measurement equipment as popular. People wish that time-domain response of the system can be estimated with the amplitude-frequency characteristics which were provided by manufacturers or experiment. The solution for this problem is to assume that the system is linear and minimum-phase system, estimate the phase frequency characteristics by amplitude-frequency characteristics through the Hilbert transform, and get the system impulse response discussed in [5, 6]. But some non-minimum phase systems is not well resolved. In addition, the vector fitting method can be used to solve this problem described in [7]. Overall, deconvolution problems which reconstruct time-domain data from frequency-domain are "sick", there are inherent deficiencies. In this paper, the shielding effect of materials against EMP was looked as a black-box system. Time-domain linear cosine swept signals were used to sufficiently excite the system. And time-domain waveform of unloaded and loaded materials was recorded. The model of SE of materials against EMP will be
established by SI. And 2 ns/50 ns double exponential EMP and square-wave EMP was used to validate the applicability of this method.

2. Model flow of SE of materials using SI
In this paper, linear cosine frequency sweep signal is an excitation signal. Electric field (or magnetic field), received in space, when shielded and unshielded was looked as an input / output (I/O) data of the system. SI was used to establish the model of SE of materials against EMP. Then, the time-domain waveform of EMP through shielding materials can be predicted by the model. Model flow chart of SE of materials against EMP was shown in figure 1.

![Modeling flow chart of SE of materials against EMP.](image)

SI is to determine an equivalent system in the specified system on the basis of I/O data [8]. Differential equation is the most basic model for identification of linear discrete systems. The relationship between input \(u(k)\) and output \(y(k)\) sample value sequence of an dynamic system can be expressed as the following n-order linear differential equation (1):

\[
y(k) + a_1 y(k-1) + \cdots + a_n y(k-n) = b_0 u(k) + b_1 u(k-1) + \cdots + b_n u(k-n)
\]  

Equation (1) is the Auto-Regressive Moving Average model, referred to as the ARMA model. Equation (1) is operated by Z transform. In zero initial conditions, the ratio of the output z-transform and the input z-transform is the system transfer function.

\[
G(z) = \frac{Z\{y(k)\}}{Z\{u(k)\}} = \frac{b_0 + b_1 z^{-1} + \cdots + b_n z^{-n}}{1 + a_1 z^{-1} + \cdots + a_n z^{-n}}
\]  

Equation (2) can be abbreviated as

\[
A(z^{-1})y(k) = B(z^{-1})u(k)
\]  

\[
A(z^{-1}) = 1 + a_1 z^{-1} + \cdots + a_n z^{-n}, \quad B(z^{-1}) = b_0 + b_1 z^{-1} + \cdots + b_n z^{-n}
\]

When you consider the noise term \(\varepsilon(k)\), equation (3) is changed to equation (4)

\[
A(z^{-1})y(k) = B(z^{-1})u(k) + \varepsilon(k)
\]
Equation (4) is called the ARX (auto-regressive model with exogenous input) model. Equation (3) can become

\[ y(k) = \frac{B(z^{-1})}{A(z^{-1})} u(k) + \varepsilon(k) \]  

Equation (5) is the OE (Output Error) model.

Above all is the commonly used model in the linear system. And it is also used in this paper. The combination of various improvements or optimization algorithm can get better results. SI is transformed into estimation of model parameters used in the least squares method, through constant change model parameters, making it the closest to the actual system parameters, and the final system model is got. The selected error criterion is the basis of the model close to the actual system. And it is one of the important elements of the identification problem. In this paper, the fitting between the predict waveform and simulation waveform is finally used to judge the pros and cons of the model. In addition, the model order selection should be the appropriate. When precision of the model meets the requirements, it should be chosen by the lower order. The order of the model in this paper is less than 10.

3. Time-domain modeling for SE of materials against EMP

Time-domain linear cosine sweep signal is used as the modeling signal. And 2ns/50ns EMP and square wave EMP is used for validation signal. SE measurement of infinite planar materials and coaxial test and windowed semi-anechoic box is simulated by CST Microwave Studio software. The time-domain waveform shielded and unshielded of three different cases is recorded. And the data is used to validate the proposed method in this paper. Linear cosine sweep signal for the expression:

\[ f(t) = f_0 + \beta t \quad (\beta = (f_1 - f_0)/t_1) \]  

2ns/50ns double exponential expression of EMP as:

\[ y(t) = k(e^{-\alpha t} - e^{-\beta t}) \]  

Detailed parameters of the three simulation signals are listed in table 1. The square wave EMP is determined by the rising time \( t_r \), falling time \( t_f \) and flat-topped to keep \( t_h \). The linear sweep frequency signal is described by sweep time range \( t \), end time \( t_1 \), initial frequency \( f_0 \) and end frequency \( f_1 \).

| Table 1. Parameters of three simulation signal. |
|-----------------------------------------------|
| **Modeling signal** | **Validation signal** |
| Linear sweep frequency signal | 2ns/50nsEMP | Square wave EMP(ns) |
| parameter of signal | \( t = 0-200 \text{ ns}, f_0 = 0 \text{ Hz}, t_1=200 \text{ ns}, f_1=1 \text{ GHz} \) | \( k=1.09, \alpha =1.54 \times 10^7, \beta =9 \times 10^8 \) | \( t_r=1, t_f=4, t_h=47 \) |

The thickness of 1 mm and the conductivity of 1000 s m\(^{-1}\) of isotropic material, is always used in the simulation. Most energy of EMP is concentrated in the sub-1 GHz, so the frequency range calculated in simulation is 0 to 1 GHz.
3.1. Method of coaxial test

Shielding of infinite planar material against vertical incidence plane wave is the classic problem of electromagnetic shielding. Through research of infinite planar materials, we can see that the proposed method in this paper is feasible in theory. This is not surprising that the minimum-phase method also succeeds in solving this problem. Only using 2-order Model can be achieved very good results, fitting up to 99.71 %. So we no longer display the results.

Simulation model of coaxial test device is established, in accordance with GJB6190-2008. One end is excitation port, the other end is load port, impedance is 50 Ω. Three signals have been given in table1, respectively, in setting the excitation port source required for modeling data and validation data. ARX model identification, take the model order \( n = 1:10 \), \( n_{a b} = 1:10 \), the pure delay \( n_k = 1:10 \), found that when \( n = 6 \), \( n_{a b} = 4 \), \( n_k = 10 \) and \( n = 10 \), \( n_{a b} = 5 \), \( n_k = 5 \), the model output and the actual simulation output agreement well, the fitting of IEC waveform, respectively 88.56 % and 88.37 % (figure 2a), but still a poor prediction of square wave EMP. OE model is used to model, assuming no delay, ie, \( n_a = n_b \). When the order is 4, the fitting of 2ns/50ns EMP and square wave EMP, respectively, achieve 97.67 % and 98.3 % (figure 2b). Transfer function of EMP SE is:

\[
H(z^{-1}) = \frac{0.0002307z^{-1} + 0.0007235z^{-2} - 0.0007587z^{-3} + 0.0002661z^{-4}}{1 - 3.842z^{-1} + 5.546z^{-2} - 3.566z^{-3} + 0.8614z^{-4}}
\]

\[(8)\]

![Figure 2. Comparison of simulation shielded waveform and model prediction waveform using the method of coaxial test. (a) 2 ns/50 ns EMP; (b) square wave EMP.](image)

3.2. Method of windowed semi-anechoic box

The method of windowed semi-anechoic box has been simulated based on IEC61587-3. Window size of 60 cm× 60 cm, box size of 1 m × 1 m × 1 m aluminium shielding box model was created by CST Microwave Studio. In order to restrain resonant caused by the box and control the space of absorber, hybrid absorber was mounted on the inner wall of the box according to the reference. The box is illuminated by a plane wave, plane wave along the window at normal incidence, the polarization direction of electric-field perpendicular to the ground. The proposed method in this paper is used to model the SE of materials against EMP using the windowed semi-anechoic box. It is found that the prediction waveform of other order of the ARX model is similar to the ARX441 model in figure 3a and figure 3b, but the proportion attenuation of unshielded materials. OE model can forecast better the 2ns/50ns EMP waveform unshielded materials, but is still large error for the forecast of square wave EMP, even if increased the model order. Although the box is loaded absorber using the windowed semi-anechoic box, there is still resonance. And taking into account the strong attenuation of the window for low-frequency electromagnetic waves coupled to box. There is much more complex than
the two previous simulation examples. Maybe, the reason is that the model data cannot take enough information for the model of SE of materials against EMP.

![Graph](image_url)

**Figure 3.** Comparison of simulation shielded waveform and model prediction waveform using the method of windowed semi-anechoic box. (a) 2 ns/50 ns EMP; (b) square wave EMP.

To this end, the phase 90°, 180°, 270° linear cosine swept signals are added to the original data. The combination signal is used for modelling the signal. 8-order OE model can well forecast the shielded time-domain waveform. The fitting degree respectively achieved 88.68 % and 89.66 % for 5ns/20ns EMP and square wave EMP. Transfer function of EMP SE is:

\[
H(z^{-1}) = \frac{0.00249z^{-1} - 0.007811z^{-2} + 0.004685z^{-3} + 0.01377z^{-4} - 0.03254z^{-5}}{1 - 3.773z^{-1} + 5.269z^{-2} - 2.383z^{-3} - 2.371z^{-4} + 4.108z^{-5}} \\
+ 0.03307z^{-6} - 0.01757z^{-7} + 0.003913z^{-8} \\
- 2.07z^{-6} + 0.01251z^{-7} + 0.2079z^{-8}
\]  

(9)

Overall, OE model is better than the ARX model, and the model order is lower. It is very important to select the appropriate modeling signal that can sufficiently excitation the system properties. Only in this way we can get a good generalization ability of the model.

4. Conclusion

In this paper, three kinds of simulation data of SE of materials are used to research the model of SE of materials against EMP based on method of SI. Model of SE of materials against EMP is successfully established through time-domain low field strength (voltage) of cosine frequency sweep signal. The time-domain waveform of a typical EMP through the shielding material is successfully predicted. It will lay the foundation to predict SE of materials against variety strong EMP.

The next step will be to study the modeling method in engineering practice, such as the rational design of SE of materials against EMP in measured experiment, data preprocessing, and so on.

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