Experimental investigation on time-domain testing of shielding effectiveness of composite materials against EMP

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Abstract: The shielding effectiveness (SE) of materials with different thickness is experimentally investigated using an improved time-domain testing system of SE and a window on a shielding enclosure in a GTEM cell. Experimental results show that the proper test position of transient electric probe (E-probe) within the enclosure is determined to make the system capable of finding out the maximum peak value of pulsed electric field inside enclosure. The SE test experiments for several shielding composite materials fabricated using nickel-plated carbon fiber proved that the SE of materials for electromagnetic pulse (EMP) is highly dependent on the thickness of materials and the proposed testing method can obtain high repeatability, and thus it can be used as a standard test system to assess the shielding effectiveness of materials for pulsed electric field.

1. Introduction
Electromagnetic pulses (EMP), as a kind of wideband and high intensity transient signal, can strongly interfere electronics or cause damages, so shielding materials were normally applied to protect sensitive electronic system against electromagnetic environment. However, how to characterize the shielding effectiveness for EMP of materials is still needing further research and attracting more and more attention. In tradition, shielding effectiveness (SE) is defined based on frequency domain. But this definition is not able to provide the amplitude of field that the electronics is exposed to and so cannot assess the possible interference or damage to electronics. So the shielding effectiveness based on frequency domain is failed in dealing with protection ability of electronics against EMP. Currently, time-domain testing methods are mainly dependent on the improved technique based on traditional standard frequency domain methods. Koc and Camp from Hannover University investigated the shielding properties of texture-based composite and carried out time-domain testing of SE using open TEM waveguide[1-2]. Herlemann and Koch measured the SE of conductive texture bags using open TEM waveguide and transient field testing system and, according to the formula proposed by Klinkenbush [3], calculated the transient SE [4]. Afterward, they carried out SE tests of a metal enclosure (size 3 m × 3 m × 2.5 m, with 1.9 m × 1.9 m window) using frequency domain in anechoic chamber and using time domain in GTEM cell for different shielding materials [5].

EMP simulator is normally big and testing working volume is small, so it is difficult to be applied for SE test directly using windows method. For this reason, an improved method using an enclosure with window for time domain SE test for materials is proposed. The test installation is setup and the

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probe position is determined. Furthermore, the SE of several composite materials (mixed with nickel-plated carbon fiber) with different thickness are measured. Test results show that the developed time-domain SE system reached high repeatability and could be applied for the SE assessment of materials.

2. The definition of SE for EMP

EMP, especially for short time rise-time EMP, has abundant frequency components. Because of the dispersion effect for different frequency electromagnetic wave of materials, EMP field will change not only in amplitude, but also in EMP waveform after transmitting through shielding materials. In ideal cases, the definition of SE should consider both the change of amplitude and waveform (frequency components) of EMP. However, because the interferences or damage effects for electronics by EMP may vary with frequency, it is hardly to define the SE for EMP using frequency changes. At this moment, the authors of the present paper will simply use the peak radiation field of EMP to define the SE of materials. Therefore, SE of materials is defined as the ratio of peak values of field (E or H field) with and without shielding materials [6], which is indicated by $\text{SE}_{E(H)tp}$, although some other researchers advised the definition to use rise-time [7]:

\[
E_{E(H)tp} = 20 \log \frac{E(H)_{tp-unshielded}}{E(H)_{tp-shielded}}
\]

or

\[
\text{SE}_{P_{tp}} = 10 \log \frac{P_{tp-unshielded}}{P_{tp-shielded}}
\]

where $E(H)_{tp-unshielded}$ is the peak value of electric field or magnetic field without shielding materials, and $E(H)_{tp-shielded}$ is the peak value of the electric or magnetic field when shielding materials applied, $\text{SE}_{P_{tp}}$ is shielding effectiveness if using power of measured radiation field, $P_{tp-unshielded}$ and $P_{tp-shielded}$ is the peak power measured without and with shielding materials applied.

3. Development of testing system

To measure the shielding effectiveness of materials for EMP, a testing system is developed based on a window method with a shielding enclosure.

3.1 Testing setup

![Figure 1. Time-domain testing system for shielding effectiveness.](image1)

![Figure 2. Different test points in the enclosure.](image2)

The developed time-domain SE testing system mainly includes GTEM cell, square wave generator, E-probe for transient EMP electric field, optical receiver and oscilloscope etc, as shown in figure 1. The GTEM cell is feed by coaxial cable using square wave pulse generator and produces pulse radiated...
field. The applied transient electrical field probe (E-probe) as electrical-optical converting unit is composed of sensor, transmitting fiber and optical receiver. The optical fiber is applied in transmitting field signals to reduce the field interferences by field-cable coupling. To avoid possible resonance within the enclosure, a trapezium shaped enclosure is applied to provide unparallel side walls of the enclosure. For the parallel two walls of front panel and bottom of the enclosure, absorbers are mounted on the opposite bottom of the front panel to reduce the resonance effects between the two walls. (figure 2). During the installation of absorbers, conductive glue is applied to keep electrical connection well with the enclosure.

3.2 The selection of field sampling positions within enclosure

When a shielding box is applied to measure SE, a key problem is to find out the correct sampling position within the box which is capable for probe to detect the maximum peak value of field. For this purpose, nine locations within the box were tested. The nine locations are chosen according to the symmetry property of box at three lines (A, B, C) at the distance of 10 cm, 15 cm and 20 cm from window (figure 2). The central line vertical to the front panel (with window) is labeled “0” and the measured field is labeled A₀, B₀ and C₀. The other two lines (10 cm away from central line “0”) are labeled “1”, “2” and the measured field is labeled A₁, B₁, C₁ and A₂, B₂, C₂, respectively. Figure 3 gives the waveform of input waveform in the GTEM cell and figure 4 gives the measured pulsed field (described by voltage reading from oscilloscope) after shielding materials installed. Table 1 presents the measured values of field (voltage from oscilloscope, mv) at nine locations. By comparing with figure 3 and 4, it can be found that the square wave within GTEM cell is changed to decayed oscillating wave at points A₀, B₀ and C₀ inside enclosure because of coupling of electromagnetic wave with window and shielding materials. It is also clearly indicated that, alone the central line and at the nearest location from test window (A₀), the measured field is higher than all other locations. So, in the following measurements, the field will be measured at the point A₀, which is at central line and close to the window and material under-test at 10 cm distance from the window.

![Figure 3. Input field waveform in the GTEM cell.](image_url)

![Figure 4. Waveform measured within enclosure at different test locations.](image_url)

| Test points | A₀     | B₀     | C₀     | A₁     | B₁     | C₁     | A₂     | B₂     | C₂     |
|-------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| voltage mv  | 0.093  | 0.086  | 0.065  | 0.075  | 0.058  | 0.043  | 0.074  | 0.056  | 0.044  |

Table 1. Measured field value (indicated by voltage from oscilloscope) at different test points in box.
3.3 Verification examination

To examine the effectiveness of the developed system for measuring SE of materials for EMP, the experimental system is setup (figure 5) and three shielding materials of nickel-plated carbon fiber mixed composites with thickness 1 mm, 2 mm and 3 mm are chosen to do the SE tests. During the test, the pulse-width of square wave resource is adjustable, the output of resource has good repeatability and the rise-time of square wave is less than 1 ns. The testing box with window is placed in the rare position and in the central line of GTEM cell and the E-probe is place in the central coaxial ling (vertical to front panel with window) of the box and 10 cm away from the window and sample under test.

Figure 5. The testing system for transient pulsed field SE measurement.

Figure 6 presents the time domain SE test results for three samples with different thickness. The three shielding materials are made of short nickel-plated carbon fiber and rubber materials at a known volume ratio. From the results, it can be found that the SE increases with the increase of thickness of materials. But with the increase of applied input voltage of square wave, i.e. with the increase of electric field E, the SE of materials decreases. This is reasonable because the materials have nonlinear response to applied electric field. It can be also concluded from test results that, in the design of electromagnetic shielding materials, the thickness of materials should be greater as possible and the content of inclusion particles should be higher to obtain higher conductivity and shielding ability.

For a standard test method, the test repeatability is a key requirement. This is because, for a stand test method, the test results should be the same when different researchers do the same particular test. For this purpose, the repeatability test is carried out using a 3 mm thickness shielding rubber material under the condition of 4 kV input square wave.

Figure 6. Dependence of Shielding effectiveness on input voltage of square wave
Table 2 shows the test results. It can be concluded that the developed testing system achieves highly repeatability and it is suitable to be applied as a standard testing system for pulsed SE test of materials.

| test | 1 | 2 | 3 | 4 | 5 |
|------|---|---|---|---|---|
| SE/dB| 8.88 | 8.86 | 8.87 | 8.85 | 8.85 |

4. Conclusions
An improved time domain SE testing system is proposed for materials under the condition of pulsed electric field, high repeatability has achieved and can be applied as a kind of standard test system. The EMP shielding effectiveness has also been investigated for materials with different thickness. It is found that the SE of materials for pulsed field depends not only on the thickness of materials, but also on the peak value of input pulse voltage, because of dispersion effect of materials to different frequency wave, it can be predicted that the SE of materials also depends on the rise-time or waveform of input EMP. These problems will be further investigated in the future research.

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