EQUIVALENT CIRCUIT EXPRESSION OF DUAL TEM CELL APPARATUS FOR SHIELDING MATERIAL EVALUATION

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Abstract: To clarify the correspondence between Shielding Effectiveness (SE) of shielding materials and their physical property, we propose an equivalent circuit for a shielding effectiveness test apparatus using a dual TEM cell, and show its validity. By considering the structure of dual TEM cell that consists of a pair of cells coupled via an aperture in their common wall, we defined the capacitance C and mutual inductance M, those respectively express the electric coupling and magnetic coupling between two center conductors. By the measurement of unloaded S-parameter, we determined the values of C and M for a dual TEM cell in hand. Next, the shielding material was approximated by the apparent sheet resistivity R_s, and was used in the equivalent circuit of loaded aperture. As a result, the coupling level calculated from the equivalent circuit agreed well with the measured data in frequencies below 300 MHz.
Key words: Shielding material, Shielding effectiveness measurement, Dual TEM cell, Electric coupling, Magnetic coupling, Equivalent circuit.

1. Introduction

For the reduction of unwanted electromagnetic radiation from the equipments, as well as for the improvement of immunity, the electromagnetic shielding is an indispensable element composing the electronic equipments. The designers of electronics equipments must choose appropriate shielding material by which the equipments fulfill EMC standards, as well as other requirements such as mechanical property, weight, appearance, cost, environmental consideration, and so on. To choose an appropriate shielding material, the materials' shielding characteristics must be properly evaluated.

In most cases, shielding materials are evaluated in terms of shielding effectiveness (SE) [1],[2]. However, it is known that the SE is not an intrinsic parameter of shielding material but the SE value depends on the condition of how the material is measured [3]. To theoretically relate SE with the material parameter, or to physically understand the shielding mechanism, the equivalent circuit approach has been effectively used [4]–[6].

The dual TEM cell (DTC) is one of the shielding measurement apparatuses which is well investigated [2],[7]–[9]. Most of theoretical treatments of DTC, except for [10] by us, employ small aperture theory [11]. However, the actual DTC has considerably large aperture so as to have practical output signal level.

In this paper, an equivalent circuit of DTC is derived without employing the small aperture theory. The equivalent circuit accounts for the electric and magnetic coupling via the aperture, both in absence or presence of shielding material. Then, a DTC apparatus available on the market is chosen for the experiment. The unknown parameter of the equivalent circuit is experimentally determined. Calculation based on the equivalent circuit agreed well with experiment for frequencies below 300 MHz.

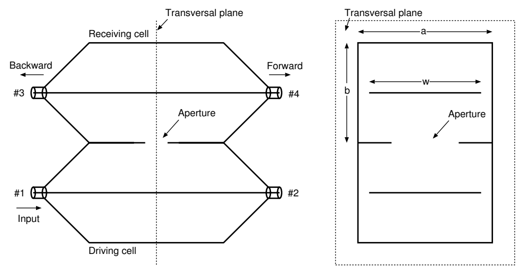

Figure 1: Longitudinal cross-section (left) and transverse cross-section (right) of a dual TEM cell.

2. Dual TEM Cell

2.1 Structure

A TEM cell is a rectangular-shaped coaxial line capable of TEM mode transmission, normally having characteristic impedance of 50 Ω. The DTC is a pair of TEM cells joint together and has a coupling aperture on their common wall, as depicted in Fig. 1. In this case, the signal is input from port #1 of the lower cell (driving cell), and two output signals are obtained from port #3 or port #4 of the upper cell (receiving cell). The aperture is loaded with the shielding material under test and the insertion loss is measured as SE.

Figure 2 shows the appearance of DTC (ADVANTEST, model TR17302)[12], whose dimensions in reference with Fig. 1 are: $a = 200$ mm, $b = 120$ mm, $w = 144$ mm. The aperture is a rectangular of 100 mm × 20 mm, with its longer sides perpendicular to the longitudinal direction. Each port has N-type female connectors.

2.2 Measurement

The DTC has four ports, and is fully characterized by a 4-by-4 S-matrix. However, only two transmission S-parameters, s_{31} and s_{41}, are sufficient to be measured. The remaining ports are terminated with 50 Ω loads. Measured s_{31} and s_{41} represents the backward and forward coupling via the aperture, respectively. By symmetry, $s_{31} = s_{42}$ and $s_{41} = s_{32}$ can be assumed.

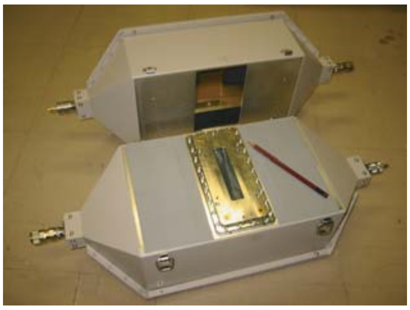

Figure 2: Appearance of DTC under investigation.

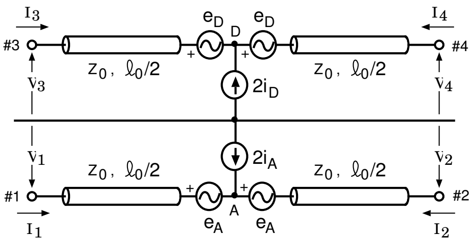

Figure 3: Equivalent circuit of DTC as coupled lines.

The SE, which is basically an insertion loss of material, can be defined in different way, depending on the coupling mode:

$$\mathrm{SE(dB)} = \begin{cases} 20\log_{10}|s_{41}^U|/|s_{41}^L| \\ 20\log_{10}|s_{31}^U|/|s_{31}^L| \\ 20\log_{10}|s_{41}^U+s_{31}^U|/|s_{41}^L+s_{31}^L| \\ 20\log_{10}|s_{41}^U-s_{31}^U|/|s_{41}^L-s_{31}^L| \end{cases} \quad (1)$$

where symbols superscribed with U or L are for unloaded or loaded apertures, respectively. Each line in the above formula, from top to bottom, corresponds to the forward coupling mode, backward coupling mode, electric coupling mode, and magnetic coupling mode, respectively.

3. Equivalent Circuit of DTC

The electromagnetic coupling via the unloaded (= empty) aperture is assumed to be a superposition of electric coupling and magnetic coupling. The DTC is then considered as a pair of transmission lines, having the coupling portion at each center. The coupling is expressed by voltage and current sources, as depicted in Fig. 3. Each delay line has characteristic impedance Z_0 (= 50Ω) and electrical length $\ell_0/2$, where ℓ_0 is the total electrical length of a TEM cell.

3.1 Electric Flux Interception by Shielding Material

If the aperture is closed by a shielding material, the most of electric flux will be intercepted by the material. In Fig. 4, R_s is the sheet resistivity of the shielding material, k the fraction of electric flux penetrating through the material, and α a constant which will be determined by the dimension of the aperture and the field distribution on the aperture. The point E represents the central

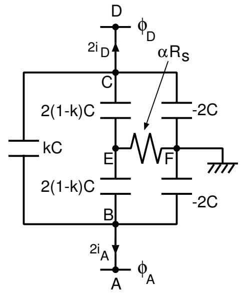

Figure 4: Equivalent circuit for capacitive coupling.

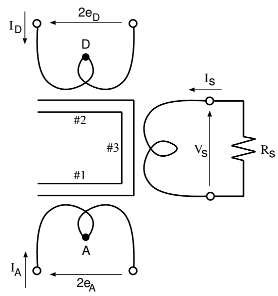

Figure 5: Equivalent circuit for inductive coupling.

part of the shielding material sheet in the aperture, and the point F corresponds to the aperture's edge where the shielding material is fixed and grounded. The following equation can be derived:

$$2i_A = 2i_D = j\omega C'(\phi_A+\phi_D),$$
$$C' = C\left\{1-\frac{1-k}{1+4j\omega(1-k)C\alpha R_s}\right\}. \quad (2)$$

3.2 Magnetic Shielding by Current Induced on Shielding Material

When the shielding material is inserted, the magnetic flux penetrating through the aperture will be intercepted by the eddy current induced on the shielding sheet. Figure 5 shows the updated transformer model which has the third coil (#3) expressing the current path on the shielding material. Let the terminal voltages be $2e_A$, $2e_D$, V_s and the terminal currents be I_A, I_D, and I_s. The self inductances of #1 and #2 are written as L and that of #3 is written as L_s. The mutual inductance between #1 and #2 is written as M and those between #3 and the rest are written as μ. Then, the matrix equation holds:

$$\begin{bmatrix} 2e_A \\ 2e_D \\ V_s \end{bmatrix} = j\omega \begin{bmatrix} L & M & \mu \\ M & L & \mu \\ \mu & \mu & L_s \end{bmatrix} \begin{bmatrix} I_A \\ I_D \\ I_s \end{bmatrix}. \quad (3)$$

Suppose that the aperture is completely closed by a perfect coductor sheet. It corresponds to letting the coil #3 shorted (i.e. $V_s = 0$). In this case, not only the transmission between #1 and #2 but also the transformer itself must vanish (i.e. $2e_A = 2e_D = 0$). It leads to

$$L = M, \quad \mu = \sqrt{L_s M}. \quad (4)$$

When the terminal #3 is loaded with a shielding material of sheet resistivity R_s, the equation

$$Vs = -R_s I_s \tag{5}$$

holds. By eliminating the third port's voltage and current, we obtain

$$2e_A = 2e_D = j\omega M'(I_A + I_D) \tag{6}$$

where M' is the effective mutual inductance given by

$$M' = M\left\{\frac{R_s}{R_s + j\omega L_s}\right\}. \tag{7}$$

The unloaded aperture's case corresponds to $R_s = \infty$. Inductances M and L_s are the specific parameters of DTC which will be determined experimentally.

In the above model, the shielding material is assumed to be non-magnetic material. If the aperture is loaded with a ferromagnetic material, the magnetic ducting effect will reduce the mutual inductance between #1 and #2. Accounting for this effect is the future task.

3.3 Scattering Matrix

After some calculation, the S-matrix of DTC can be reduced to the form

$$\mathrm{S} = \frac{e^{-j\omega\ell_0/c}}{(1-2e)(1+2m)} \cdot \begin{bmatrix} e{+}m & 1{-}e{+}m & e{+}m & e{-}m{+}4em \\ 1{-}e{+}m & e{+}m & e{-}m{+}4em & e{+}m \\ e{+}m & e{-}m{+}4em & e{+}m & 1{-}e{+}m \\ e{-}m{+}4em & e{+}m & 1{-}e{+}m & e{+}m \end{bmatrix}. \tag{8}$$

where c is the speed of light, m and e are

$$m = \frac{j\omega M'}{2Z_0}, \quad e = \frac{j\omega C' Z_0}{2}. \tag{9}$$

Therefore, the electric and magnetic coupling can be written as

$$s_{41} + s_{31} = \frac{2e}{1-2e} e^{-j\omega\ell_0/c}, \tag{10}$$

$$s_{41} - s_{31} = \frac{-2m}{1+2m} e^{-j\omega\ell_0/c}. \tag{11}$$

Hence, the electric coupling is dependent only on e and the magnetic coupling is dependent only on m, which is consistent with the physical meaning of the equivalent circuit.

Thus, the shielding material is characterized by two parameters, R_s and k. The S-parameter for unloaded aperture can be calculated by letting $R_s = \infty$.

4. Measurement and Calculation

4.1 Determination of Apparatus-Specific Parameters

S-parameters of DTC with unloaded aperture were measured. Then, $s_{41} + s_{31}$ and $s_{41} - s_{31}$ in decibels were obtained, and compared with calculation. Figure 6 shows those comparisons as functions of frequency, where C and M were chosen so that the calculation agreed well with the measured result, and $C = 0.0030$ pF, $M = 0.31$ nH were obtained. Except for frequencies higher than 300 MHz or for low frequencies where the measured signal was as low as noise level, the calculated values agreed very well with the measured values.

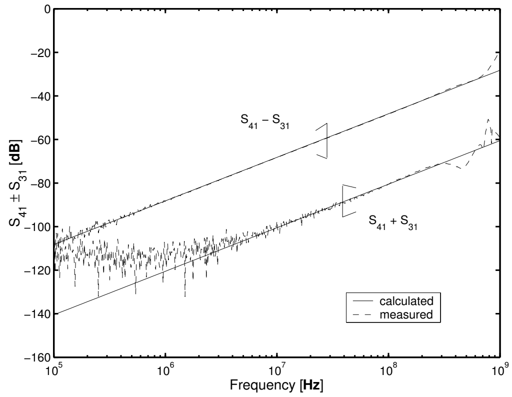

Figure 6: Measured electric and magnetic couplings of DTC with unloaded aperture compared with their calculation. $C = 0.0030$ pF, $M = 0.31$ nH were used in the calculation.

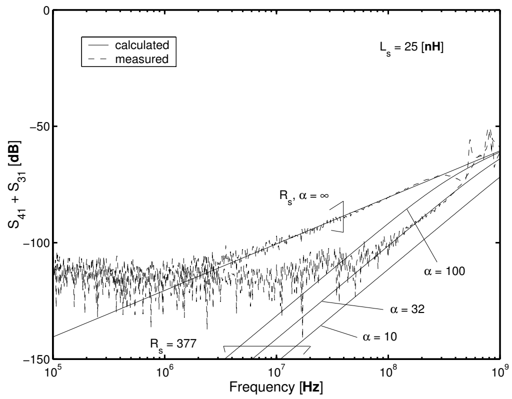

Figure 7: Electric coupling of DTC with unloaded aperture and aperture loaded with a resistive sheet having $R_s = 377\Omega$. For loaded aperture, calculation agrees with measurement when $\alpha = 32$.

Next, a resistive sheet with known sheet resistivity ($R_s = 377\Omega$) was used to determine the parameter α. Figure 7 shows measured $s_{41}+s_{31}$ data for both loaded and unloaded apertures. Since the coupling mode is electric, the received level is easily reduced even with a resistive sheet having relatively high sheet resistivity. For the loaded aperture measurement, the meaningful result is observed in frequencies from 100 MHz to 400 MHz. The comparison with calculated values, with several values of α, shows that a good agreement is obtained when $\alpha = 32$.

For the remaining apparatus-specific parameter L_s, its value was estimated to be $L_s = 25$ nH, which will be explained in the next subsection.

4.2 Determination of Shields' R_s

In the equivalent circuit, the sheet resistivity of shielding material is necessary. However, the sheet resistivity in a rigorous sense is defined only when

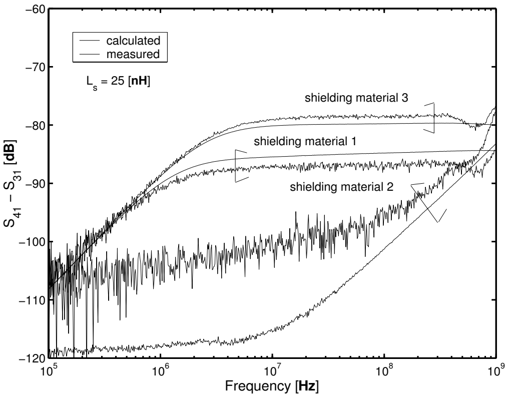

Figure 8: Magnetic coupling measured and calculated for three kinds of non-woven conductive clothes.

the shielding material is electrically thin which is not always fulfilled. Therefore, we determined the apparent value of sheet resistivity R_s, on the basis that the magnitude of transmission coefficient for normal incident wave is equal between shielding material and pure resistive sheet having R_s. as a result, the apparent sheet resistivity is calculated by

$$R_s = \frac{1}{2}\eta_0 \left(\frac{1}{|s_{21}|} - 1 \right)^{-1} \tag{12}$$

where η_0 is the intrinsic impedance of free space (= 376.7 Ω), s_{21} is the transmission s-parameter measured by coaxial holder. The R_s thus obtained is used in the following calculations.

4.3 Comparison by Using Shielding Materials

Three kinds of shielding materials, which were all non-woven conductive cloths made of metal fiber or metal-plated fiber, were measured. Figure 8 shows magnetic coupling $s_{41} - s_{31}$ as functions of frequencies. Here, the unknown parameter L_s has much influence on the calculated values, and L_s was estimated to be 25 nH, which gives a fair agreement between calculation and measurement. As a result, the measurement and calculation in frequencies below 300 MHz agreed within 5 dB, provided that the signal was higher enough than noise level.

In the forementioned calculations, the parameter k was always assumed to be 0. However, it is expected that the parameter k plays a role for the shielding material with many holes. Verifying this will be the future task.

5. Conclusion

In this paper, we proposed an equivalent circuit for a shielding effectiveness test apparatus using a dual TEM cell, and showed its validity.

The proposed equivalent circuit is based on the physical interpretation of the electric and magnetic coupling mechanism, and is considered to be useful to understand the correspondence between SE of shielding materials and their physical property.

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