PAPER

A Simple Method for Predicting Common-Mode Radiation from a Cable Attached to a Conducting Enclosure

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SUMMARY Common-mode (CM) radiation from a cable attached to a conducting enclosure has a typical dipole-type antenna structure, in which an equivalent noise voltage source located at the connector excites the attached cable against the enclosure to produce radiated emissions. Based on this mechanism, a simple method for predicting the CM radiation from the cable/enclosure structure was proposed. The method combines an equivalent dipole approximation with sinusoidal current distribution and CM current measurement at a specified location on the cable. Its validity was examined in comparison with the far-field measurement and finite-difference time-domain (FDTD) modeling. The predicted resonance frequencies and CM radiation levels were validated with engineering accuracy, i.e., within 30 MHz and 6 dB, respectively, from the measured and FDTD-modeled results in the frequencies above 150 MHz.

key words: *common-mode radiation, cable, conducting enclosure, asymmetrical dipole*

1. Introduction

Electronic equipment is commonly installed in a conducting enclosure and connected to the outside via input/output cables. The electronic equipment inside the enclosure may produce common-mode (CM) currents on the cables which causes the majority of radiated emissions [1]. The CM radiation from a cable attached to a conducting enclosure is therefore a primary concern in meeting electromagnetic interference (EMI) specifications. The configuration is a typical structure of a dipole-type antenna with an equivalent noise source located at the connector which excites two distinct conductors to produce radiated emissions. One part of the EMI antenna is the cable, and the other part of it is the conducting enclosure. With adequate modeling for the noise voltage source at the connector, it would be possible to predict the radiated emission levels and resonance frequencies. A feasible EMI prediction may save the time and reduce the cost for radiated emission measurement in early stage of test.

The problem is that it is difficult to quantify the equivalent noise voltage source at the connector in an actual system including printed circuit boards (PCBs). This is because the mechanisms how the noise sources inside the conducting enclosure produce CM currents on the cable are not well understood.

With the rapid progress of computers, it is becoming possible for numerical techniques to predict the radiated emissions for configurations such as a conducting enclosure with attached cables. Hockanson et al. have demonstrated the utility of the finite-difference time-domain (FDTD) method in modeling the CM radiation from cables [2], [3]. Tarumoto et al. attempted to predict the radiated emission using the transmission-line method (TLM) by replacement of the cable/enclosure structure with an equivalent dipole antenna [4]. These studies, however, did not describe how to determine the equivalent noise voltage source. In order to extract the equivalent noise voltage source at the connectors, Antonini et al. proposed a partial element equivalent circuit (PEEC) model for analyzing surface currents on the enclosure walls [5]. By the PEEC analysis the input impedance and the corresponding open voltage of the equivalent noise voltage source can be determined, which enables one to predict EMI from the cables. However, typical electronic equipment with attached cables are too complex to model with the present computer performance so that these numerical techniques are still in the distant future to model an actual electronic equipment for EMI prediction.

Another approach is to derive the CM radiation from calculated or measured CM currents. The radiated electric fields are then predicted by far field approximation from the CM currents. Caniggia et al. has proposed a method for calculating the currents along shielded cables based on the transmission line theory [6]. A knowledge about the noise voltage exciting the cables is, however, indispensable. Sasabe et al. adopted direct measurement of the CM currents by using a current probe [7]. Application of the measurement approach to a parallel trace line structure on a PCB has demonstrated its feasibility, while the requirement for a number of CM current measurement data is still a burden.

In this paper, a simple method for predicting the CM radiation from a cable attached to a conducting enclosure is proposed. The method is based on the asymmetrical dipole approximation as attempted in [4]. It combines the dipole approximation and CM current measurement at a specified location along the attached cable. Such a combination results in a very rapid and

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simple CM radiation prediction with engineering accuracy. Comparisons among the predicted, measured and FDTD modeling results have shown its validity and usefulness.

2. Principle

This section begins with simplifying the structure of a cable attached to a conducting enclosure to an asymmetrical dipole antenna, and describes a simple CM radiation prediction method.

2.1 Asymmetrical Dipole Approximation and CM Current Distribution

Figure 1 shows a typical model of a conducting enclosure with an attached cable. The cable assumed to be a coaxial cable, a bundle of parallel lines and so on, and its ground-line or shield is connected to the enclosure surface. The current flowing along each conductor of the cable could be decomposed into a differential-mode (DM) current and a CM current. The radiated field components due to the DM currents would be canceled because they are 180° out of phase each other, while the radiated field components due to the CM currents would be superposed because they are in phase each other. Only the CM current is therefore necessary for a far field prediction. The mechanism of the CM radiation for this structure can be modeled with an equivalent noise voltage source at the connector [3]–[5], which excites the attached cable against the conducting enclosure. This assumption is based on the following mechanism. CM currents should occur when return currents lose their pairing with their original signal path due to splits or breaks. At the connector location with the cable's ground-line directly connected to the enclosure, the return current splits to a new portion which flows on the enclosure surface. This split results in an imbalance between the currents on the signal line and the ground line of the cable, and thus produces a CM current. In such a form the cable and the enclosure act as an EMI antenna to radiate emissions from the CM currents. It is therefore a reasonable approximation to predict the CM radiation with an equivalent dipole antenna with its noise source at the connector location. The dipole antenna is asymmetrically fed at the connector location, as shown in Fig. 2, where l_c is the length of the attached cable and l_e is an equivalent length resulting in a radiation level similar to that from the conducting enclosure.

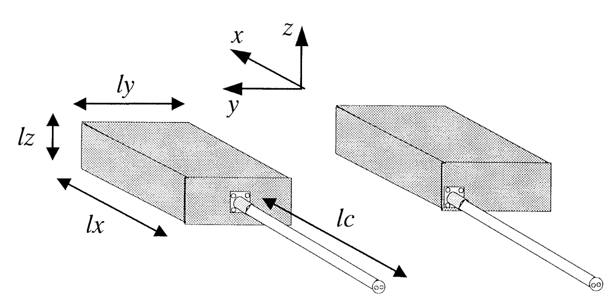

Fig. 1 Models of a cable attached to a conducting enclosure.

According to Schelkunoff and Friis [8], the CM current on the asymmetrical antenna can be approximated with sinusoidal functions. Referring to Fig. 2, by starting with sinusoidal functions which vanish at $x = 0$ and $x = l_c + l_e$, we have

$$\begin{aligned} I_{CM}(f,x) &= I_1(f)\sin(kx) && x \le l_c \\ &= I_2(f)\sin[k(l_c + l_e - x)] && x \ge l_c \end{aligned} \quad (1)$$

where $I_{CM}(f,x)$ is the CM current and $k = 2\pi/\lambda = 2\pi f/c$ (λ: wavelength; f: frequency; c: speed of light). From the continuity of current at the feeding point l_c, we obtain

$$I_1(f)\sin(kl_c) = I_2(f)\sin(kl_e). \quad (2)$$

To satisfy this equation, we have

$$\begin{aligned} I_1(f) &= I_m(f)\sin(kl_e) \\ I_2(f) &= I_m(f)\sin(kl_c) \end{aligned} \quad (3)$$

where $I_m(f)$ is a current amplitude at frequency f. The approximate expression for the CM current distribution on the asymmetrical dipole is thus

$$\begin{aligned} I_{CM}(f,x) &= I_m(f)\sin(kl_e)\sin(kx) && x \le l_c \\ &= I_m(f)\sin(kl_c)\sin[k(l_c + l_e - x)] && x \ge l_c. \end{aligned} \quad (4)$$

2.2 Radiated Fields

The radiated fields from the equivalent asymmetrical dipole can be calculated as superposition of the fields due to many small Hertzian dipoles of length dx having a current which is constant and equal to the value of the current $I_{CM}(f,x)$, as shown in Fig. 3. The measurement point P in EMI specifications is in the far field region for these current elements because the specified measurement distance d is 3 m or 10 m. The electric far-field from one of the Hertzian dipoles is given as [9]

$$dE_{CM}(f,\theta) = \frac{j\omega\mu_0}{4\pi}\frac{\sin\theta'}{d'}e^{-jkd'}I_{CM}(f,x)dx \quad (5)$$

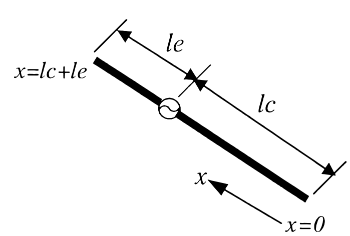

Fig. 2 Asymmetrical dipole antenna.

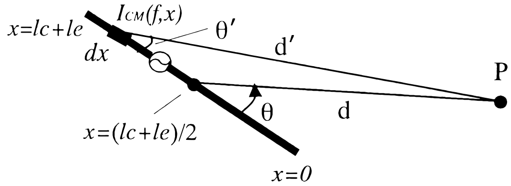

Fig. 3 Calculation of the radiated fields of the equivalent dipole.

where $\omega = 2\pi f$ and μ_0 is the permeability of free space. Substituting $\theta \cong \theta'$ into the numerator, $d \cong d'$ into the denominator, $d' \cong d + (x - \frac{l_c+l_e}{2})\cos\theta$ into the phase term of Eq. (5), and integrating it from 0 to $l_c + l_e$ give

$$E_{CM}(f,\theta) = \frac{\mu_0 f}{2d}\sin\theta \times \int_0^{l_c+l_e} I_{CM}(f,x) e^{jk(\frac{l_c+l_e}{2}-x)\cos\theta} dx. \quad (6)$$

It should be noted that this formula always holds so long as either l_c or l_e is not equal to zero.

2.3 Prediction Method

Based on the above approximation and formularization, the CM radiation from a cable attached to a conducting enclosure can be predicted as follows:

- Determine the length l_e of the equivalent asymmetrical dipole[†];
- Measure the CM current $I_{CM}(f, x_0)$ at a specified location $x = x_0$ on the cable by using a CM current probe;
- Estimate $I_m(f)$ in Eq. (4) from the measured $I_{CM}(f, x_0)$ at $x = x_0$, and then determine the CM current distribution along the asymmetrical dipole;
- Calculate the maximum radiated electric fields from Eq. (6) by using the estimated CM current distribution;

3. Experimental Configuration, Measurement and FDTD Modeling

The proposed prediction method was examined in comparison with predicted, measured and FDTD modeling results for a rectangular conducting enclosure with an attached two-parallel-wire cable.

3.1 Experimental Configuration

The enclosure under investigation was constructed of aluminum plates with dimensions of l_x=30 cm, l_y=18 cm and l_z=8 cm. The cable, with a length l_c=55.5 cm, was connected to a battery powered unbalanced 28-mV (across 50 Ω) sinusoidal sweeping signal generator inside the enclosure via a BNC connector. The internal and external conductors of the BNC connector were soldered directly to the two wires of the cable. Such a connection corresponded with our assumption in Sect. 2.1 for the mechanism of CM current occurrence. The connector location was either in the center or in the corner of the right-side wall. The two wires in the cable had a radius of 0.45 mm and a separation of 1.4 mm, whose far ends were terminated with a chip resistor of 51 Ω not matching to the characteristic impedance of the cable. The choice of the enclosure dimensions and cable lengths was made just from the standpoint of demonstrating the usefulness of our prediction procedure. The resistance value does not also affect the verification of the prediction procedure although different resistance values may result in different CM current magnitudes.

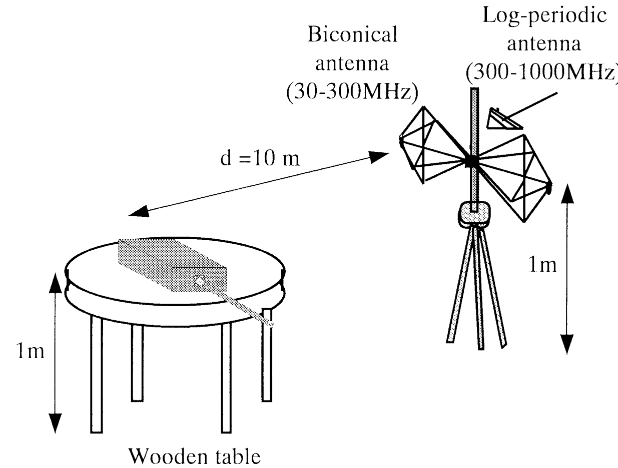

Fig. 4 Setup for the radiated emission measurement.

3.2 Measurement

The radiated emission measurement was made in a 10-m anechoic chamber, as shown in Fig. 4, with a biconical antenna in the frequency range from 30 MHz to 300 MHz and a log-periodic antenna from 300 MHz to 1 GHz. The distance between the test enclosure and the antenna was set just 10 m, and measurement was made with a spectrum analyzer as root mean square (rms) peak voltages in the frequency range from 30 MHz to 1 GHz. Since the field strength of horizontal polarization was higher than the vertical polarization for this arrangement, decision was made to measure only the horizontal polarization.

3.3 FDTD Modeling

The FDTD method was used to model the configuration also for examining the validity of the prediction method. A cell size of 4 mm × 1.4 mm × 4 mm was employed in the FDTD modeling. A fine discretization along the y direction was used in order to model

[†]This will be discussed in Sect. 4.

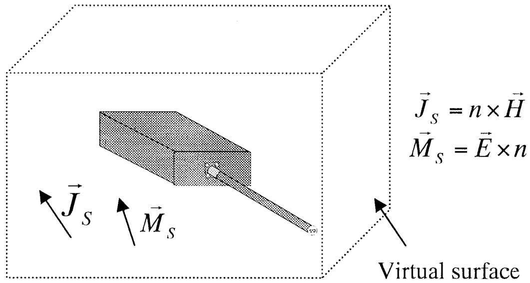

Fig. 5 Application of equivalence principle for far-field calculation in FDTD modeling.

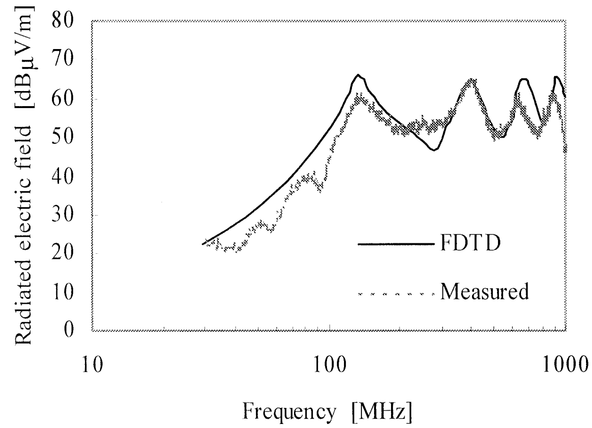

Fig. 6 Comparison of measured and FDTD-modeled radiated emissions. Only the results for the corner attachment are shown. The center attachment has a better agreement.

the separation of the two parallel wires in the cable. Since the two parallel wires had a radius of 0.45 mm still smaller than one cell size even in the y direction, a sub-cell algorithm was therefore used to model the two wires in which the wires' radius was taken into consideration. The aluminum plates and the parallel wires were modeled with perfectly electrical conductors by setting the corresponding electric field components to zero. δ-gap feeding was employed in a single cell between the conducting enclosure and one of the wires. The feeding source was a Gaussian pulse voltage source with 50-Ω resistance incorporated into the single cell. The parameters of the Gaussian pulse were chosen to have a smooth spectrum, i.e., varying within 3 dB below 1 GHz. The total calculation space consisted of $275 \times 190 \times 80$ cells, and twelve perfectly matched layers (PML) were employed to absorb the outgoing scattered waves at the boundaries that had a spacing of at least 30 cells from the cable/enclosure configuration. The reflection coefficient with incidence perpendicular to the PML boundaries was set to -120 dB.

The radiated electric fields were obtained by applying the equivalence principle to the FDTD modeling results. Referring to Fig. 5, the FDTD method was used to calculate the electric field $\vec{E}$ and magnetic field $\vec{H}$ on a virtual surface completely surrounding the FDTD model. From the calculated values of the electric and magnetic fields on this surface, equivalent magnetic and electric surface current distributions ($\vec{M}$ and $\vec{J}$, respectively) were determined as $\vec{M} = \vec{E} \times n$ and $\vec{J} = n \times \vec{H}$ where n is the normal vector on the surface. The far fields were obtained by using a near-field to far-field transformation [10] from the above surface current distributions. The Fast Fourier Transformation (FFT) of the time-domain far field data gives the radiated emission as a function of frequency.

Besides, the CM currents along the cable was calculated by integrating the magnetic fields along a small curve around the cable according to the Ampere's law. The results in the frequency domain were also obtained from the FFT.

3.4 Measured and FDTD Modeling Results of Radiated Emission

Figure 6 shows measured and FDTD-calculated frequency spectra of the maximum radiated electric fields in the horizontal plane. It was found that good agreement was achieved between the measurement and the FDTD modeling in both the center attachment and the corner attachment cases. The FDTD modeling results gave radiated emission levels within 4 dB and resonance frequencies within 30 MHz in comparison with the measured ones in the frequency range of 100–1000 MHz. These results demonstrated the validity of the FDTD modeling. Moreover, the resonance occurred near the frequencies where the length l_c of the attached cable (half of the equivalent dipole) was corresponding to $\lambda/4$, $3\lambda/4$, $5\lambda/4$ or $7\lambda/4$, which exhibited a typical $\lambda/2$ dipole radiation mechanism and also suggested that the other half of the equivalent dipole due to the enclosure could be approximated to have the same length as l_c in this case.

4. CM Radiation Prediction

CM radiation prediction was made in this section by using the proposed method.

4.1 Prediction Results

The first step was to determine the length l_e of the equivalent asymmetrical dipole shown in Fig. 2. Tarumoto et al. attempted in [4] to determine l_e from a physical average of the enclosure configuration, whereas this approach failed to predict the resonance frequencies because they are very sensitive to the dipole length. Except for very small enclosures, however, in most cases of actual systems the enclosure wall attached with a cable can be assumed to have a size which is large enough

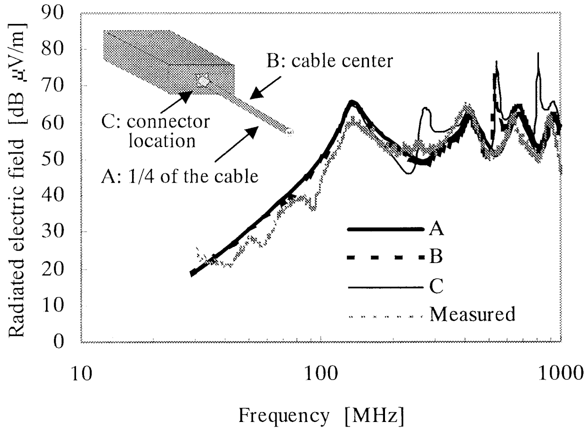

Fig. 7 Prediction results of radiated emission from CM currents estimated from the data at three different locations on the cable.

to model the enclosure with $l_e = l_c$ for the equivalent dipole (twice as long as the cable). This was adopted here as a first approximation.

In the second step, the CM current in some specified location on the cable should be measured as a function of frequency. Three locations on the cable were considered as shown in Fig. 7, which were referred as location A, B and C, respectively, for demonstrating how to choose an adequate measurement location. In lieu of the measurement of CM currents in the specified locations, the FDTD modeled CM currents were adopted for convenience because the FDTD modeling has proven to be a good representation of measurement (Of cause in actual application of the prediction method, the CM currents must be obtained from measurement). From the CM current in any one location, $I_m(f)$ in Eq. (4) can be determined and then $E_{CM}(f, \theta)$ can be calculated from Eq. (6). Figure 7 shows the predicted maximum radiated electric fields in the horizontal plane from the CM currents in locations A, B and C. Some obvious prediction errors were observed at 540 MHz in the case of location B, and 270 MHz, 540 MHz and 810 MHz in the case of location C. These frequencies are corresponding to $l_c = n\lambda$ (n: integer) for location B ($x = l_c/2$), and $l_c = n\lambda/2$ for location C ($x = l_c$). Referring to Eq. (4), the approximate CM current $I_{CM}(f, x)$ should be zero at the above frequencies in the two locations. Therefore it is impossible to determine the current magnitude from Eq. (4) at these singular frequencies. For applying the proposed prediction procedure an adequate measurement location on the cable must be chosen to avoid these singular frequencies. This can be made simply by a trial calculation before measurement. For example, one substitutes a measurement location $x = x_0$ into Eq. (4) and checks whether there is a frequency at which $I_{CM}(f, x_0)$ $= 0$ in the concerned frequency band. If there is not such a frequency, that measurement location is acceptable. In the example demonstrated above, the location A ($x = l_c/4$) was able to give a reasonable prediction result because there is not a singular frequency in the frequency range below 1000 MHz.

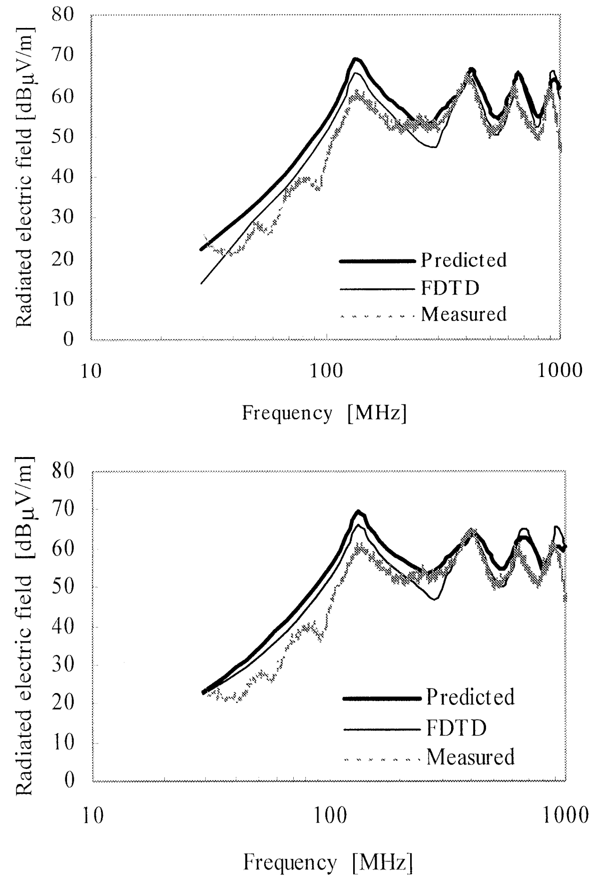

Fig. 8 Predicted, FDTD-modeled and measured radiated emissions. The enclosure dimensions are 30 × 18 × 8 cm. Above: center attachment; below: corner attachment.

Table 1 Resonance frequencies and emission levels.

	Center attachment		Corner attachment	
	Resonance [MHz]	Level [dBμV/m]	Resonance [MHz]	Level [dBμV/m]
Predicted	133	69	133	70
	413	67	413	64
	663	66	678	63
	943	64	899	60
FDTD	133	66	133	66
	413	65	398	65
	663	66	663	65
	929	66	928	66
Measured	145	60	140	60
	426	63	407	65
	647	61	635	59
	912	62	890	61

Figure 8 shows the predicted, FDTD-modeled and measured frequency spectra of the maximum radiated electric fields in the horizontal plane, and Table 1 summarizes the resonance frequencies and emission levels at these frequencies. The predictions were made from the CM currents at the location A. As can be seen from Fig. 8 and Table 1, the predicted emission levels had a fair agreement with the FDTD modeling and measurement. In comparison with the FDTD-modeled results, the resonance frequencies and emission levels were predicted with accuracy within 10 MHz and 6 dB, respectively. In comparison with the measured results, they were predicted with accuracy within 30 MHz and 6 dB, respectively, in the frequencies above 150 MHz. In the frequency range below 150 MHz, however, the emission level was overestimated up to 10 dB between the prediction and the measurement. This phenomenon suggests that l_e should be shorter than l_c at lower frequencies. In such situations the CM radiation from the conducting enclosure may be insignificant. The larger overestimation at the first resonance frequency was also due to the same reason, i.e., the l_e should be shorter than l_c. In addition, compared to the measurement, good agreement with the FDTD modeling in Table 1 was due to the fact that the CM current used in the prediction was derived not from the direct CM current measurement but from the FDTD modeling as previously mentioned in Sect. 4.1.

4.2 Box Size Effects

Figure 9 shows the predicted results similar to Fig. 8, while the front wall dimension of the conducting enclosure was shortened from 30 cm to 10 cm. In comparison with Fig. 8, no obvious shifts on the resonance frequencies were observed. The predicted results were in the same accuracy as the previous configurations, except that the predicted emission levels gave a somewhat larger overestimation compared to the FDTD result. The investigated enclosures had a dimension in the order of 18 cm at maximum for the wall with the attached cable, which was approximately $\lambda/10$ at a frequency of 150 MHz. The approximation of $l_e = l_c$ for the configuration in such an order has given a reasonable prediction for the radiated emissions in the frequencies above 150 MHz. The finding also suggested that the enclosure dimension in the x direction is not dominant to the resonance frequencies as long as the wall with the attached cable is large enough. This phenomenon can be easily understood by considering a monopole antenna case in which a sufficiently large ground plane, even if it is infinitely thin, can still act as an image plane to realize an equivalent dipole antenna structure. The thickness of the ground plane is insignificant in this case. Larger prediction errors observed below 150 MHz were because the wall dimension was not large enough with respect to the wavelength so that the approximation of l_e=l_c had a poor accuracy. Actually, even if reducing the maximum wall dimension to its half, i.e., 9 cm or about $\lambda/20$ at 150 MHz, the predicted result was still acceptable to some extent as shown in Fig. 10. However, the resonance at 340 MHz was not predicted well by using the equivalent dipole model. These results indicates that a dimension larger than $\lambda/10$ for the wall with an attached cable is able to give a reasonable accuracy when the maximum CM radiation at resonance frequencies is taken notice.

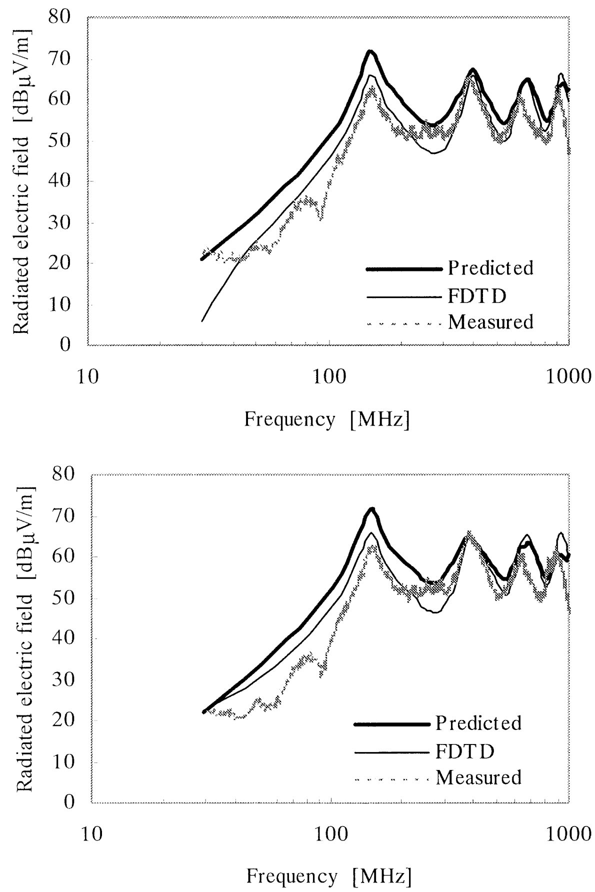

Fig. 9 Predicted, FDTD-modeled and measured radiated emissions. The enclosure dimensions are $10 \times 18 \times 8$ cm. Above: center attachment; below: corner attachment.

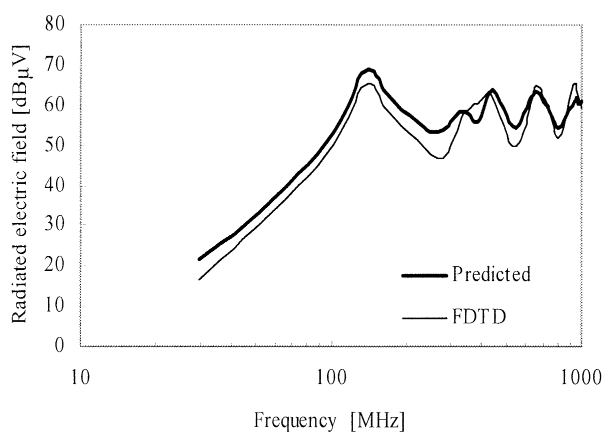

Fig. 10 Predicted and FDTD-modeled radiated emissions. The enclosure dimensions are $10 \times 9 \times 4$ cm. Corner attachment.

5. Conclusions

CM radiation from a cable attached to a conducting enclosure is a primary concern in meeting EMI specifications. The mechanism of the CM radiation can be modeled with a noise voltage source at the connector, which excites the attached cable against the conducting enclosure. To predicate the CM radiation from the cable/enclosure configuration, a simple method has been presented, which combines an equivalent dipole approximation and CM current measurement at a specified location on the cable. Approximating the conducting enclosure to a dipole element with the same length as the cable has proven to be a reasonable representation for the frequencies where the enclosure wall with the attached cable has a size larger than $\lambda/10$. Current distribution on the equivalent dipole has been formularized and its estimation requires only one CM current measurement at some specified location on the cable. The prediction method has been examined in comparison with the FDTD modeling and far-field measurement. The resonance frequencies and emission levels have been predicted within 30 MHz and 6 dB, respectively, from the measured and FDTD-modeled results in the frequencies meeting the above condition.

Although the prediction method does not require any complicated calculation and only a one-point CM current measurement, an acceptable engineering accuracy has been obtained. Its application in early stage of test is promising. The future subject is to improve the prediction accuracy in modeling the conducting enclosure as a asymmetrical dipole antenna element, i.e., the accurate determination of l_e, and extend the prediction method to the case where both sides of the cable are connected to electrical equipment.

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