# Estimation of Common Mode Current on Coaxial Cable with Twisted Wire Pair

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***Abstract*— In this study, common mode current, a dominant factor of unintentional radiation, on coaxial cable with twisted wire pair (TWP) is estimated. This cable model is a simplified model of a popular combination of balanced and unbalanced circuit, such as printed circuit board (PCB) with TWP. For the convenience of calculation and measurement the coaxial cable is employed as an unbalanced circuit instead of PCB. The estimation method is based on the imbalance theory which focuses on the difference of balance factors between connected circuits, and some effects of TWP are considered. According to the theory the common mode current is proportional to a differential mode voltage at the connecting point. Thus the differential mode voltage is calculated by cable transmission theory with accounting on TWP electrical characteristic and radiation impedance of cables. The estimated result is compared with measurement, and good agreement is obtained.**

***Keywords—electromagnetic radiation; coaxial cable; twisted wire pair; imbalance difference; common mode current***

## I. INTRODUCTION

The radiation from the electronic device with cable is an important issue in the problem of electromagnetic compatibility (EMC). Since the length of many cables is close to the wave length of the frequency range in which unintentional radiation from the electronic system is regulated, it acts important role for the radiation. Most electronic devices have many cables for the purpose of power supply, interface with peripheral devices and communication with other devices. Not only high speed signal transmission cable but also cable for low frequency such as DC power supply cable would help radiation, because common mode current flows similarly on those cables and the current generates significant radiation through the cable which works as a kind of antenna.

One of the typical simplified models for this problem is a simple printed circuit board (PCB) with attached cable. Although the radiation from such a model could be calculated using 3D electromagnetic calculation tool, radiation estimation based on a simple mechanism is still useful for instant estimation and for giving prospect of the noise control. There are many conventional works to estimate of the radiation from this model. One of the well-known mechanisms is based on current-driven and voltage-driven model [1-3]. According to the noise source on the PCB common mode current is induced on the attached cable by current and voltage-driven coupling. These effects are experimentally studied and show reasonable results.

Recently imbalance difference method is proposed [4] to estimate the radiation from the model consists of different type of transmission lines such as PCB with attached cable like mentioned above. This method uses difference of balance factors of each transmission lines at the point of attachment, and estimates common mode voltage at the point. This method has successfully applied to many kinds of models and gives good estimation [5-8].

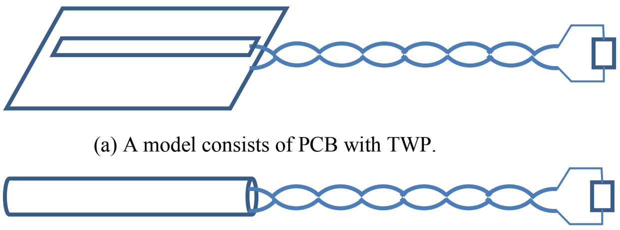
In this paper, a model of the coaxial cable with attached twisted wired pair (TWP) is studied as a typical connection model of unbalanced and balanced circuit. Instead of PCB, the coaxial cable is employed which works as perfectly unbalanced transmission line. It helps us to avoid analytical complication of calculation for estimation. On the other hand, the TWP is used as balanced transmission line. The imbalance difference method is applied to this model and the common mode current is calculated for estimation of radiation. The extremely wound and short pitched TWP is also employed to enhance the effect the role of TWP. The results are compared with both numerical calculation and measurement.

## II. COMMON MODE CURRENT ON COAXIAL CABLE WITH TWP

### A. Unbalanced and balanced circuit model

In this paper the model which consists of unbalanced and balanced circuits, such as micro strip line on a PCB with attached TWP as shown in Fig.1 (a), is assumed. TWP is a traditional balanced wire with expecting noise reduction. This configuration can be seen in many electronic products, and is used not only for low frequency signal transmission or power feeding but also even for high speed signal transmission.

In order to make the model be simple and convenient for calculation and measurement, a coaxial cable is employed as unbalanced circuit instead of the PCB, as shown in Fig.1 (b). And since it is difficult to feed stable voltage to the circuit on the table during the measurement, we put this model in a standing position on the ground plane as shown Fig.2. The voltage is fed under the ground from a signal generator through a coaxial cable. This realizes stable and simple voltage feeding to the model. Then it is expected that the common mode current on the model at lowest resonant frequency shall be lambda/4 wave distribution as illustrated in Fig.2.



(a) A model consists of PCB with TWP.

(b) A model consists of coaxial cable with TWP.

Fig.2 A model consists of unbalanced and balanced circuit.

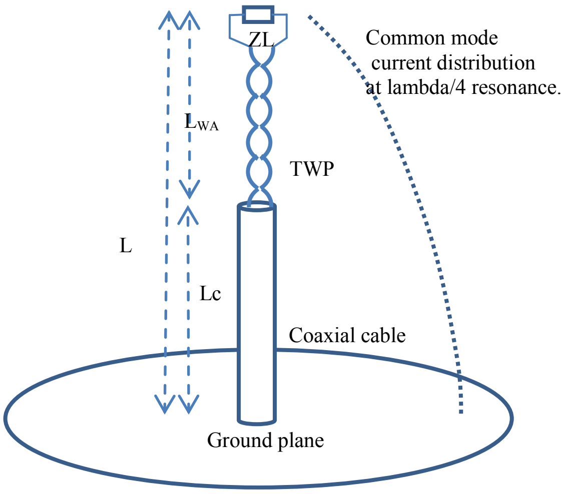



Fig.2 The model put in standing on the ground.

## B. *Imbalance difference theory*

The imbalance difference theory is used to estimate the common mode radiation from connected two transmission lines [4-8]. According to the theory, the equivalent common mode source voltage between the two lines is proportional to the difference of imbalance factors of the two lines and to the differential mode voltage at the connection point. The imbalance factor of each line is defined as a ratio of capacitances or inductances of signal and ground line.

For example, a coaxial cable and a parallel line pair have imbalance factor 1.0 and 0.5 respectively. Then the difference of imbalance factors is 1.0 – 0.5 = 0.5. The common mode source voltage $V_{cm}$ is calculated by

$$Vcm = 0.5 \times Vdm \tag{1}$$

,where $V_{dm}$ is the differential mode voltage of connection point of two lines. The common mode current and radiation could be estimated with source voltage $V_{cm}$.

## C. *Calculation process*

In order to estimate the common mode current on the model in Fig.2, the differential mode voltage $V_{dm}$ at the connecting point of the coaxial cable and the TWP should be obtained. The $V_{dm}$ could be calculated by simple circuit theory as follows.

The model is shown again in Fig.3 (a). At the end point of the coaxial cable, input impedance of the TWP $Z_{inW}$ and antenna input impedance $Z_{inA}$ are loaded as shown Fig.3 (b). The input impedance $Z_{inW}$ of the TWP is calculated by

$$Z_{inW} = Z_{0W} \frac{Z_L \cosh \gamma_W L_{WN} + Z_{0W} \sinh \gamma_W L_{WN}}{Z_L \sinh \gamma_W L_{WN} + Z_{0W} \cosh \gamma_W L_{WN}} \tag{2}$$

,where $Z_L$, $Z_{0W}$, $\gamma_W$ and $L_{WN}$ are terminal impedance, characteristic impedance, propagation constant and net wire length of TWP respectively. About $Z_{0W}$, $\gamma_W$ and $L_{WN}$ are discussed later. According to the imbalance difference theory the $V_{dm}$ drives cable as an antenna. Thus this antenna impedance $Z_{inA}$ should be loaded parallel to the $Z_{inW}$ at the connection point of the lines. This effect could be confirmed by observing $V_{dm}$. The $Z_{inA}$ is also discussed later.

The input impedance of coaxial cable $Z_{inC}$ is calculated by

$$Z_{inC} = Z_{0C} \frac{Z_{inWA} \cosh \gamma_C L_C + Z_{0C} \sinh \gamma_C L_C}{Z_{inWA} \sinh \gamma_C L_C + Z_{0C} \cosh \gamma_C L_C} \tag{3}$$

,where $Z_{0C}$, $\gamma_C$ and $L_C$ are characteristic impedance, propagation constant and wire length of coaxial cable respectively. And $Z_{inWA}$ is parallel impedance of $Z_{inW}$ and $Z_{inA}$.

The signal voltage is fed to the coaxial cable under the ground plane with 50 Ohm signal generator through 50 Ohm feeding cable, and 50 Ohm oscilloscope is also attached at this point through 50 Ohm cable for monitoring voltage waveform. The equivalent circuit is shown in Fig.4. The voltage $V_0$ at feeding point is calculated by

$$V_0 = \frac{Z_{inC} \| 50}{50 + Z_{inC} \| 50} \times Vg \tag{4}$$

,where $V_g$ is an open circuit voltage of the signal generator and || is the operation of parallel impedance composition.

The differential mode voltage $V_{dm}$ at the end of the coaxial cable, as shown in Fig.3 (c), is calculated by

$$Vdm = \frac{Z_{inWA}}{Z_{inWA} \cosh \gamma_C L_C + Z_{0C} \sinh \gamma_C L_C} \times V_0 . \tag{5}$$

Since the common mode voltage $V_{cm}$ at connection point is obtained from equation (1), the common mode current $I'_{cm}$ could be calculated using the antenna impedance $Z_{inA}$ by

$$I'cm = \frac{Vcm}{Z_{inA}} = \frac{Vdm}{2 \times Z_{inA}} \tag{6}$$

The maximum common mode current $I_{cm}$ is observed at the bottom of the coaxial cable at $\lambda/4$ resonant frequency as shown Fig.3 (d), and could be extrapolated using $I'_{cm}$ by

$$Icm = \frac{I'cm}{\cos(\pi / 2 \times Lc / L)} \tag{7}$$

,where $L$ is total length of the model.

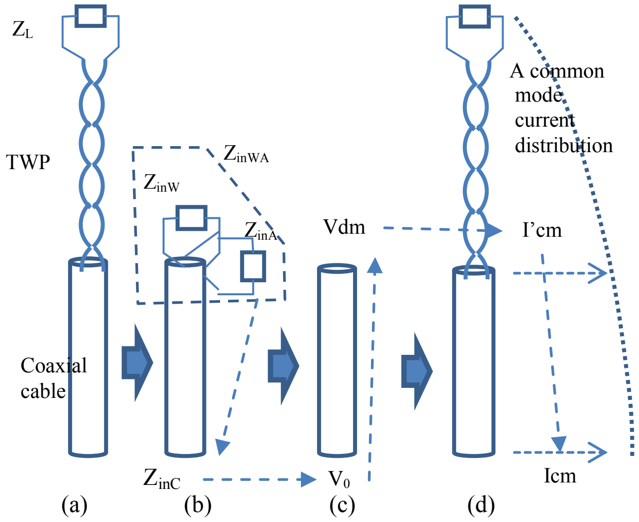



Fig.3 A process of common mode current calculation.

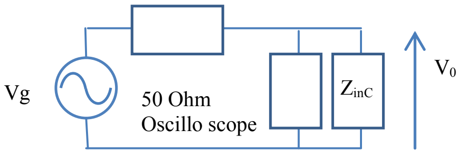



Fig.4 Equivalent circuit at feeding point.

## III. Electrical Characteristics of TWP

As mentioned above the some characteristic of TWP should be investigated before common mode current calculation [11].

### A. Transmission characteristics

TWP is geometrically represented as a bifilar helix line structure. Basically it is expected that these characteristics in differential mode follow the characteristics of parallel wire pair. As the twist pitch is smaller, however, wire separation toward the longitudinal direction becomes gradually small. In this case, it is expected that the characteristic impedance of TWP would be changed due to twist pitch size.

To investigate the transmission characteristics of TWP, numerical calculation [12] and measurement are employed to observe the electromagnetic behavior of them. The AWG24 metal single wires were wound on the side face of 1/4 inch wood rod to avoid a deformation of the TWP. The characteristic impedance of this TWP model was calculated and measured with different pitches. All results agree well. The phase velocity $v$ and effective relative permittivity are also calculated and used for common mode current calculation.

### B. Effect of Helical Line Antenna

As mentioned in section 2, the input impedance is needed at the connection point of coaxial cable and TWP, when the cables work as an antenna. First we applied a simple dipole antenna model with length $L$, however, it worked good for parallel wire pair but did not work for TWP. Then we employed a simplified helical antenna model [9, 10] and calculate it using numerical calculation.

According to the [10], the helical line is represented as a sequence of small line segments and small inductance $L_{seg}$ as shown in Fig.5 (a). The inductance $L_{seg}$ represents an inductance $L_{self}$ of a loop of helical line including mutual inductance $M$ between loops as follows

$$L_{seg} = L_{self} + 2M \tag{8}$$

$$L_{self} = L_{loop} \cos\theta \tag{9}$$

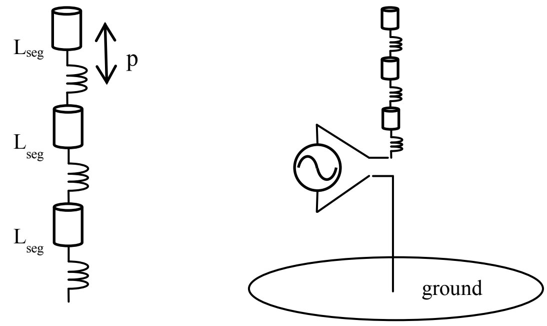
,where $\theta$ is an angle of helical line. $L_{loop}$ and $M$ are obtained by

$$L_{loop} = \mu_0 \frac{s}{2}\left[\ln\left(\frac{8s}{d}\right) - 2\right] \tag{10}$$

$$M = \frac{\pi\mu_0 (s/2)^4}{2\left((s/2)^2 + p^2\right)^{\frac{3}{2}}} \tag{11}$$

,where $s$, $d$ and $p$ are separation of two wires, diameter of wire and pitch of loops, respectively.

To apply this to the coaxial cable with TWP model in this study, the coaxial cable is represented as a simple line and the TWP is as an equivalent circuit as shown in Fig.5 (b), and input impedance is calculated between two lines by numerical calculation. In the calculation the inductance of the loop is put together in every 10 cm to reduce complexity of the model.




(a) Equivalent circuit of helical antenna.
(b) Numerical calculation model of coaxial cable with TWP.

Fig.5 Equivalent circuit of helical antenna.

## IV. Measurement and Calculation of Common Mode Current on Coaxial Cable with TWP

The coaxial cable with TWP was put in standing on the ground floor in the semi-anechoic chamber as shown Fig.6 and differential voltage and common mode current at the bottom of the cable were measured. The sinusoidal signal (R&S SMB100A) was fed to the end of coaxial cable under the ground floor and was also monitored by oscilloscope (Tektronix MSO4104) with 50 Ohm termination. The common mode current was measured with current probe (Fisher F-33-1).

The measurement was carried out on the three cases, coaxial cable with parallel wire pair (para), with 10 mm pitched TWP (twp10) and with 3.3 mm pitched TWP (twp3.3).

The coaxial cable is RG58AU with its length 0.5 m. The TWP investigated in section 3 is attached to the coaxial cable. All of TWPs are in open termination. The measured voltages and common mode currents on the case (twp10) are plotted in Fig.7. The calculated voltage and current are also shown in Fig.7. The calculated results have some difference with measurement, however, complicated changes in both current and voltage measurement are well estimated.

## V. CONCLUSION

The common mode current on the coaxial cable with TWP was estimated using imbalance difference theory. In order to obtain the common mode voltage, the differential mode voltage at connecting point of lines was calculated by simple transmission line calculation with considering both input impedance of TWP and input impedance of lines which works as antenna. Both input impedance and some other characteristic of TWP are investigated by numerical calculation and measurement including extremely wound TWP.

As for the radiation from TWP with coaxial cable, it is demonstrated that common mode current distribution could be calculated by the transmission theory and the imbalance difference theory.

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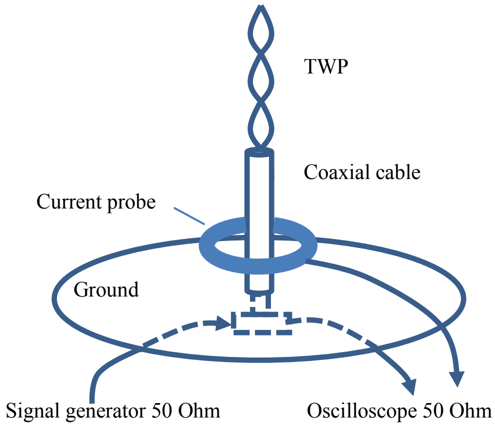
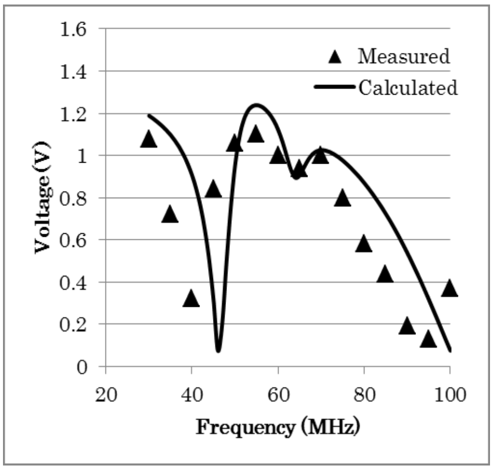
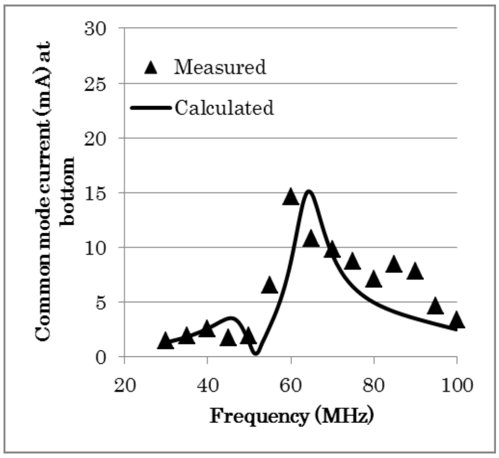



Fig.6 Measurement setup.




(a) Differential voltage at bottom.




(b) Common mode current at bottom.

Fig.7 Voltage and common mode current of 10 mm pitched TWP with coaxial cable (twp10)