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Coupling Analysis for Shielded Cables in the Train Using Hybrid Method

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ABSTRACT Due to the limited space on the train, the shielded cables were utilized to protect signal cables against influence by the disturbance from power cables which arranged in parallel with the signal cables. To reduce cable coupling, the cables are usually arranged close to train body. The influence of the body of the train should not be ignored. To analyze the coupling of shielded cables in the train, a hybrid method is proposed based on the circuit model. To solve the influence from the reflection of the train body, Green's function deduced from image theory is utilized. The current on the shielding layer is calculated by lumped circuit model, which is set up by admittance parameter matrix. And then, the coupling voltage on the core of shielded cable is given by using BTL function. Finally, a laboratory test case and a field test were investigated. Results of the proposed method were validated by measurement results.

INDEX TERMS Coupling, Shielded Cables, Mixed-potential Integral Equation (MPIE), Railway System.

I. INTRODUCTION

In railway system, shielded cables are widely used for protecting signal transmission against external electromagnetic interference (EMI). However, because of the space limitation of the carriage, the power cables and signal cables are arranged in parallel close to the train body sometimes. The coupling between cables lead to electromagnetic compatibility (EMC) fault.

Lots of works have been done dealing with the shielded cables coupling issue by using MTL theory [1]–[3], or electromagnetic numerical methods [4]–[7]. Most of these research focuses on the cables located above an infinitely large lossless metal plane. However, the cables are generally arranged close to the perpendicular metal plane when the floor and one side of train body are both taken into consideration. It is difficult to calculate the inductance or capacitance parameters of the cables. The method based on image theory is utilized to calculate inductance and capacitance with the assumptions of weak coupling with nearby metal surface in [8] and [9]. However, the forms of L and C parameters are too complex. It is easy to understand, but hard to calculate. The hybrid solver combining the multiconductor transmission line (MTL) theory with the method of moments (MoM) was proposed in previous works [10]–[12]. However, the interactions between the cable harness and the metal surface are ignored in this hybrid method. Besides that, in the hybrid method MoM is used to solve the radiation from nearby metal surface. The metal surface near the cables has to be characterized by finely discretized mesh regions, which leads to a large computational burden. To evaluate the current flows on the bundles with an arbitrary shape metal surface, multiple scattering (MS) method is mentioned in [13]. This method is universally applicable, but the calculation is too complicated for analyzing the coupling of shielded cables.

This paper intensively focuses on solving the shielded cables crosstalk problem with complex boundary condition. A new hybrid analytical method is presented in this paper, which combines MTL method [1] with one common formulation of MoM, the mixed-potential integral equations (MPIE) formulation [14]–[17]. The interactions between the cables and nearby metal surface is solved by using Green's function, which could reduce the calculated amount and make the calculation of distribution parameters easier. In our proposed method, the modeling of the shielded cables is divided into two distinct regions [18], [19]: external cables region and

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interior cables region. For external cables region, the circuit extraction method based on MPIE is used to solve the influence of train body on the coupling of cables and calculate the current on the shield. The nearby metal surface and the cables' location surrounding are considered as the boundary for the shielded cables. The different type of Green's function in the MPIE formula based on the image theory is used depending on the boundary condition [20], [21]. By using Green's function, the coupling current on the shielding layer could be calculated without metal surface meshing. Then, the distributed voltage and current sources are set up on the interior cables region by using transfer parameters of shielded cables. The terminal voltages on the core of the shielded cable is given based on MTL.

The paper is organized as follows. In Section II the circuit extraction procedure for the external cables' region and the interior cables region are presented. Comparisons between modeled and measured results are done in Section III. Finally, the paper ends with conclusions and reference.

II. FORMULATION

For better fixation of cables, in high-speed train, the cables between devices locate and close to the floor and side walls of the train. Sometimes, the signal cables are inevitably parallel arranged with power cable.

The structure of shielded cables inside the train is illustrated in Fig. 1. The signal cable between device 1 and device 2 is parallel arranged with power cable. The train body is considered as reference ground. The cables could be considered to locate above orthogonal ground planes.

For analyzing the coupling issue with the cables' location, the cables' structure can be set into two regions, external region and interior region, as shown in Fig. 2. In external region, the infinite orthogonal ground planes where the cables located are taken as the reference ground. The structure inside the shielded cable is ignored. The shielded cables are considered as the single cable. The coupling between the shielding layers of two cables is analyzed in this region. I_p is the common-mode current flowing on the power cable, which is considered as the EMI source. I_s is the induced current on the shielding layer of signal cable, which is coupled from the power cable. The four-port network is extracted from the external region structure. $I_p(0)$, $I_p\ (l)$, $I_s(0)$ and $I_s\ (l)$ are the ports' currents. The interior region is used to analyze the terminal voltage V_r and current I_r, which are coupled on the core of signal cable. Z_r and Y_r are impedance and admittance of the core. The two regions are connected by the transfer impedance Z_t and admittance Y_t.

The current I_{rs} and V_{rs} are the excitation sources for the interior region, which are produced from V_s and I_s on the shielding layer.

$$\begin{aligned} V_{rs}(x) &= Z_t I_s(x) \\ I_{rs}(x) &= -Y_t V_s(x), \end{aligned} \tag{1}$$

The length of the parallel cables is l. x $=[0,x_1,\ x_2,\ldots l]$. Since Y_t is too small [22], only the transfer impedance Z_t

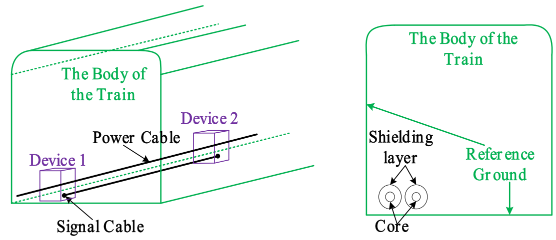

FIGURE 1. Structure for coaxial cables inside the train.

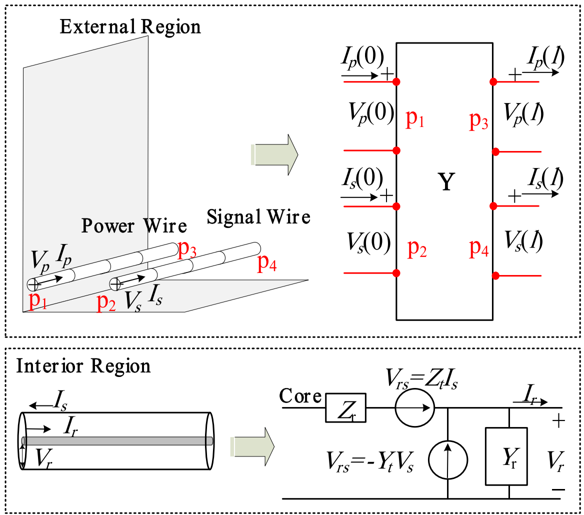

FIGURE 2. Conception of external cables region and interior cables region.

is considered. Thus, I_s and zt are the important elements to get the coupling disturbance for the core of the shielded signal cable.

A. LUMPED CIRCUIT MODEL FOR EXTERNAL REGION

The MPIE formulation is applied to solve the influence of train body on the coupling of cables and calculate the current I_s on the shielding layer. Assume the incident field $\boldsymbol{E}^{inc}$ to be zero, and the cables are replaced by $\boldsymbol{J}$. The MPIE equation can be expressed as [14]:

$$\boldsymbol{a}_n \times \left[\begin{array}{l} j\omega\mu \int_{s'} \boldsymbol{J}\left(\boldsymbol{r'}\right) \boldsymbol{G}^A\left(\boldsymbol{r'},\boldsymbol{r}\right) ds' \\ +\frac{1}{\varepsilon}\nabla \int_{s'} G^{\phi}\left(r',r\right)\rho\left(r'\right) ds' \end{array} \right] = 0. \tag{2}$$

$\boldsymbol{G}^A$ is dyadic Green's function. G^{ϕ} is the scalar Green's function, ρ is the charge density.

The MPIE equation could be solved as [16]:

$$\begin{bmatrix} j\omega\mathbf{C} & \mathbf{\Lambda}^{\mathbf{T}} \\ -\mathbf{\Lambda} & j\omega\mathbf{L} \end{bmatrix} \begin{bmatrix} \boldsymbol{\phi} \\ \mathbf{I} \end{bmatrix} = \begin{bmatrix} -\mathbf{I^e} \\ 0 \end{bmatrix}. \tag{3}$$

In MPIE formulation, each segment can be considered as a node and two connect nodes made an edge. $\boldsymbol{\phi}$ is node potential matrix, $\mathbf{I}$ is branch-current, which flow crosses the edge, as shown in Fig3. It can be deduced from (3):

$$\mathbf{I} = \mathbf{\Lambda}^{\mathbf{T}} - \omega^2 \mathbf{C}\mathbf{\Lambda}^{-1}\mathbf{L}\mathbf{I^e}. \tag{4}$$

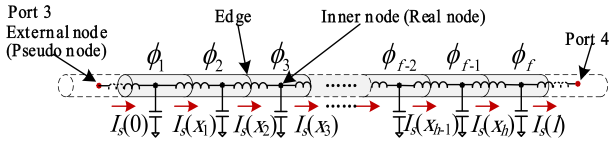

FIGURE 3. Conception of pseudo node and equivalent circuit model of cable.

where, $\mathbf{\Lambda}$ is a connectivity matrix, $\mathbf{C}$ is capacitance matrix, $\mathbf{L}$ is inductance matrix and $\mathbf{I^e}$ is impressed current source matrix.

$\mathbf{I}$ matrix is made up by current matrixes of power cable and signal cable, $\mathbf{I_{P\_MPIE}}$ and $\mathbf{I_{S\_MPIE}}$. Thus, $\mathbf{I}$ matrix in the MPIE formulation could write as:

$$\mathbf{I} = \begin{bmatrix} \mathbf{I_{P\_MPIE}} \\ \mathbf{I_{S\_MPIE}} \end{bmatrix}. \quad (5)$$

The signal cable into F segments, and H edges between segments will be produced at the same time. Thus, $\mathbf{I_{S\_MPIE}}$ could be expressed as:

$$\mathbf{I_{S\_MPIE}} = \left[I_S(x_1)\ I_S(x_2)\ \cdots\ I_S(x_{h-1})\ I_S(x_h) \right]^{\mathrm{T}}_{1\times \mathrm{H}}. \quad (6)$$

It is found that, there are no $I_s(0)$ and $I_s(l)$ in $\mathbf{I_{S\_MPIE}}$ matrix. For calculating $I_s(0)$ and $I_s(l)$, pseudo nodes [14] are set at the terminals of the real cables structure, as shown in Fig3. Pseudo node can benefit calculating the half-inductance which is not calculated by the original equivalent circuit model. Because the area or the length of that pseudo node is zero, the pseudo node doesn't introduce additional partial capacitance terms. It also could be used to set the ports for the cables. If power cable and signal cable are divided into 2F segments and 2H edges, and 2S pseudo segments and 2T pseudo edges are set at the cable terminals, the discretized equation extract from MPIE is:

$$\begin{bmatrix} \mathrm{j}\omega\mathbf{C}_{(2F+2S)\times(2F+2S)} & \mathbf{\Lambda}^{\mathbf{T}}_{(2H+2T)\times(2F+2S)} \\ -\mathbf{\Lambda}(2H+2T)\times_{(2F+2S)} & \mathrm{j}\omega\mathbf{L}_{(2H+2T)\times(2H+2T)} \end{bmatrix} \begin{bmatrix} \boldsymbol{\phi}_{1\times(2F+2S)} \\ \mathbf{I}_{1\times(2H+2T)} \end{bmatrix} = \begin{bmatrix} -\mathbf{I^e} \\ 0 \end{bmatrix}, \quad (7)$$

The extended $\mathbf{I}$ matrix is:

$$\mathbf{I} = \left[\mathbf{I_{P\_MPIE}}\ \mathbf{I_{S\_MPIE}}\ I_P(0)\ I_P(l)\ I_S(0)\ I_S(l) \right]^{\mathrm{T}}. \quad (8)$$

Rearrange the matrix, I_s on the shielding layer of signal cable can be got:

$$\mathbf{I}_s = \left[I_S(0)\ \mathbf{I_{S\_MPIE}}\ I_S(l) \right]^{\mathrm{T}}. \quad (9)$$

1) GREEN'S FUNCTION AND DISTRIBUTION PARAMETERS

Green's functions stand for the interrelation of source and field. Thus, the interaction between cables and surfaces deals with Green's functions, which could simplify the calculation of the distribution parameters of the cables [20]. In this paper, Green's function is utilized to analyze the boundary condition of infinitely orthogonal metal surfaces. The spatial Green's function representation arises by virtue of the image theory;

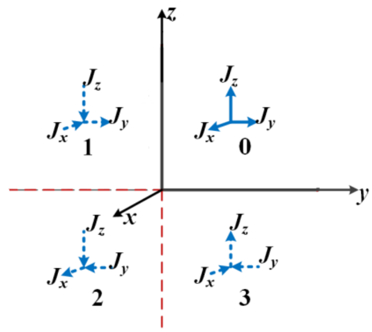

FIGURE 4. Unit cell for computation of waveguide green's function: source term (0) and its three-image term.

each scalar term of the Green's function can be expressed summing up all contributions due to the images produced by the PEC wall, as shown in Fig. 4.

With image theory, the real current source is (J_x, J_y, J_z). The image source electric dipole will have components (-J_x, J_y, -J_z), (J_x, -J_y, -J_z), and (-J_x, -J_y, J_z). The Green's function can be written as:

$$G^A(|X_i|, |Y_i|, |Z_i|) = \sum_{i=0}^{3} K^i_{qq} \frac{e^{-jk\sqrt{X_i^2+Y_i^2+Z_i^2}}}{4\pi\sqrt{X_i^2+Y_i^2+Z_i^2}}, \quad (10)$$

$$G^\phi(|X_i|, |Y_i|, |Z_i|) = \sum_{i=0}^{3} K^i_{\phi} \frac{e^{-jk\sqrt{X_i^2+Y_i^2+Z_i^2}}}{4\pi\sqrt{X_i^2+Y_i^2+Z_i^2}}. \quad (11)$$

Table 1 lists the coefficients of source and image K^i_{qq} and K^i_{ϕ}. Table 2 list the distance vector, which is a vector from source point r' (x', y', z') to the observation point r (x, y, z) and made up by X_i, Y_i and Z_i at x, y, z direction.

TABLE 1. Green's function coefficients.

i	0	1	2	3
K^i_{xx}	1	-1	1	-1
K^i_{yy}	1	1	-1	-1
K^i_{zz}	1	-1	-1	1
K^i_{ϕ}	1	-1	1	-1

TABLE 2. $_i$, Y_i and Z_i components.

i	0	1	2	3
X_i	x-x'	x-x'	x-x'	x-x'
Y_i	y-y'	y+y'	y+y'	y-y'
Z_i	z-z'	z-z'	z+z'	z+z'

Based on this Green's function, the body of the train could be considered as the reference ground for the multiple-line transmission system, which is made up by power cable, signal cable and the body of the train. Thus, inductance matrix and capacitance matrix could be got [12]:

$$\mathbf{L} = \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1(2H+2T)} \\ L_{21} & L_{22} & \cdots & L_{2(2H+2T)} \\ \vdots & \vdots & \ddots & \vdots \\ L_{(2H+2T)1} & L_{(2H+2T)2} & & L_{(2H+2T)(2H+2T)} \end{bmatrix}$$

$$\mathbf{C} = \mathbf{K}^{-1}$$

$$\mathbf{K} = \begin{bmatrix} K_{11} & K_{12} & \cdots & K_{1(2F+2S)} \\ K_{21} & K_{22} & \cdots & K_{2(2F+2S)} \\ \vdots & \vdots & \ddots & \vdots \\ K_{(2F+2S)1} & K_{(2F+2S)2} & & K_{(2F+2S)(2F+2S)} \end{bmatrix}, \quad (12)$$

The element L_{mn} of matrix $\mathbf{L}$. It is written as:

$$L_{mn} = \mu \left(M_{l_m^- l_n^-} + M_{l_m^+ l_n^+} - M_{l_m^+ l_n^-} - M_{l_m^- l_n^+} \right), \quad (13)$$

$$M_{pq} = \frac{1}{l_p l_q} \int_{l_p} \int_{l_q} \left(\mathbf{r} - \mathbf{r}_{l_p}\right) \left(\mathbf{r}' - \mathbf{r}_{l_q}\right) \mathbf{G}^A \left(\mathbf{r}', \mathbf{r}\right) \mathrm{d}l' \mathrm{d}l. \quad (14)$$

$\mathbf{K}$ is the inverse of the capacitance matrix $\mathbf{C}$, and W_{pq} is the term for $\mathbf{K}$.

$$K_{l_p l_q} = \frac{1}{\varepsilon} W_{l_p l_q}, \quad (15)$$

$$W_{l_p l_q} = \frac{1}{l_p l_q} \int_{l_p} \int_{l_q} G^{\phi} \left(\mathbf{r}, \mathbf{r}'\right) \mathrm{d}l' \mathrm{d}l. \quad (16)$$

l_p and l_q are the lengths of cable segment p and segment q respectively.

2) IMPRESSED CURRENT

$\mathbf{I}^e$ is impressed current source matrix. The impressed current source could be added at any segment even pseudo segment. For the system in Fig.2, the impressed current sources are added to the terminal of the cables. To get the impressed current sources, the network analysis methodology is utilized. The pseudo nodes are set as ports. A circuit model is extracted from the structure of external region and the admittance of the network can be written as:

$$\mathbf{Y}^{-1} \mathbf{I}_{\mathbf{port}} = \mathbf{V}_{\mathbf{port}}, \quad (17)$$

The currents at the ports $\mathbf{I}_{\mathbf{port}}$ is a part of impressed current sources for MPIE formulation. $\mathbf{V}_{\mathbf{port}}$ is port voltages matrix. $\mathbf{Y}$ is the admittance of the network. It can be got by applying the MPIE formulation.

A relationship between ϕ and $\mathbf{I}^e$ can be derived from (3) as:

$$\mathbf{Y}_{\mathrm{MPIE}} \cdot \boldsymbol{\phi} = -\mathbf{I}^e, \quad (18)$$

where

$$\mathbf{Y}_{\mathrm{MPIE}} = \mathrm{j}\omega \mathbf{C} + \frac{1}{\mathrm{j}\omega} \boldsymbol{\Lambda}^T \cdot \mathbf{L}^{-1} \cdot \boldsymbol{\Lambda}. \quad (19)$$

The impressed current source matrix $\mathbf{I}^e$ can be expressed as:

$$\mathbf{I}^e = \begin{bmatrix} -\mathbf{I}_{\mathbf{port}} \\ -\mathbf{I}_{\mathbf{seg}} \end{bmatrix}, \quad (20)$$

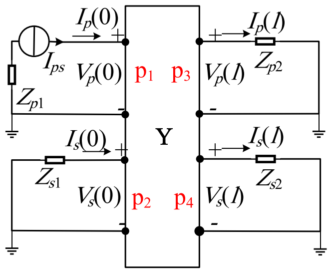

FIGURE 5. Lumped circuit model for cable external region.

Because there are no current sources on any segment, the current matrix on segments $\mathbf{I}_{\mathbf{seg}}$ will be set to zero. Thus, for calculating the $\mathbf{Y}$-matrix of the network, (18) is changed as:

$$\begin{bmatrix} \mathbf{Y_A} & \mathbf{Y_B} \\ \mathbf{Y_C} & \mathbf{Y_D} \end{bmatrix} \begin{bmatrix} \boldsymbol{\phi}_{\mathbf{port}} \\ \boldsymbol{\phi}_{\mathbf{seg}} \end{bmatrix} = \begin{bmatrix} \mathbf{I}_{\mathbf{port}} \\ 0 \end{bmatrix}, \quad (21)$$

where $\boldsymbol{\phi}_{\mathbf{port}}$ is port potential matrix and $\mathbf{I}_{\mathbf{port}}$ is port current matrix, respectively. While, $\boldsymbol{\phi}_{\mathbf{seg}}$ is real segments potential matrix. $\mathbf{Y_A}$ is admittance parameter matrix for pseudo segments, while $\mathbf{Y_D}$ is Y-parameter matrix for real segments. $\mathbf{Y_B}$ and $\mathbf{Y_C}$ represent the interrelation between real segments and pseudo segments by Y-parameter [16].

Since the port voltages matrix $\mathbf{V}_{\mathbf{port}}$ is equal to the potential difference between the potential of the port and reference ground, the admittance $\mathbf{Y}$ matrix of the network in (17) could be got:

$$\mathbf{Y} = \left(\mathbf{Y_A} - \mathbf{Y_B} \mathbf{Y_D}^{-1} \mathbf{Y_C} \right), \quad (22)$$

Add the common source I_{ps} at port 1, which is the terminal source of the power cable. Z_p1 and Z_p2 are the two terminal impedances of power cable. Z_s1 and Z_s2 are the two terminal impedances of the shielding layer of signal cable, respectively. They are added at port 3 and port 4, shown in Fig.5.

With these terminal boundary condition, the current at the ports $\mathbf{I}_{\mathbf{port}}$ could be got as:

$$\mathbf{I}_{\mathbf{port}} = \left[I_p(0) \ I_p(l) \ I_s(0) \ I_s(l) \right]^{\mathrm{T}}, \quad (23)$$

B. INTERIOR REGION

For interior region, the shielding layer is considered as the ground of the core of signal cable. The equivalent circuit of unit length core is shown in Fig. 2. Thus, the interrelation of voltage and current is:

$$\begin{aligned} \frac{\mathrm{d}V_r(x)}{\mathrm{d}x} + Z_r I_r(x) &= V_{rs}(x) \\ \frac{\mathrm{d}I_r(x)}{\mathrm{d}x} + Y_r V_r(x) &= I_{rs}(x), \end{aligned} \quad (24)$$

where, Z_r and Y_r are impedance and admittance of the core.

By using BTL function, the coupling voltage and current could be solved [22]:

$$\begin{bmatrix} I_r(0) \\ I_r(l) \end{bmatrix} = \frac{1}{Z_C} \begin{bmatrix} 1-\rho_1 & 0 \\ 0 & 1-\rho_2 \end{bmatrix} \begin{bmatrix} -\rho_1 & e^{\gamma l} \\ e^{\gamma l} & -\rho_2 \end{bmatrix}^{-1} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$

$$\begin{bmatrix} V_r(0) \\ V_r(l) \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \begin{bmatrix} -\rho_1 & e^{\gamma l} \\ e^{\gamma l} & -\rho_2 \end{bmatrix}^{-1} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}, \quad (25)$$

where, Z_c is the characteristic impedance of the cable. γ is the propagation constant. ρ_1 and ρ_2 are the reflection coefficients at the two terminals of the signal cable.

$$S_1 = \frac{1}{2}\int_0^l e^{\gamma l} Z_t I_s(x)dx$$
$$S_2 = -\frac{1}{2}\int_0^l e^{\gamma(l-x)} Z_t I_s(x)dx, \tag{26}$$

S_1 and S_2 are the source of the core, which are produced due to I_s the current on the shielding layer.

In engineering practice, braided shielded cable is usually used. The transfer impedance could be expressed as [23]:

$$Z_t = Z_d + j\omega\left(L_h + L_b\right), \tag{27}$$

where, Z_d is the scattering impedance, L_b and L_h are the inductances of braid and gap on the braid respectively.

$$Z_d = \frac{4\left(1+\mathrm{j}\right)d/\delta}{\pi d^2 Nk\sigma\cos\beta\sinh\left[\left(1+\mathrm{j}\right)d/\delta\right]}, \tag{28}$$

$$L_h = \frac{2\mu_0\left(4\pi b\cos\beta - kNd\right)^4}{\pi\cos\beta\left(2\pi b\right)^2 k^3} \exp\left(-\frac{k\pi d}{4\pi b\cos\beta - kNd} - 2\beta\right), \tag{29}$$

$$L_b = \begin{cases} -\dfrac{2\mu_0 d^2 k(1-\tan^2\beta)}{8\pi b(dk + 4\pi b\cos\beta - kNd)}, & \beta < \dfrac{\pi}{4} \\ \dfrac{2\mu_0 d^2 k(1-\tan^2\beta)}{8\pi b(dk + 4\pi b\cos\beta - kNd)}, & \beta \geq \dfrac{\pi}{4}, \end{cases} \tag{30}$$

where, b is the radius of shielding layer, k is number of carriers, N is the number of strands in one carrier, d is strands diameter, β is braid angle, and the δ is the skin depth,

$$\delta = \sqrt{1/\pi f\sigma\mu}, \tag{31}$$

III. VALIDATION AND APPLICATION

A. VALIDATION

To validate the hybrid method, the structure with two shielded cables on the ground was studied. Result of the coupling analyzing model is compared with measurements.

The measurement set-up is shown in Fig 6. The signal generator E8257C and receiver HP E7404A are used in the test. The height of cables to the ground is 10 cm and the distance between cables is 20 cm. the disturbance source feed on cables by current injection pliers, and measured by a current clamp. The terminal voltage on the core of victim cable was measured by the receiver.

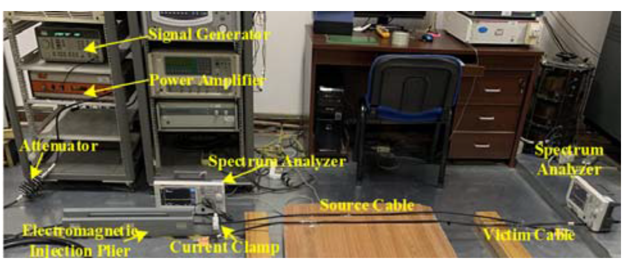

FIGURE 6. Measurement set-up.

The coupling voltage at the terminal of victim cable is analyzed. Good agreement between measurements, MTL method, and our approach is presented in Fig. 7. There is only 2dB difference between the results of measurement and our method from 150 kHz to 10MHz. With the increasing of the frequency, from 10 MHz to 15 MHz, the measurement result is larger than our method and the MTL method result with the same trends, which may be due to that the ground and cables are assumed to be lossless in our method and MTL method simulations.

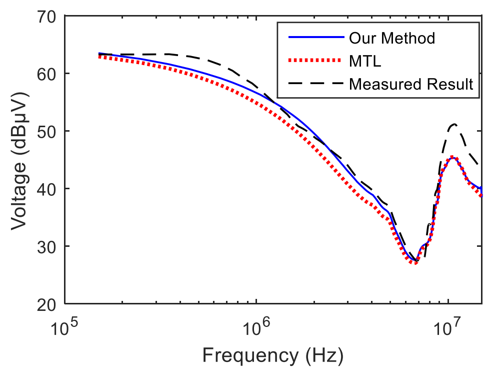

FIGURE 7. Results comparison between measurement and our method.

In this case, half-free space Green's function is utilized for our method. It is denoted as:

$$\overline{\overline{G}}^A_{ground}\left(|X_i|, |Y_i|, |Z_i|\right) = K^o_{qq}\frac{e^{-jkR_o}}{4\pi R_o} + K^i_{qq}\frac{e^{-jkR_i}}{4\pi R_i}, \tag{32}$$

where

$$K^o_{qq} = 1, \quad qq = xx, yy, zz$$
$$K^i_{qq} = \begin{cases} -1, & qq = xx, yy \\ 1, & qq = zz \end{cases}$$
$$R_o = \sqrt{(x-x')^2 + (y-y)^2 + (z-z')^2}$$
$$R_i = \sqrt{(x-x')^2 + (y-y)^2 + (z+z')^2}.$$

The ground is assumed as an infinity large PEC plane. The boundary effect and loss of the ground are ignored in our model.

B. APPLICATION

The Driver - Machine Interface (DMI) and Automatic Train Protection (ATP) are unable to communicate properly, when a certain type train passes the neutral zone. It is found that the fault may be caused by the coupling between the signal cable and power cable, according to the investigation for field environmental of equipment connection status and wiring.

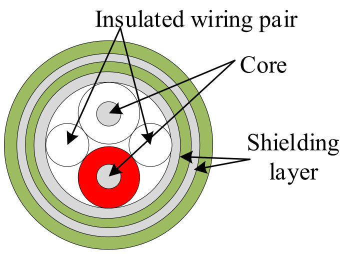

FIGURE 8. The cross-section of signal wire.

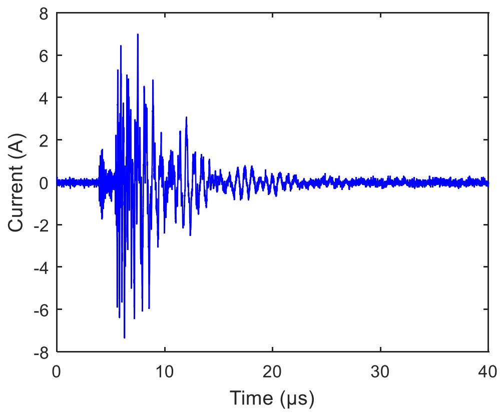

FIGURE 9. Common-mode disturbance current flow on power cable.

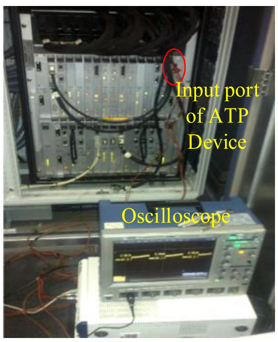

FIGURE 10. Field test set-up.

In order to make sure the cause of failure, the method proposed in this paper is utilized to analyze the coupling between the power cable and the signal cable.

As shown in Fig.1, device 1 is supposed as DMI and device 2 is the cabin of ATP. The signal cable is shielded cable which connects with DMI and ATP. The signal cable is arranged parallel with 220V power cable for 19 m. The distance between cables and the floor and wall of the train is 30cm. The structure of signal cable is shown in Fig. 8. The area of core is 0.5mm^2, the radius of inner shielding layer and outer shielding layer are 2.8mm and 3.45mm respectively.

When the train passes the neutral section, circuit structure of the train power supply system is changed and the transient disturbance appears. Fig.9 shows the common-mode current of harassment on the power supply cable.

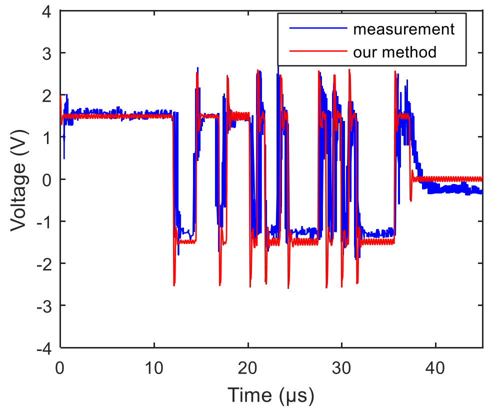

FIGURE 11. Voltage of signal wire at the input port of ATP.

To prove our approach could be used for analyzing the engineering problem, field test is set up, shown in Fig.10. The differential voltage on the signal cable at the terminal of ATP is tested by oscilloscope.

The comparison result between field test and our model is shown in Fig. 11. The two results are matched well. Due to the crosstalk between the power cable and the signal cable, the disturbance is superimposed on a useful signal. Even though the signal was not interfered yet, the disturbance on the signal wire should not be ignored. The maximum value of the disturbance voltage is as high as 1V.

IV. CONCLUSION

In this paper, a hybrid method combining with MPIE circuit method and MTL method is proposed to analyze the coupling of shielded cables located in the train. The segmentation method is utilized in this approach to divide the problem into two regions. The interaction between the cables and train body was analyzed by utilizing MPIE formulation with Green's function. The coupling disturbance on the core was calculated by using BTL function. The result between measurements and the proposed method matched well. Furthermore, a practical engineering application was given to approve the practicability of our proposed methodology.

REFERENCES

[1] C. R. Paul, "Frequency domain analysis of multiconductor lines," in *Analysis of Multiconductor Transmission Lines*, 2nd ed. Hoboken, NJ, USA: Wiley, 2007, pp. 282–337.

[2] A. Orlandi, "Full SPICE model for transfer impedance and transfer admittance inclusion in shielded coaxial cables analysis," *IEE Proc.-Sci., Meas. Technol.*, vol. 150, no. 6, pp. 297–306, Nov. 2003.

[3] H. Xie, J. Wang, R. Fan, and Y. Liu, "SPICE models for prediction of disturbances induced by nonuniform fields on shielded cables," *IEEE Trans. Electromagn. Compat.*, vol. 53, no. 1, pp. 185–192, Feb. 2011.

[4] M. Feliziani and F. Maradei, "Full-wave analysis of shielded cable configurations by the FDTD method," *IEEE Trans. Electromagn. Magn.*, vol. 38, no. 2, pp. 761–764, Mar. 2002.

[5] A. Tatematsu, "A technique for representing coaxial cables for FDTD-based surge simulations," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 3, pp. 488–495, Jun. 2015.

[6] A. Tatematsu, "A technique for representing lossy thin wires and coaxial cables for FDTD-based surge simulations," *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 3, pp. 705–714, Jun. 2018.

[7] J. Wang, X. Han, K. Yang, Y.-S. Xia, and W.-Y. Yin, "Hybrid FDTD method for studying electromagnetic coupling effects of transmission line networks," *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 5, pp. 1650–1653, Oct. 2017.

[8] Z. Li, L. L. Liu, J. Yan, A. W. Xu, Z. Y. Niu, and C. Q. Gu, "An efficient simplification scheme for modeling crosstalk of complex cable bundles above an orthogonal ground plane," *IEEE Trans. Electromagn. Compat.*, vol. 55, no. 5, pp. 975–978, Oct. 2013.

[9] X. He, "Grounding structures for the EMC protection of cabling and wiring," M.S. thesis, Beijing Jiaotong Univ., Beijing, China, 2016.

[10] D. Topchishvili, R. Jobava, F. Bogdanov, B. Chikhradze, and S. Frei, "A hybrid MTL/MoM approach for investigation of radiation problems in EMC," in *Proc. 9th Int. Seminar/Workshop Direct Inverse Problems Electromagn. Acoustic Wave Theory*, Oct. 2004, pp. 65–68.

[11] H. Chobanyan, I. Badzagua, T. Injgia, A. Gheonjian, and R. Jobava, "Application of hybrid MOM/MTL method to simulation of interaction between cable harness and antennas," in *Proc. Int. Seminar/Workshop Direct Inverse Problems Electromagn. Acoustic Wave Theory*, Sep. 2009, pp. 33–38.

[12] I. Badzagua, H. Chobanyan, G. Chikovani, I. Oganezova, E. Yavolovskaya, T. Injgia, A. Gheonjian, and R. Jobava, "Effective computational techniques for EMC analysis of cable harness," in *Proc. 15th Int. Seminar/Workshop Direct Inverse Problems Electromagn. Acoustic Wave Theory (DIPED)*, Sep. 2010, pp. 96–102.

[13] Y. Wang, D. Liu, Y. S. Cao, R. W. Kautz, N. Altunyurt, S. Chandra, and J. Fan, "Evaluating field interactions between multiple wires and the nearby surface enabled by a generalized MTL approach," *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 4, pp. 971–980, Aug. 2018.

[14] D. Liu, Y. Wang, R. W. Kautz, N. Altunyurt, S. Chandra, and J. Fan, "Accurate evaluation of field interactions between cable harness and vehicle body by a multiple scattering method," *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 2, pp. 383–393, Apr. 2017.

[15] Y. Wang, R. Kautz, N. Altunyurt, and J. Fan, "An equivalent circuit model for the wire-to-surface junction based on method of moments," in *Proc. IEEE/ACES Int. Conf. Wireless Inf. Technol. Syst. (ICWITS), Appl. Comput. Electromagn. (ACES)*, Honolulu, HI, USA, Mar. 2016, pp. 1–2.

[16] D. Liu, "Common mode current estimation for cable bundle inside a vehicle," Ph.D. dissertation, Missouri Univ. Sci. Technol., Rolla, MO, USA, 2013.

[17] J. Fan, H. Shi, A. Orlandi, J. L. Knighten, and J. L. Drewniak, "Modeling DC power-bus structures with vertical discontinuities using a circuit extraction approach based on a mixed-potential integral equation," *IEEE Trans. Adv. Packag.*, vol. 24, no. 2, pp. 143–157, May 2001.

[18] G. Antonini and A. Orlandi, "Spice equivalent circuit of a two-parallel-wires shielded cable for evaluation of the RF induced Voltages at the terminations," *IEEE Trans. Electromagn. Compat.*, vol. 46, no. 2, pp. 189–197, May 2004.

[19] H. Xie, J. Wang, R. Fan, and Y. Liu, "SPICE models to analyze radiated and conducted susceptibilities of shielded coaxial cables," *IEEE Trans. Electromagn. Compat.*, vol. 52, no. 1, pp. 215–222, May 2010.

[20] R. Araneo and G. Lovat, "Fast MoM analysis of the shielding effectiveness of rectangular enclosures with apertures, metal plates, and conducting objects," *IEEE Trans. Electromagn. Compat.*, vol. .51, no. 2, pp. 274–283, May 2009.

[21] M.-J. Park and S. Nam, "Rapid summation of the Green's function for the rectangular waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 46, no. 12, pp. 2164–2166, Dec. 1998.

[22] F. M. Tesche, M. Ianoz, T. Karlsson, and T. Karlsson, "Shielded cables,"in *EMC Analysis Methods and Computational Models*, 2nd ed. Hoboken, NJ, USA: Wiley, 1996.

[23] Q. Shan, "Research on key techniques of electromagnetic compatibility for the new generation of China railway high-speed," Ph.D. dissertation, Beijing Jiaotong Univ., Beijing, China, 2013.

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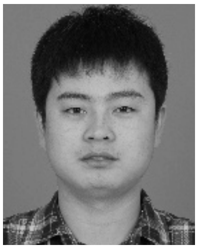

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