

# Reduced Modeling for Electromagnetic Coupling to Randomly Wiring Automotive Cable Harness

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**Abstract** – The random wiring of automotive cable harness makes electromagnetic compatibility (EMC) analysis of the whole vehicle very complicated; thus, this paper proposes a simplification modeling technique to model the electromagnetic (EM) illumination on automotive cable harness. First, the stochastic process theory is applied to determine the cable route in a randomly bundling way. Then, the inductance and capacitance parameters of the cable harness at different location are established according to multiconductor transmission lines network (MTLN) theory. On this basis, the simplification modeling technique is developed to generate the electrical and geometrical parameters of the equivalent cable model. Finally, a model of shielded nine-conductor with randomly twisted and a model of unshielded nine-conductor with stochastic wiring in the vehicle are performed to validate the proposed approach by full-wave simulation. The presented method simplifies the complexity of modeling the complete cable harness significantly with a good accuracy.

**Index Terms** – Random wiring, automotive cable harness, simplification modeling, EM coupling, stochastic process.

## I. INTRODUCTION

The cable harness provides a main gateway for electromagnetic interference (EMI) in automotive system. The unreasonable electromagnetic compatibility (EMC) design of cable harness will produce EMI to other on-board electronic equipment, bringing great safety risks to the system [1–4]. Theoretical research and engineering practice indicate that many electromechanical systems cannot satisfy EMC standards, which can be attributed to the EMI generated by cables [5–8]. As for the electro-

magnetic (EM) coupling analysis in modern automotive industry, reliable and efficient generation of a full numerical model of automotive cable harness is increasingly welcomed by the EMC designers [9–12]. Therefore, a more effective method to solve the modeling problem of automotive cable harness is needed.

During the wiring process in automotive, the cable harness always has some stochastic wiring factors of “spatial bending” and “randomness” as shown in Figure 1 [13–15], which bring a great challenge to the modeling of the EM illumination. Conventional modeling and simulation methods cannot easily accommodate complicated automotive system because of the difficulties in EMC modeling for cable harness [16–18]. Numerical simulation of the whole cable harness model requires strict conditions on calculation resource and even makes it impossible. Therefore, having the purpose of simplifying the structural modeling and improving the analytic efficiency, this paper focuses on the simplification technique of automotive cable harness with stochastic wiring factors.

The equivalent cable bundle method (ECBM) is a modeling method that reduces multiconductor to no more than four conductors. The ECBM method is first presented to simplify the modeling of the EM illumination on multiconductor above the ideal conducting plane, which is used to predict the coupling common-mode (CM) current [19]. On this basis, the ECBM method is extended to model the EM radiated emission from multiconductor above an ideal conducting plane [20]. Besides, the ECBM method is applied to solve the crosstalk calculation problem of cable harness with the situation in an ideal conductive plane, an ideal cylindrical shielded cavity, and an orthogonal plane [21]. Moreover, some literatures have used the

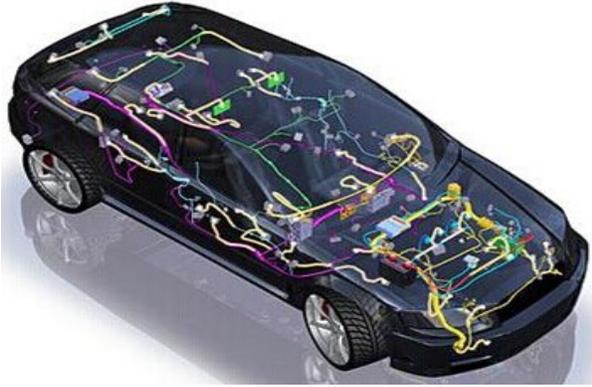


Fig. 1. Schematic diagram of automobile wiring harness distribution.

ECBM method to obtain induced current on differential cables [22].

The existing ECBM method mainly aims at simplifying the deterministic wiring cable harness; however, uncertain factors for the application cannot be ignored. The generation of cross-sectional geometry for randomly wiring cable harness is quite different from that in a deterministic wiring way reflected in the processing of random wiring parameters.

Therefore, this paper proposes a generalized ECBM method for the EM illumination on cable harness with stochastic wiring factors. First, the stochastic process theory is applied to determine the cable route in a randomly bundling way. Second, the inductance and capacitance parameters of the cable harness at different locations are established according to multiconductor transmission lines theory. In this case, the simplification modeling technique is developed to generate the electrical and geometrical parameters of the equivalent cable model. Third, the proposed method is validated by full-wave simulation. The presented method simplifies the complexity of modeling the complete cable harness significantly with a good accuracy.

## II. THEORETICAL MODELING OF GENERALIZED ECBM

### A. Statement of EM coupling to automotive cable harness with stochastic wiring factors

Figures 2(a) and 3(a), respectively, illustrate a typical model of braid shielded automotive cable harness in a randomly twisted bundling way and a model of unshielded cable harness with stochastic wiring factors. The corresponding schematic diagram and cross section can be seen in Figures 2(b) and 3(b). For the shielded cable harness, the geometric cross section remains the original shape along the cable length direction, while the relative position of the inner conductor changes. For the

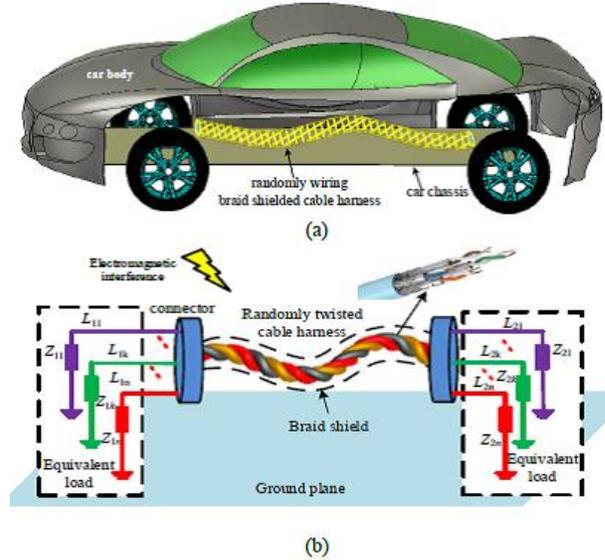


Fig. 2. Schematic diagram and cross section of braid shielded automobile cable harness in randomly twisted bundling way. (a) Cable harness in automobile. (b) Schematic diagram.

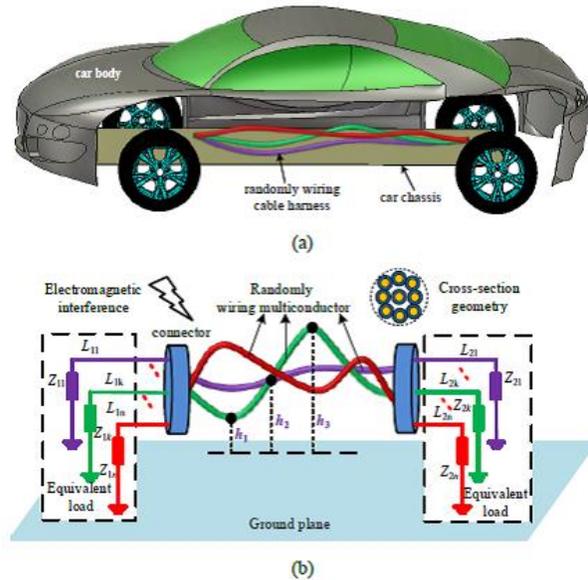


Fig. 3. Schematic diagram and cross section of unshielded automobile cable harness in randomly wiring way. (a) Cable harness in automobile. (b) Schematic diagram.

unshielded cable harness, the conductors are not exactly parallel and the position of the inner conductors is of uncertainty.

Considering the required computer resources, there is no possibility for the EM coupling problems of the

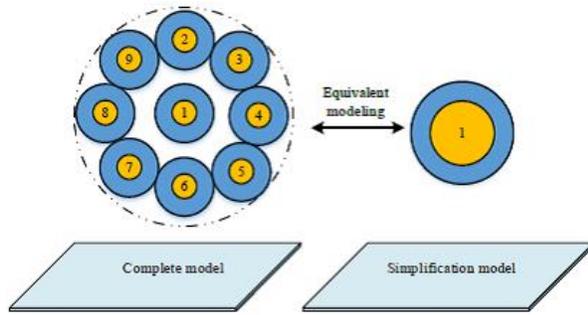


Fig. 4. Cross-sectional geometry of the complete and simplification cable harness model.

whole cable harness to be solved. However, a solution that all the conductors are wired in a determined manner was put forward by the previous ECBM method to the immunity case, but it cannot be directly applied to the case where the cable harness is in a randomly wiring way. Therefore, this paper proposes a generalized ECBM method to reduce the randomly wiring automotive harness into a single-conductor model as demonstrated in Figure 4. That is, the EM coupling to the single conductor is equivalent to describe that on a complete cable harness model.

## B. Simplification modeling procedure

To simplify the cable harness with random wiring, this paper mainly discusses two stochastic wiring factors, including the relative position of the conductors within the cylindrical shielded structure and the height of the unshielded conductors to the ground.

### a) Capacitance and Inductance Parameters of Equivalent Cable Harness Model

This step aims at defining the inductance  $l_{eq}$  and capacitance  $c_{eq}$  of simplification cable in multiconductor transmission lines network (MTLN) formalism [23]. The distributed parameters of capacitance matrix and inductance matrix are uncertain under the influence of the stochastic wiring factors; this phenomenon, in mathematics, can be described with expectations  $E\{c\}$  and  $E\{l\}$ . And, the voltage and current along the conductors are defined as  $V_1, V_2, \dots, V_n$  and  $I_1, I_2, \dots, I_n$ . In the general case of  $N$ -conductor harness cable, the MTLN equations with stochastic factor can be expressed as

$$E\left\{\frac{\partial}{\partial z}[I]\right\} = -j\omega[E\{c\}][V], \quad (1)$$

$$E\left\{\frac{\partial}{\partial z}[V]\right\} = -j\omega[E\{l\}][I], \quad (2)$$

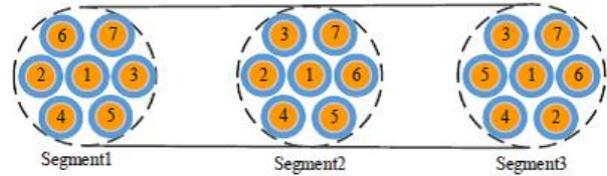


Fig. 5. Schematic diagram of transposition among conductors in a harness.

where  $[I] = [I_1, I_2, \dots, I_n]$ ,  $[V] = [V_1, V_2, \dots, V_n]$ ,

$$[E\{c\}] = \begin{bmatrix} E\{c_{11}\} & E\{c_{12}\} & \cdots & E\{c_{1n}\} \\ E\{c_{21}\} & E\{c_{22}\} & \cdots & E\{c_{2n}\} \\ \vdots & \vdots & \ddots & \vdots \\ E\{c_{n1}\} & E\{c_{n2}\} & \cdots & E\{c_{nn}\} \end{bmatrix}, \quad (3)$$

$$[E\{l\}] = \begin{bmatrix} E\{l_{11}\} & E\{l_{12}\} & \cdots & E\{l_{1n}\} \\ E\{l_{21}\} & E\{l_{22}\} & \cdots & E\{l_{2n}\} \\ \vdots & \vdots & \ddots & \vdots \\ E\{l_{n1}\} & E\{l_{n2}\} & \cdots & E\{l_{nn}\} \end{bmatrix}. \quad (4)$$

According to the MTLN theory, the per-unit-length capacitance parameters  $E\{c_{eq}\}$  and  $E\{l_{eq}\}$  of the simplification cable can be written as

$$E\{c_{eq}\} = \sum_{p=1}^n \sum_{q=1}^n E\{c_{pq}\} \quad (5)$$

$$E\{l_{eq}\} = \sum_p \sum_q E\{l_{pq}\} / n^2 \quad (6)$$

where the conductors are numbered  $p, q$ , and  $n$ .

### b) Case 1: Shielded Cable Harness in Randomly Twisted Way

#### Step 1: Description of Capacitance and Inductance Parameters Matrix

Since the application of the randomly twisted way, the relative position of the inner conductor changes with the length direction of the cable. As shown in Figure 5, a schematic diagram of random transposition among conductors in a harness, the relative position of the inner conductors is uncertain, but they are limited to the connector plug-in at both ends of the cable harness where the terminals are determined. Cable harness has several adjacent segments of cable harness, and when the first segment is converted into the second segment, the positions of no. 3 conductor and no. 6 conductor are transformed. Also, with the second segment being converted into the third, the positions of no. 2 and no. 5 are transformed. Put simply, parameter matrix does not add any new element but only converts each other in element position.

#### Step 2: Determination of Stochastic Wiring Factors

In this step, a random spline interpolation technique is applied to solve the discontinuity problem in the con-

struction of cable harness model. At first, a number of randomly distributed coordinate points, conforming to Gaussian distribution, are generated. Then, the cable harness is divided into a series of homogeneous subsegments by the insertion of more points at other locations through spline interpolation. Finally, the piecewise polynomial form of cubic spline interpolation method is utilized to generate the cascade segments. After all these operations, a randomly twisted cable harness model can be determined.

It should be noted that the length of the subsegments should be up to one of the following two criteria: 1) Each subsegment length should be less than 1/10 of the minimum wavelength to ensure the spatial resolution of the highest frequency wave; 2) adequate subsegments (no less than 10) of the spline segment are inevitable for the continuity of the harness. Then, the smaller of the subsegments identified in the two criteria is adopted to generate the cascade subsegments through the usage of piecewise polynomial form of cubic spline interpolation technology.

### Step 3: Determination of Cross-Sectional Geometry of Simplification Cable Model

In Figure 6, a model of  $n$ -conductors with a radius of  $r_i$  within a perfectly conducting cylindrical shield is displayed. The screen's radius is denoted by  $r_s$  and the distances of conductors from the shield axis are denoted by  $d_i$ , whereas the angular separations of the conductors from the shield axis are denoted by  $\theta_{ij}$ . According to the study in [23], we can obtain

$$E\{l_{ii}\} = \frac{\mu}{2\pi} \ln \left( \frac{r_s^2 - E\{d_i^2\}}{r_s E\{r_i\}} \right). \quad (7)$$

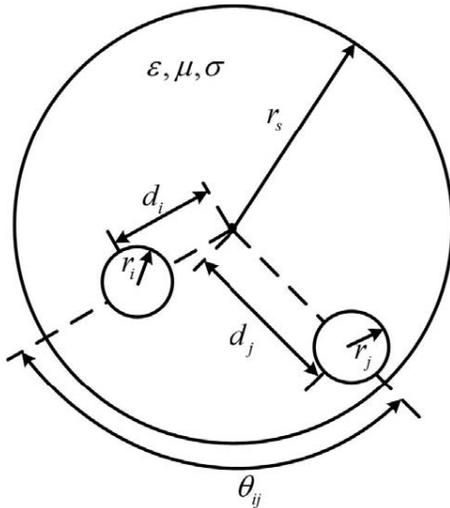


Fig. 6.  $n$ -conductors within a perfectly conducting cylindrical shield.

This step, aiming at generating the cross-sectional geometry of the equivalent cable mainly consists of two phases. The inductance and capacitance parameters are associated with the structural factors, such as the distance between the conductor and shield, and the relative distance among conductors. For this reason, the cross-sectional geometry parameters of equivalent model can be determined based on the knowledge of inductance  $E\{l_{eq}\}$ .

1. Phase 1: Estimate the central distance  $d_i$  between the equivalent inner conductor and the central axis of the shield.  $d_i$  of equivalent conductor corresponds to the average of the distance of all the conductors at any location in the complete cable bundle model.
2. Phase 2: Estimate the radius  $r_i$  of the equivalent cable. According to the analytical formula of self-inductance  $E\{l_{ii}\}$  in eqn (7), the radius  $r_i$  of each equivalent conductor can be approximated by

$$r_i = \frac{r_s^2 - E\{d_i^2\}}{r_s \exp\left(\frac{2\pi E\{l_{ii}\}}{\mu}\right)}. \quad (8)$$

### c) Case 2: Unshielded Cable Harness in Randomly Wiring Way

#### Step 1: Description of Capacitance and Inductance Parameters

Figure 7(a) is an illustration of randomly wiring  $n$ -conductors located above an ideal conducting plane. In the figure,  $r_i$  and  $r_j$  represent the radius of any two conductors and  $h(z)$  refers to the height to the ground plane at position  $z$  along the cable length direction, which satisfies Gaussian distribution as demonstrated in Figure 7(b). The corresponding probability distribution of the height to ground is illustrated in Figure 7(c), in which  $S_{ij}(z)$  is the conductor's spacing and  $\Delta r_A$  and  $\Delta r_B$  stand for the insulation thickness of the conductor. According to study in [23], the calculation formula of per-unit-length inductance parameter can be written as

$$E\{l_{ij}(z)\} = \begin{bmatrix} \frac{\mu}{2\pi} \ln\left(\frac{2\chi_1}{r_i}\right) & \frac{\mu}{4\pi} \ln\left(1 + \frac{4\chi_2}{\chi_3}\right) \\ \frac{\mu}{4\pi} \ln\left(1 + \frac{4\chi_2}{\chi_3}\right) & \frac{\mu}{2\pi} \ln\left(\frac{2\chi_4}{r_j}\right) \end{bmatrix} \quad (9)$$

where  $\chi_1 = E\{h_i(z)\}$ ,  $\chi_2 = E\{h_i(z)\} \cdot E\{h_j(z)\}$ ,  $\chi_3 = E\{S_{ij}(z)^2\}$ , and  $\chi_4 = E\{h_j(z)\}$ . The diagonal element represents the self-inductance, while the off-diagonal element describes the mutual inductance. It can be seen from eqn (9) that the inductance parameters are related to the position of the conductors.

#### Step 2: Determination of the Cross-Sectional Geometry Parameters of Equivalent Cable

According to eqn (6) and (9), the per-unit-length capacitance parameter  $E\{l_{eq}\}$  of the simplification cable model can be calculated and the geometric cross-

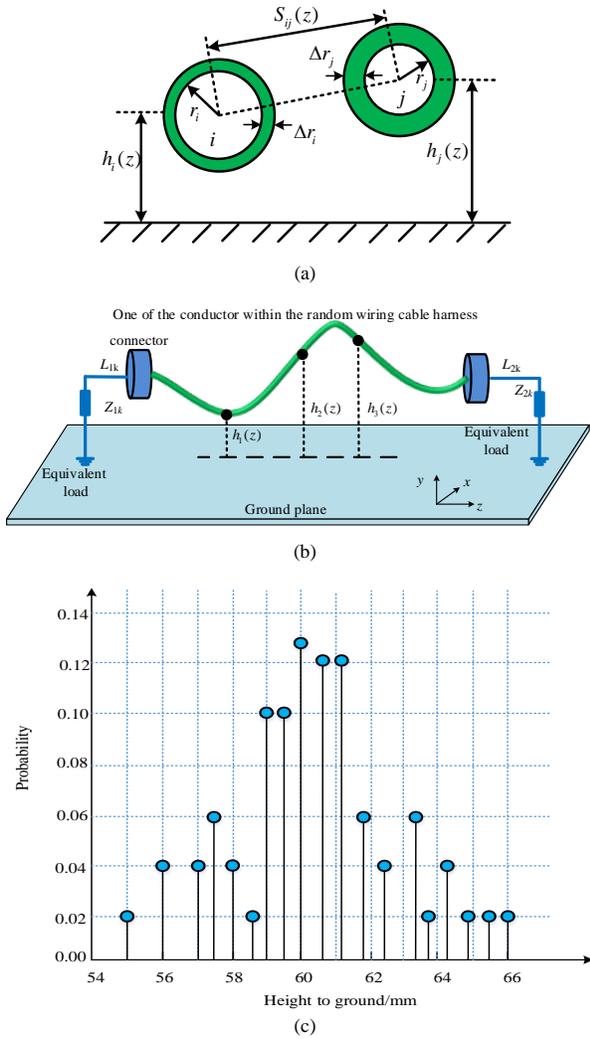


Fig. 7. Randomly wiring unshielded  $n$ -conductors. (a) Double conductors above ideal conducting ground plane. (b) Wiring diagram of one of the conductors. (c) The probability distribution of the height to ground.

sectional structure can be established with the corresponding radius  $r_{eq}$  and the ground height  $h_{eq}$ .

Calculation of  $r_{eq}$ : According to eqn (6) and (9),  $r_{eq}$  is

$$r_{eq} = 2E\{h_i\} / e^{2\pi E\{l_{eq}\}/\mu}. \quad (10)$$

Calculation of  $h_{eq}$ : The height of the simplified cable to the reference ground equals the average height of  $n$ -conductors to the ground at any cross section of the cable harness:

$$h_{eq} = \frac{E\{h_1(z)\} + E\{h_2(z)\} + \dots + E\{h_n(z)\}}{n}. \quad (11)$$

#### d) Equivalent Terminal Loads of Simplification Cable Model

This step aims at calculating the terminal loads of the equivalent model. Here, the equivalent CM loads are defined as the connection between conductor ends and the shield. The terminal load connected to the simplified cable end equals the loads at the end of all the conductors in parallel.

### III. NUMERICAL VALIDATIONS

In this section, a model of braid shielded nine-conductor in randomly twisted bundling way and a model of unshielded nine-conductor with stochastic wiring in the automotive chassis are constructed for the validation of the proposed approach by CST Cable Studio with full-wave simulation. In this paper, the EM coupling value of the whole model is taken as the standard value, and the EM coupling value of the simplification model is compared.

#### A. Case 1: Shielded Cable Harness in Randomly Twisted Way in the Automotive

##### a) Description of the Validation Model

As shown in Figure 8, a nine-conductor point-point connected cable harness within a braid shielded cylindrical structure above the automotive chassis is modeled. All the conductors are bundled in a randomly twisted way. The wiring route is composed of stochastic locations and the corresponding coordinate value is listed in Table 1.

Each conductor has a radius of 0.5 mm and is surrounded by dielectric coating with a thickness  $\Delta r = 1$  mm and dielectric constant of  $\epsilon_r = 2.5$  and  $\mu_r = 1$ . The radius

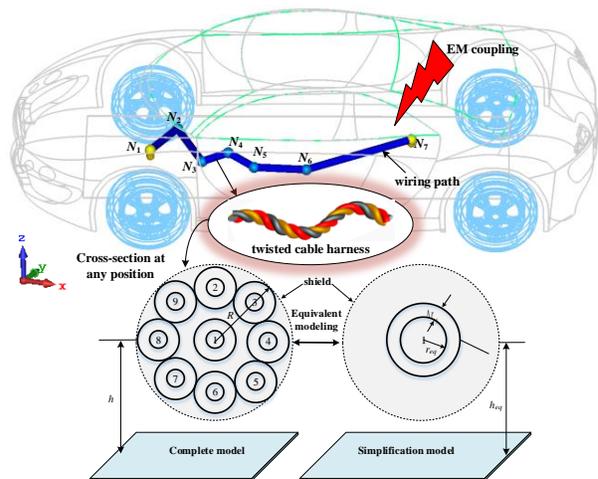


Fig. 8. The full-wave simulation model of a shielded nine-conductor cable harness model and the corresponding simplification cable model in the automotive.

Table 1: Coordinate position of arbitrarily bent cable harness (unit: mm)

Position	$N_1$	$N_2$	$N_3$
$(x, y, z)$	(0, 0, 60)	(200, 400, 10)	(400, -100, 20)
Position	$N_4$	$N_5$	$N_6$
$(x, y, z)$	(600, -100, 100)	(800, -200, 30)	(1200, -200, 10)
Position	$N_7$	—	—
$(x, y, z)$	(2000, 200, 40)	—	—

of the shield is 3 mm. The conductors with a serial number “2, 3, 4, 5, 6, 7, 8” in Figure 10 are evenly distributed on the circle with a radius of 2 mm. The terminal load connected to the ends of each conductor is  $50 \Omega$ . The plane wave incident direction is along the  $Y$ -axis and the electric field direction is along the  $X$ -axis with an amplitude of 100 V/m as shown in Figure 8. The full-wave simulation model in CST is shown in Figure 9.

The cross-sectional geometry of simplification cable model is determined through the simplification procedure of case 1 described in Section 2.2. The correspond-

ing  $r_{eq}$  of the equivalent cable is 3.8 mm and the equivalent CM terminal loads are  $5.6 \Omega$ .

## b) Results and Discussion

The induced CM current at the near and far ends of complete cable harness and simplification cable in frequency domain are calculated through the method of CST Cable Studio with full-wave simulation. Based on the co-simulation technique, the TLM technique and AC result solver are, respectively, adopted in the existing numerical approach to analyze the electric field around the conductors and compute the coupling to terminal loads.

In Figure 9, a comparison between the CM currents obtained at the ends of the complete cable harness model and the simplification cable model over frequency (0.200 MHz) is clearly demonstrated. The red line represents the simulation results of the complete cable model, while the black line describes that of the simplification model. The good agreement indicates a validation of the proposed method.

## B. Case 2: Unshielded Cable Harness with Stochastic Wiring in the Automotive

### a) Description of the Validation Model

The full-wave simulation model in CST is shown in Figure 10, and a nine-conductor point-point connected unshielded cable harness above the automotive chassis is modeled and all of the conductor is wired in a randomly bundling way. Each conductor, with a radius of 0.5 mm, is surrounded by dielectric coating with a thickness  $\Delta r=1$  mm and dielectric constant of  $\epsilon_r = 2.5$  and  $\mu_r = 1$ , and the terminal load connected to the ends of each conductor is  $50\Omega$ . The plane wave incident direction is along the  $Y$ -axis and the electric field direction is along the  $X$ -axis with an amplitude of 100 V/m.

Under the simplification procedure of case 2 described in Section 2-B, the randomly wiring route and cross-sectional geometry of simplification cable model is determined. The radius of equivalent conductor is 4 mm and the thickness of corresponding insulation layer is 1mm.

### b) Results and Discussion

The comparison results of the coupling current on near end and far end of the complete cable harness model and simplification cable model over frequency (0.200 MHz) are, respectively, shown in Figures 11(a) and (b), which proves the efficacy of the proposed method. As it is seen in the figure, the red line represents the result of the complete cable model, while the black line describes that of the simplification model.

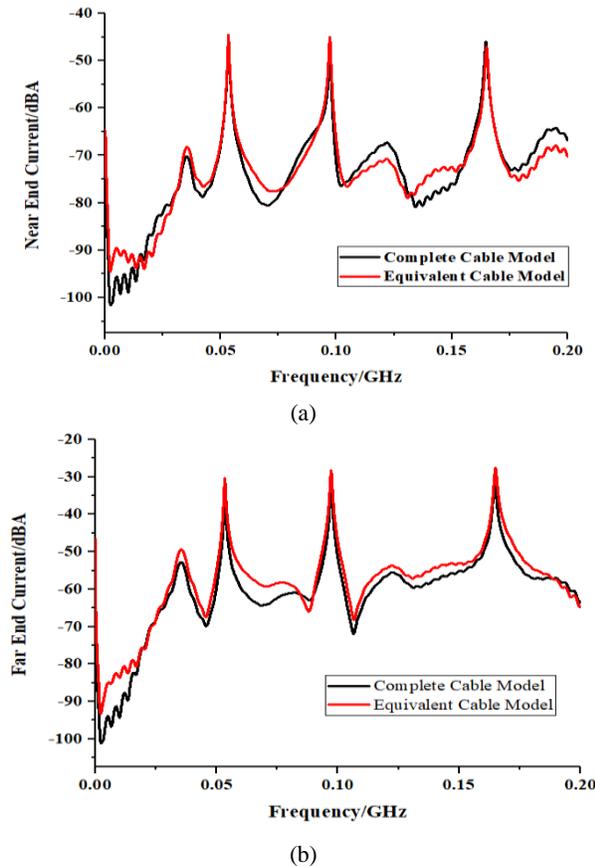


Fig. 9. Comparison of the CM current in frequency domain on complete cable harness model and equivalent cable model. (a) Near end. (b) Far end.

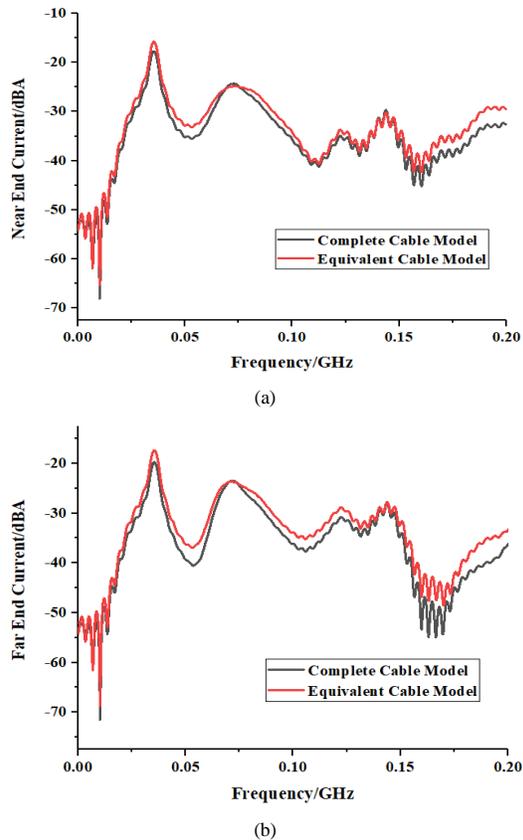


Fig. 10. Comparison of the CM current in frequency domain on complete cable harness and equivalent cable. (a) Near end. (b) Far end.

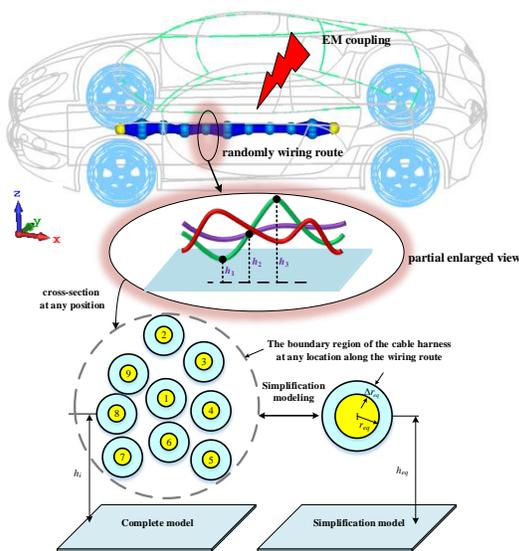


Fig. 11. The full-wave simulation model of an unshielded nine-conductor cable harness model and the corresponding simplification cable model in the automotive.

## IV. CONCLUSION

This paper proposes a generalized simplification technique to model the EM illumination on automotive cable harness with stochastic wiring factors. The combination of the conductors contributes to the simplification of modeling the complete cable harness.

The randomly wiring problem in generating the cross-sectional geometrical parameters of the simplification cable model is successfully solved by the application of the Gaussian distribution and spline interpolation, which are used to determine the route of cable harness. As the position of the conductors within the harness is related to the inductance and capacitance parameters, the inductance and capacitance matrixes of the cable harness at different locations are established by the utilization of transposition relationship between the subsegments of the conductors. To this end, the generalized simplification modeling technique is developed to determine the electrical and geometrical parameters of the simplification cable. Furthermore, a model of braid shielded nine-conductor with random twisting and a model of unshielded nine-conductor with random wiring above automotive chassis are constructed to validate the proposed method by CST Cable Studio with full-wave simulation.

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