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Hybrid MoM-circuit models to analyze the radiated susceptibility of multiconductor shielded cables within complex structures

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Abstract

This paper presents an analysis of the radiated susceptibility of multiconductor shielded cables within complex structures following a hybrid method using moments (MoM) circuit models. The MoM code was used to compute the currents on the shielding induced by an external electromagnetic field and incorporated into a circuit model. The proposed method can be employed for nonlinear loads. The method was tested on two cases: coaxial shielded cables inside a cavity and a car with complex wiring, including a coaxial cable, a twinax cable (a cable with two parallel wires), and a triaxial cable (a cable with three parallel wires), all of which are excited by an incident plane wave. The proposed method provides high accuracy and significant speed gain, and its results are in good agreement with those obtained in other studies.

Introduction

Transmission lines are material structures serving as support for the propagation of electromagnetic (EM) fields that are associated with electrical signals. Transmission lines have at least two conductors, but they can take more complicated configurations. Many studies have examined the modeling and analysis of transmission lines. Several techniques and models have been used in this research work, such as the lumped-circuit approximate model, which enables the representation of the line in the form of a resistance, inductance, capacitance, and conductance RLCG-equivalent circuit model. This also applies to the analysis of multiconductor transmission lines (MTLs) [1], which complicates the equivalent circuit considerably. It causes oscillations to temporal responses and requires a large calculation time, which makes it useless. The method of characteristics, also called Branin's method [2], seeks to analyse an ideal transmission line by representing it in the form of a quadruple. The advantage of this quadruple form is that it does not presuppose load conditions applied at its ends (i.e. the loads at the ends of the line can be linear or not). The application of this approach is presented in detail in this paper. This model is limited to only lossless lines; whereas some other models in the literature can be used to study MTLs with low losses [3] and with frequency-dependent losses [4].

This paper presents an investigation of the immunity of a system to interference created by natural or industrial sources of disturbance, which is one of the many EM compatibility problems. These types of interference can create high voltages and currents in electronic cards placed in equipment and in wire links between equipment. To protect against these EM attacks, the traditional solution is shielding [5], which takes the form of a metal enclosure for electronic equipment or a circular sheath for wire connections. A technology related to the filtering cable, which also has the potential to improve the EM compatibility of the cable is proposed in [6].

In recent years, the research field of shielded cables has become the subject of increasing interest. These cables are usually used in transport applications, power plants, wired communication networks, to protect the inner conductor from radiated interferences and conducted. However, due to the complex configuration of an electronic systems, including not only EM structures (cavities, apertures) but also wires, PCBs, and semiconductors, and because of its many coupling paths, including front-door and back-door couplings, the external EM wave interaction with an electronic system is a complex issue, one which will disturb this system.

Several numerical methods are developed to simulate a large electrical system. Those methods are considered the most efficient techniques, but they are complex and computationally demanding in terms of time and memory usage. Numerical EM modeling methods include finite-difference time domain methods (FDTD) [7, 8], MoM [9], finite element methods [10], and the partial element equivalent circuit [11]. These numerical methods are applied to three-dimensional (3D) EM analyses. However, some problems can be thoroughly analyzed using just two-dimensional (2D) analysis; for example, the Baum-Liu-Tesche equation [12] and the simulation program with integrated circuit emphasis (SPICE) [13] models are often used to model EM propagation along cables, strip lines, microstrips, and more.

EM field coupling analysis of MTLs has been performed by many researchers. The challenge of those approaches is in modifying the telegrapher's classical equations by incorporating additional voltage and current sources to model the external excitation fields [14, 16]. The authors of [17] propose a circuit model of lossy coaxial shielded cables to analyze radiated and conducted susceptibilities with unmatched line loads. They used the Branin's model to obtain the voltage and current distributions. However, this model is limited to analyzing the radiated susceptibility of shielded unifilar cables. In this paper, we are interested in combining numerical and circuit EM analysis methods to create a hybrid method. We aim to explore their benefits through an analysis of the studied problem.

In recent years, considerable research has been conducted on hybrid methods, such as the method of moments-based iterative method [18], the hybrid FDTD SPICE method [13], the time-domain integral equation [19] method, and the hybrid finite difference-finite volume [20] method. However, these methods have been used to evaluate only MTLs without shields. In reality, the shielded cables considered in this paper are usually used in wired communication systems to protect the signal transmission from external interference. Recently, the FDTD method has been proposed to obtain the transient EM responses of coaxial shielded cables in a complex structure, such as a metallic cabin with arbitrary thin slots [5] and metallic enclosures [21] excited by an EM pulse. However, nonlinear and time-varying loads cannot be handled with these models. It is difficult to study the responses at the terminators of the transmission lines that end with nonlinear loads because the response of the nonlinear loads is more complicated than that of linear ones.

In this paper, we present a fast, rigorous hybrid MoM circuit model to analyze the radiated susceptibility of multiconductor shielded cables (coaxial twinax cables) in complex structures. An MoM code is used to compute the currents on the shielding, which are induced by an external EM field and incorporated into a circuit model. This technique can be used to analyze nonlinear loads. The obtained results are analyzed and compared with those from other approaches.

This article is organized as follows. The theory of the hybrid MoM circuit model method used in this study is given in section "Theory of hybrid MoM circuit models". In the section "Simulation results", the simulation results obtained from applying the proposed hybrid approach are presented. Section "Conclusion" concludes this article and gives some future perspectives.

Theory of hybrid MoM circuit models

The principle of hybridization consists of dividing the entire system into two or more subsystems. Each subsystem is individually treated by the most suitable calculation code to reduce the calculation time. In the following sub-sections, we present with the hybridization approach that is used in our paper, the current recovery method. Then, we explore the excitation of multiconductor shielded cables by an incident EM field and discuss their excitation fields in a complex structure. Finally, we describe the circuit models of the inner wires.

Excitation of multiconductor shielded cables by an incident electromagnetic field

The transmission line equations for multiconductor shielded cables with perfect, infinite conducting and excited by an incident EM field, as shown in Fig. 1, can be written as follows:

Outer system

$$\begin{cases} \frac{\delta V_{shd}}{\delta z} + jwL_{shd}I_{shd} + R_{shd}I_{shd} = V_{FD} \\ \frac{\delta I_{shd}}{\delta z} + jwC_{shd}V_{shd} + G_{shd}V_{shd} = I_{FD} \end{cases} \tag{1}$$

Inner system

$$\begin{cases} \frac{\delta V_{wr}}{\delta z} + jwL_{wr}I_{wr} + R_{wr}I_{wr} = Z_t I_{shd} \\ \frac{\delta I_{wr}}{\delta z} + jwC_{wr}V_{wr} + G_{wr}V_{wr} = 0 \end{cases} \tag{2}$$

where V_{shd} and I_{shd} are the shield-to-ground voltage and the current flowing between the external shield and the ground, respectively. G_{shd}, R_{shd}, L_{shd}, and C_{shd} represent the per-unit-length (PUL) conductance, resistance, inductance, and capacitance of the outer system, respectively.

$V_{wr} = [V_{wr1},\ V_{wr2},\ \ldots V_{wrN}]^{\ T}$ and

$I_{wr} = [I_{wr1},\ I_{wr2},\ \ldots I_{wrN}]^{\ T}$ are the line voltage and current vectors,respectively.

$N\times N$ matrices G_{wr}, R_{wr}, I_{wr}, and C_{wr} are the PUL conductance, resistance, inductance, and capacitance matrices of the inner system, respectively.

$Z_t = [Z_{t1},\ Z_{t2},\ \ldots Z_{tN}]^{\ T}$ represents the transfer impedance vector. For the braided shield, the transfer impedance is given by the following equation [22]:

$$Z_{tk} = Z_{dk} + jwL_{tk} \tag{3}$$

where Z_{dk} and L_{tk} represent the diffusion term and the inductance, respectively, which indicates the effect of the field penetrating through the braid apertures, respectively. The expression of these two parameters is derived from[21]. For simplicity, the transfer impedance Z_{tk} is expressed as [23]:

$$Z_{tk} = R_{dk} + jwL_{tk} \tag{4}$$

where R_{dk} is the constant PUL transfer resistance of the shield relative to the k^{th} wire.

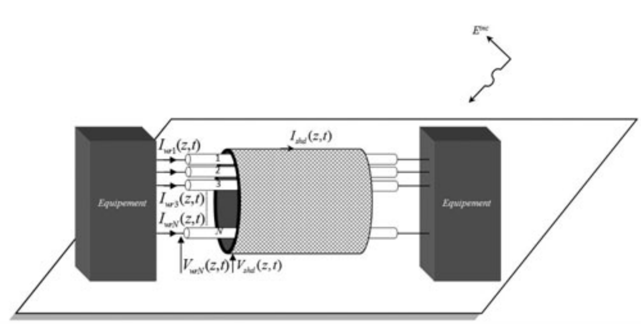

Fig. 1. Coaxial shielded cable over a perfectly conducting ground.

V_{FD} and I_{FD} are the distributed voltage and current sources; they represent the effects of the incident fields and are computed based on the components of the incident magnetic and electric fields (for further details, see [24]).

Excitation fields of multiconductor shielded cables in a complex structure

To analyze multiconductor shielded cables within a complex structure, such as an automobile or a cavity excited by a non-uniform incident wave, as shown in Fig. 2(a), the line must be discretized into cells; the length of each cell is $\Delta Z = \lambda/10$. A currents recovery method is used to compute the current of the shield in each segment I_{shdi}. Currents are needed to compute the terminal voltages and currents of the wires, as expressed in equation (2).

Currents recovery method

The first subsystem of the proposed hybrid method consists of the structure and shielding, as shown in Fig. 2(b), which are processed using a 3D method. In our application, we use the 3D MoM; this digital approach has been implemented in the commercial software FEKO. The objective is to recover the current in the shielding as a function of the frequency. The second subsystem is made up of inner wires, which are processed by a line theory-type code (Fig. 2(c)). In our application, we use Branin's model. We recover the current in the shielding generated using FEKO to insert it into the Branin model.

Note that, because it is necessary to identify only currents of the shield, the inner wires do not have to be meshed; consequently, the meshes are smaller than those used with only 3D MoM code. The currents of the shield I_{shd} for each cell are saved in data files and incorporated into an equivalent circuit model, which is used to compute the terminal voltages and currents of the inner system.

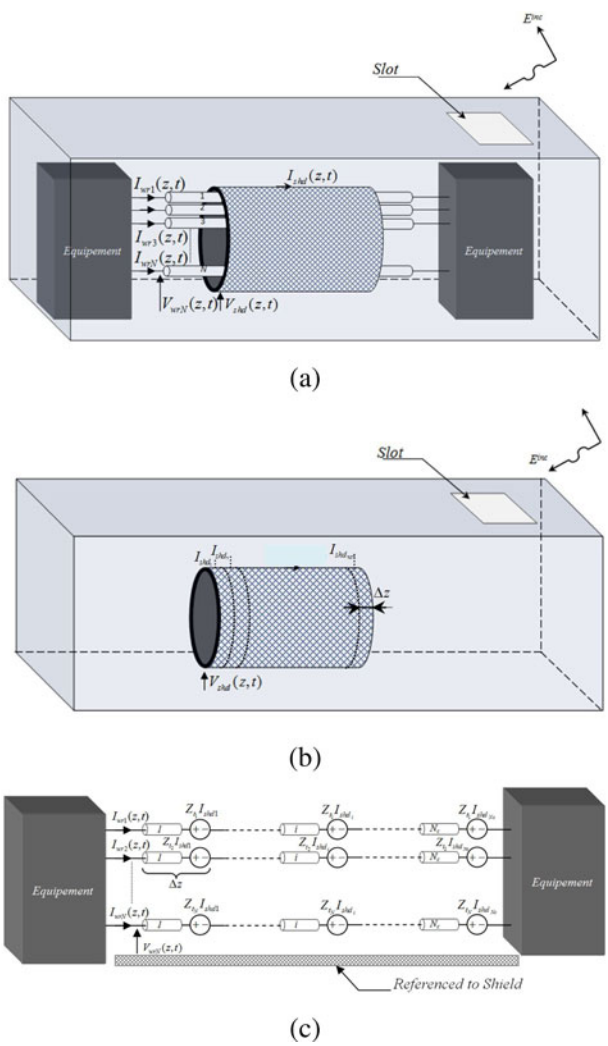

Fig. 2. (a) Multiconductor shielded cables inside a cavity with slot excited by an external plane wave field. (b) The configuration composed of a cavity with slot and shield only used to compute the current of the shield in each segment by MoM. (c) The configuration composed by inner wires used to compute the terminal voltages and currents after incorporating currents of the shield for each cell.

Circuit models of the inner wires

Equation (2) consists of coupled sets of partial differential equations. Here, a similar transformation is needed to decouple them into modal voltages V_{wrm} and currents I_{wrm}[20].

$$\begin{cases} V_{wr} = T_V V_{wrm} \\ I_{wr} = T_I I_{wrm} \end{cases} \tag{5}$$

Substituting (5) in (2), yields

$$\begin{cases} \frac{\delta}{\delta z} V_{wrm} + jwL_{wrm} I_{wrm} + R_{wrm} I_{wrm} = T_v^{-1} Z_t I_{shd} \\ \frac{\delta}{\delta z} I_{wrm} + jwC_{wrm} V_{wrm} + G_{wrm} V_{wrm} = 0 \end{cases} \tag{6}$$

where

$$L_{wrm} = T_V^{-1} L_{wr} T_I \tag{7a}$$

$$C_{wrm} = T_I^{-1} C_{wr} T_V \tag{7b}$$

$$R_{wrm} = T_V^{-1} R_{wr} T_I \tag{7c}$$

$$G_{wrm} = T_I^{-1} G_{wr} T_V \tag{7d}$$

and where T_I and T_V represent the voltage and current transformation matrices, respectively. T_I and T_V are chosen in order to simultaneously diagonalize both L_{wr} and C_{wr}. From (6), the relation between the terminal mode voltages and currents for each cell can be written as follows [22]:

$$\begin{cases} V_{rm} = V_{rwm}(z_0) - Z_{cm} I_{wrm}(z_0) \\ V_{im} = V_m(z_0 + \Delta z) + Z_{cm} I_{wrm}(z_0 + \Delta z) \end{cases} \tag{8}$$

$$\begin{cases} V_{rm} = e^{-\gamma_m \Delta z}[V_{rwm}(z_0 + \Delta z) - Z_{cm} I_{wrm}(z_0 + \Delta z) \\ \qquad - T_V^{-1} Z_t I_{sdh}(z_0 + \Delta z)] \\ V_{im} = e^{-\gamma_m \Delta z}[V_{rwm}(z_0) + Z_{cm} I_{wrm}(z_0)] \\ \qquad + T_V^{-1} Z_t I_{sdh}(z_0 + \Delta z) \end{cases} \tag{9}$$

where Z_{cm} and γ_m are the mode characteristic impedances and propagation constants, respectively. They are given by the following equations:

$$Z_{cw} = \sqrt{\frac{R_{wrm} + jwL_{wrm}}{G_{wrm} + jwC_{wrm}}} \tag{10}$$

$\gamma_m = \alpha_w + j\beta_w$

$$\gamma_m = \sqrt{(R_{wrm} + jwL_{wrm})(G_{wrm} + jwC_{wrm})} \tag{11}$$

Ignoring the PUL conductance G_{wrm} and using the first term of the Taylor series expansion, we obtain the following equations:

$$Z_{cw} = \sqrt{\frac{R_{wrm} + jwL_{wm}}{jwC_{wm}}} = R_{cm} + \frac{1}{jwC_{cm}} \tag{12}$$

where $R_{cm} = \sqrt{\frac{L_{wrm}}{C_{wrm}}}$ and $C_{cm} = \frac{2L_{wrm}}{R_{wrm}R_{cm}}$

$$\gamma_m = \alpha_w + j\beta_w = \frac{R_{wrm}}{2R_{cm}} + jw\sqrt{L_{wrm}C_{wrm}} \tag{13}$$

In this case, the characteristic impedance can be viewed as resistance and capacity connected in series. From (8), (9), and (12), we can deduce the equivalent circuit presented in Fig. 3. From (5), the terms of the generators controlled voltage and current placed in each cell can be obtained by the following equations:

$$V_{wr}(z, t)_i = \sum_{k=1}^{N} [T_V]_{ik} V_{wm}(z, t)_k \tag{14}$$

$$I_{wrm}(z, t)_i = \sum_{k=1}^{N} [T_I^{-1}]_{ik} I_{wr}(z, t)_k \tag{15}$$

Simulation results

In this section, we analyze the simulation results obtained by the proposed hybrid approach. First, we analyze the radiated susceptibility of coaxial cables, followed by the radiated susceptibility of coaxial cables in the presence of a trough and an automobile.

Analysis of the radiated susceptibility of coaxial cables

Figure 4 shows the configuration of the radiated susceptibility analyzed to study the validity of the hybrid MoM circuit models method. The configuration consists of a coaxial shielded cable, which consists of an inner solid wire ($R_w = 5$ mm) and a shield with an interior radius R_S of 2.5 mm, over a perfectly conducting ground. The line length is 1 m, and the conductors are suspended 5 m above a ground plane. The relative permittivity ε_r of the inner insulation equals 2.375.

The constant PUL transfer resistance R_T and the transfer inductance L_T are 100 $m\Omega$/m and 0.5 nH/m, respectively. The shield is grounded at both ends with terminations impedances

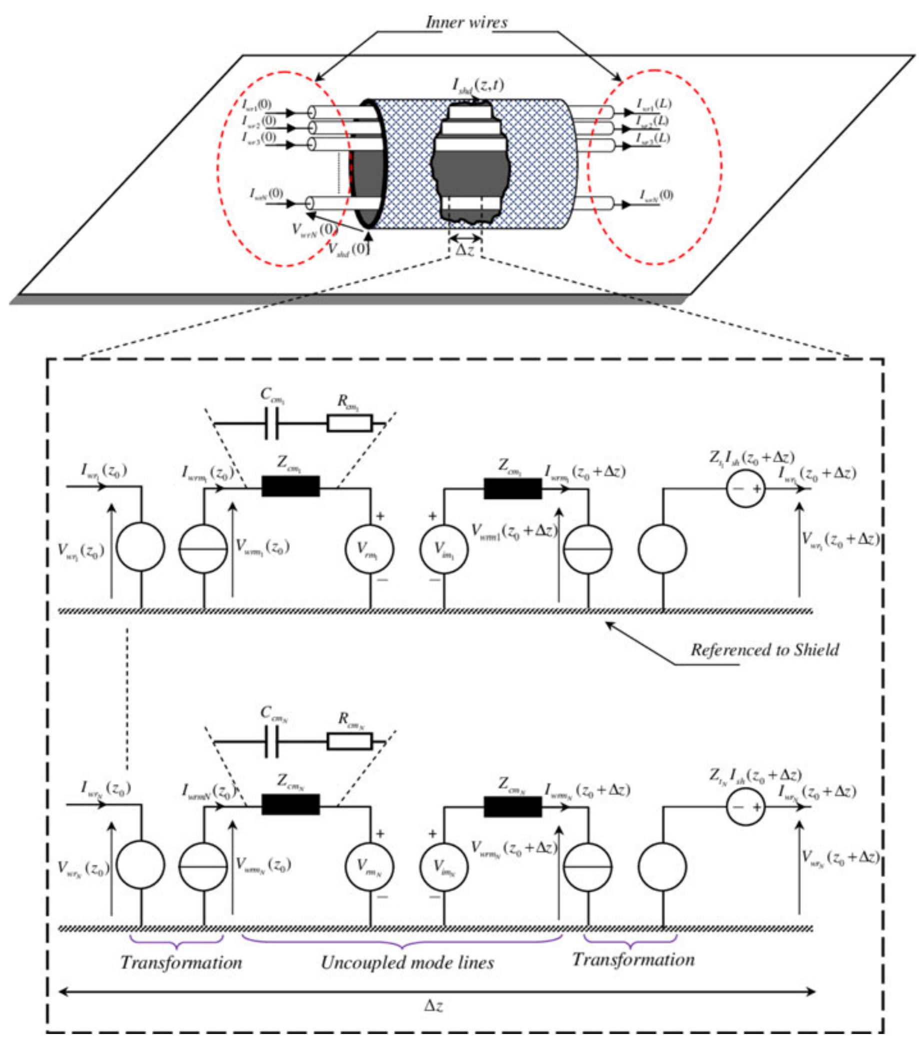

Fig. 3. Equivalent circuit of inner wires obtained from the method of characteristics (Branin's method) [18] as implemented in ESACAP [22].

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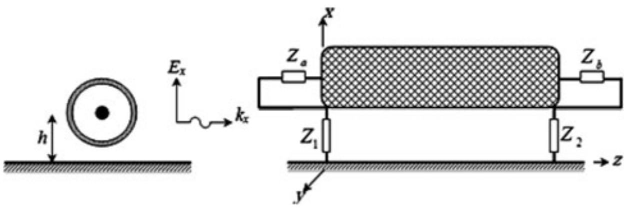

Fig. 4. Coaxial shielded cable over a perfectly conducting ground.

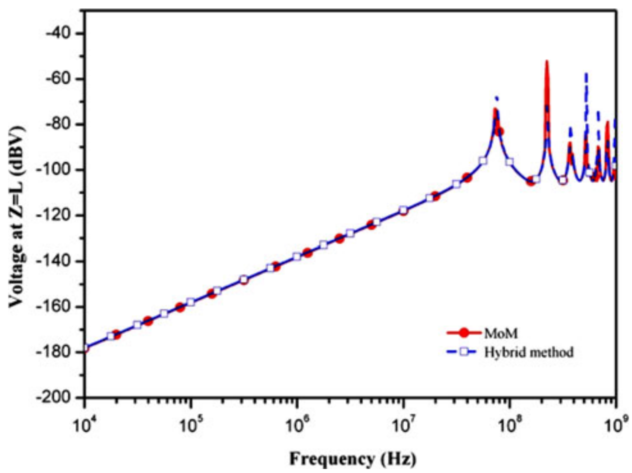

Fig. 5. Wire to shield voltage of the coaxial cable at the far end.

$R_{sh1} = 1\ \mathrm{M\Omega}$ and $R_{sh2} = 154.365\Omega$, while the inner terminations are matched: $R_{w1} = R_{w2} = 50\Omega$. The coaxial cable is excited by an incident plane wave oriented along the x axis of amplitude $\mathrm{E} = 1\mathrm{V/m}$ and propagating along z axis ($E_x - k_z$).

Figure 5 illustrates the amplitude evolution of the wire-to-shield voltage at the far end as a function of frequency, which is obtained by the proposed hybrid method, together with the outcomes determined by the MoM. The results obtained by our method are in excellent agreement with those obtained by the MoM method, which confirms the validity of the proposed hybrid method approach.

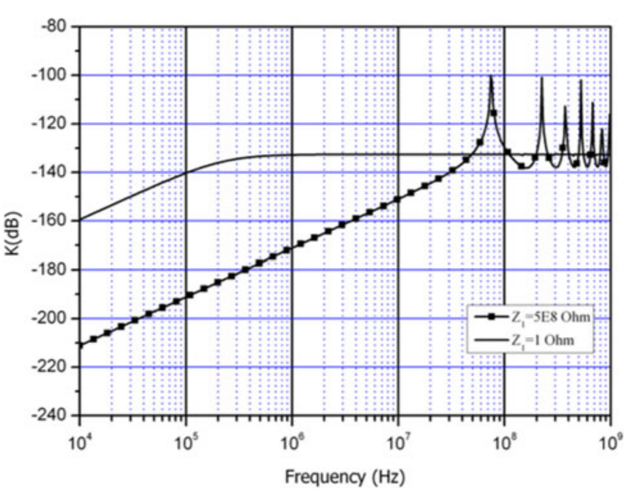

Fig. 6. Result of the induced current in dBA, on shielded cable excited by uniform Ex-Kz, computed with ESACAP.

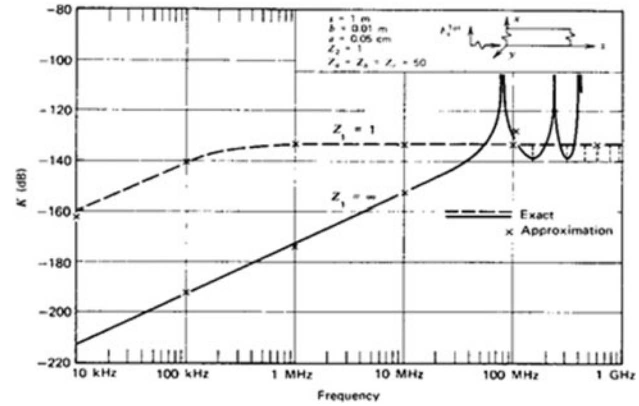

Fig. 7. Solution for the induced current on shielded cable excited by uniform Ex-Kz [27].

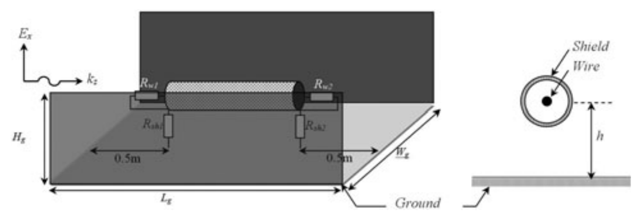

Fig. 8. Coaxial shielded cable in the vicinity of a trough excited by an external plane wave field.

The two curves depicted in this figure have two characteristic parts corresponding to the low frequency domain (assumption of short lines: length < <λ wavelength) and high frequencies (long line). In the first part of the curves, the voltages are proportional to the transfer impedance Z_t [28]. The second part is characterized by anti-resonances specific to the propagation phenomenon.

The shielding is short-circuited on the right ($Z_2 = 0.5\Omega$). Figure 6 illustrates the induced current in dBA on shielded cables excited by uniform Ex-Kz, which is obtained by the hybrid model. Comparing these with the analytical results published by Smith [27] shown in Fig. 7 shows exact agreement between the results of the hybrid and analytic methods.

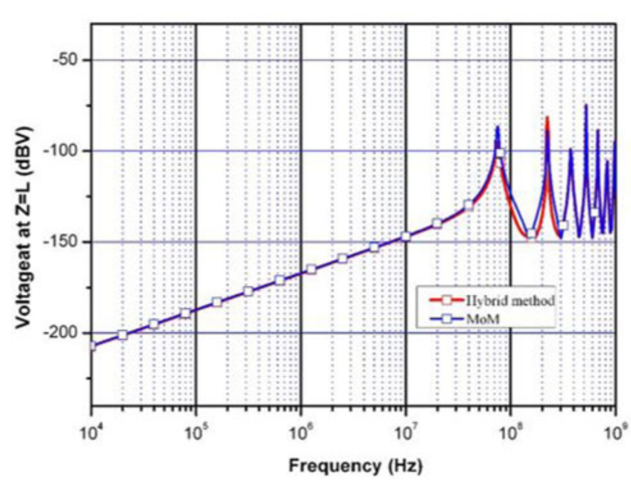

Fig. 9. Wire-to-shield voltage of the coaxial cable at the far end.

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Table 1. Needed time by the hybrid method and MoM

Methods	Hybrid MoM-circuit model	MoM
The cost time	5 m 5 s	14 m 44 s

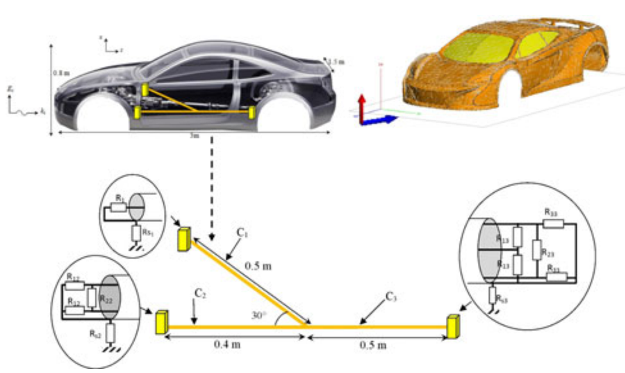


Fig. 10. Three shielded cables within a car excited by an external plane wave field.

Analysis of the radiated susceptibility of coaxial cable in the presence of a trough

To validate the proposed hybrid method in complex structures, we consider a coaxial shielded cable similar to that depicted in Fig. 4 in the presence of a trough. The length L_g, width W_g, and height H_g of the trough are 2, 0.2, and 0.2 m, respectively, as shown in Fig. 8. The entire structure is excited by an incident plane wave oriented along the x-axis and propagated along the z-axis ($E_x - k_z$) with an amplitude of $E = 1$ V/m.

The wire-to-shield voltage at the far end of the coaxial cable obtained by the proposed approach is given in Fig. 9. The results obtained by our method are in excellent accord with those obtained by the MoM method, which validates the use of the hybrid method in complex structures.

Table 1 compares the computing time needed in the two methods. This shows that the MoM method requires significantly more computing time, than the hybrid method. Because the inner wires must not mesh while computing the shields currents, they are not meshed when using the hybrid method.

Table 3. Electrical parameters of lines configuration shown in Fig. 8

Terminal network resistance of C_1	R_1 = 88.77 Ω; R_{S1} = 0.5 Ω
Terminal network resistance of C_2	R_{12} = 61Ω; R_{22} = 176Ω; R_{S2} = 0.5ω
Terminal network resistance of C_3	R_{13} = 41Ω; R_{23} = 23Ω; R_{33} = 154.7Ω; R_{S3} = 1GΩ
Transfer impedance of C_1	R_{T1} = 10 mΩ/m L_{T1} = 1.3 nH/m
Transfer impedance of C_2	R_{T1} = 10 mΩ/m L_{T1} = 1.3 nH/m
	R_{T2} = 10 mΩ/m L_{T1} = 1.2 nH/m
Transfer impedance of C_3	R_{T1} = 10 mΩ/m L_{T1} = 1.2 nH/m
	R_{T2} = 10 mΩ/m L_{T2} = 1.3 nH/m
	R_{T3} = 10 mΩ/m L_{T3} = 1.2 nH/m

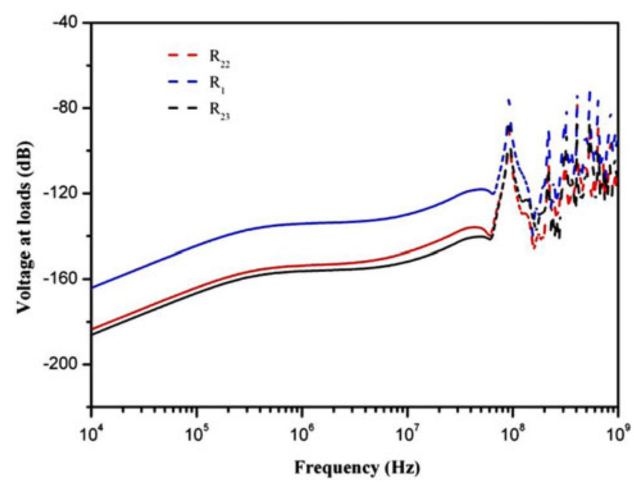
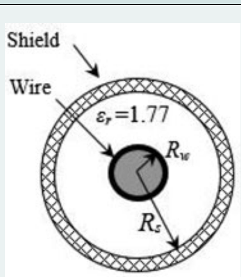
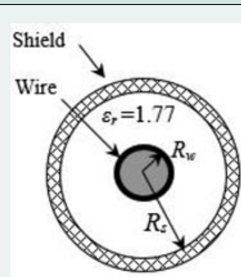
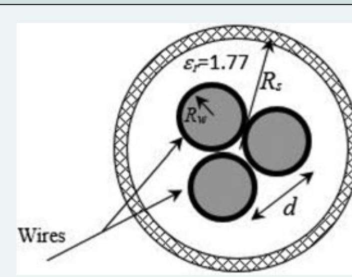


Fig. 11. Three shielded cables within a car excited by an external plane wave field.

Analysis of the radiated susceptibility of coaxial cables in the presence of an automobile

Figure 10 shows that the complex wiring inside a car, illuminated by an incident plane wave oriented along the x-axis and propagated along the z-axis ($E_x - k_z$), has an amplitude of E = 1 V/m. The wiring consists of three shielded cables: C_1, a coaxial cable; C_2, shielded

Table 2. Parameters of shielded cables

Shielded coaxial cable	Shielded twinax cable	Shielded triax cable
		
R_s = 1.5 mm	R_s = 2.5 mm	R_s = 2.5 mm
R_w = 0.25 mm	R_w = 0.25 mm	R_w = 0.25 mm
	d = 3 mm	d = 3 mm

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cables with two parallel wires (i.e. twinax cable); and C_3, shielded cables with three parallel wires (i.e. triaxial cable).

The lengths of shielded cables C_1, C_2, and C_3 are $L_{C1} = 0.5$ m, $L_{C2} = 0.4$ m, and $L_{C3} = 0.5$ m respectively. All the cables have the same height, $h = 5$ mm. The characteristics of the shielded cables can be defined in terms of the shield radius R_s, the inner wire radius R_w, and the interval between wires d (the values of which are reported in Table 2). The transfer impedances and load networks with the adopted values are given in Table 3.

The voltages calculated using the proposed method at the far end in the frequency analysis are illustrated in Fig. 11. It can be observed that the lines resonate at $f = n \times (3 \times 10^8\ 4/\lambda)$, $n = 1,\ 3,\ 5$ ($f1 = 75$ MHz, $f2 = 225$ MHz, and $f3 = 375$ MHz). The magnitudes of these induced voltages can reach − 70 V.

Conclusion

This paper presented a hybrid MoM circuit model of the analysis of the radiated susceptibility for lossy multiconductor shielded cables. The advantage of this method is its applicability for nonuniform transmission lines with nonlinear loads. The proposed hybrid method also requires a much smaller amount of computation time than other numerical methods. This paper has described the proposed technique in detail. The method's validity was confirmed by comparing its results with those derived by other methods. It is easy to extend the proposed models to multiconductor shield cables within a complex structure excited by a non-uniform incident wave (e.g. antennas). We will discuss this question in future papers.

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