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New approaches in Electromagnetic Compatibility / Nouvelles approches en Compatibilité Electromagnétique

A reduction modeling method to assess the electromagnetic emission of multiconductor transmission lines

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Abstract

This article deals with the extension of the so-called "equivalent cable-bundle method" to assess the electromagnetic emission of a cable-bundle. As in the immunity case, the purpose of the method is to reduce the complexity of a reference cable-bundle by creating a "reduced cable-bundle" composed of a limited number of "equivalent conductors". The significant reduction of the thereby obtained model makes possible its introduction in 3D models without any real increase of their size. ***To cite this article: G. Andrieu et al., C. R. Physique 10 (2009).***

Résumé

Méthode de réduction pour l'évaluation de l'émission électromagnétique de lignes de transmission multiconducteurs. Cet article traite de l'extension de la méthode dite du « faisceau équivalent » pour le calcul de l'émission électromagnétique d'un faisceau de câbles. Comme dans le cas de l'immunité, l'objectif de la méthode est de réduire la complexité d'un faisceau de référence en créant un faisceau « réduit » composé d'un nombre limité de « conducteurs équivalents ». La prise en compte du faisceau réduit dans la simulation à la place du faisceau de référence entraîne une diminution importante des ressources informatiques nécessaires. ***Pour citer cet article : G. Andrieu et al., C. R. Physique 10 (2009).***

Keywords: Cable-bundle; Electromagnetic emission; Numerical modeling; Method of moments

Mots-clés : Faisceau de câbles ; Émission électromagnétique ; Modélisation numérique ; Méthode des moments

1. Introduction

In the context of Electromagnetic Compatibility (EMC), the "equivalent cable-bundle method" [1] has been developed for high frequency modeling of complex cable-bundles in electromagnetic (EM) immunity problems (when

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Table 1
Conductor classification table.

	Extremity 1	Extremity 2
Group 1	$Z_1 < Z_{mc}$	$Z_2 < Z_{mc}$
Group 2	$Z_1 < Z_{mc}$	$Z_2 > Z_{mc}$
Group 3	$Z_1 > Z_{mc}$	$Z_2 < Z_{mc}$
Group 4	$Z_1 > Z_{mc}$	$Z_2 > Z_{mc}$

an EM wave illuminates the cable). First developed throughout several previous works [2,3], this method allows the calculation of the common mode current induced at the ends of a cable-bundle by taking into account a "reduced" cable-bundle model made of a limited number of equivalent conductors. The reduction of the complexity of the cable induces a large decrease of the computer needs which makes possible the introduction of the cable models within a 3D code solving rigorously the Maxwell's equations at "high frequencies" (for which the full modeling of the reference cable-bundle would be impossible). To extend this method to the EM emission of a complex cable-bundle problem, the method requires some theoretical adjustments. Indeed, in EM emission problems, all the conductors can possibly be excited by voltage sources of various magnitudes and impedances.

In this paper, we first present the theoretical adjustments required for the application of the method in an emission problem and second the numerical validations performed on a simple point-to-point cable-link. In EM emission problems, the main hypothesis consists in considering that the EM emission of a cable-bundle mainly comes from the common mode current developed by all the conductors and not from the differential mode currents.

2. Equivalent cable-bundle method used in EM emission problems

As already mentioned, the main objective of the equivalent cable-bundle method, initially developed for immunity problems, is to reduce the complexity of the model of a complete multiconductor cable-bundle by creating a reduced cable-bundle model instead of the full model of the reference cable. When extended to the emission case, by using the multiconductor transmission line (MTL) formalism and making reasonable assumptions, the electrical and geometrical characteristics of the reduced cable-bundle can be defined thanks to a five-step-procedure presented in the following. Compared to the immunity case [1], the procedure requires one additional step. Indeed, in EM emission problems, each conductor of the cable-bundle is likely to carry its proper source of functional signal. Thus, the magnitude of the voltage source and its impedance can theoretically be different on each conductor. This difference, fundamental compared to the immunity case, introduces a second degree of freedom for the creation of the groups of conductors and a supplementary step to determine the equivalent voltage sources.

2.1. Step 1: Creation of groups of conductors

The first step of the procedure consists in sorting all the conductors of the reference cable-bundle in groups with respect to the loads and to the voltage sources at the ends of each conductor.

First, all the conductors of the reference cable-bundle are sorted into 4 different groups described in Table 1, thanks to the comparison of both wire-end loads of each conductor (Z_1 and Z_2 considered as real loads) to the reference cable-bundle common mode characteristic impedance Z_{mc} which is determined by from the modal decomposition of the MTL formalism.

Second, inside the four groups previously made, a new classification is made according to the magnitude of the voltage source applied on each conductor. Thus, after analyzing a large number of numerical results obtained on cable-bundles containing between 5 and 10 conductors, we finally came to the following empirical rule: the ratio of the voltage source magnitude applied on two conductors belonging to the same group must not be larger than a factor 3. If this condition is not respected, a non-negligible degradation of the results is observed. To explain this result, we make the assumption that the strong contrast of the voltage source magnitude originates important differential mode currents creating significant EM emission not taken into account when grouping the conductors in the model.

2.2. Step 2: Reduced cable-bundle matrices

The second step of the procedure consists in determining the per-unit-length inductance $[L_{\text{reduced}}]$ and capacity $[C_{\text{reduced}}]$ matrices of the reduced cable-bundle according to the MTL formalism. The general matrix system of a cable-bundle containing N conductors can be written under the following form in the MTL formalism:

$$\frac{\partial}{\partial z}[I]_N = -j\omega[C]_{N\times N}[V]_N \tag{1}$$

$$\frac{\partial}{\partial z}[V]_N = -j\omega[L]_{N\times N}[I]_N \tag{2}$$

where $[I]$ and $[V]$ respectively correspond to the current and voltage matrices of the N-conductor cable.

To determine the inductance $[L_{\text{reduced}}]$ and capacity $[C_{\text{reduced}}]$ matrices of the reduced cable-bundle, the method requires some hypothesis.

First, for each group of conductors, a group-current and a group-voltage are defined. The group-current equals the sum of the currents in all the conductors of the group. The group-voltage is defined by considering that all the conductors of a group have the same electric potential with respect to the ground reference as if all the wires of the group were short-circuited together (but not to the ground).

Second, as it has been explained in the introduction, the method assumes that the EM emissions of a cable-bundle mainly comes from the common mode current. Thus, the differential mode currents are neglected. This assumption involves that an identical current flows along each conductor belonging to the same group.

By applying these hypotheses and after some simple calculations, we obtain the following reduced matrix system corresponding to a reduced cable-bundle model now containing M equivalent conductors.

$$\frac{\partial}{\partial x}[I_{\text{EC}i}]_{M\times 1} = -j\omega[C_{\text{reduced}}]_{M\times M}[V_{\text{EC}i}]_{M\times 1} \tag{3}$$

$$\frac{\partial}{\partial x}[V_{\text{EC}i}]_{M\times 1} = -j\omega[L_{\text{reduced}}]_{M\times M}[I_{\text{EC}i}]_{M\times 1} \tag{4}$$

where $[I_{\text{CE}}]$ and $[V_{\text{CE}}]$ respectively correspond to the current and voltage matrices of the M-equivalent-conductor cable model.

The reader can note that the size of the reduced matrix system equals the number of groups identified in the first step of the method.

2.3. Step 3: Reduced cable-bundle cross-section geometry

The third step of the procedure consists in determining an appropriate cross-section geometry of the reduced cable-bundle from which per-unit-length inductance and capacity matrices determined by an electrostatic code correctly have to match the $[L_{\text{reduced}}]$ and $[C_{\text{reduced}}]$ matrices obtained at the previous step. The optimization process is decomposed in 6 phases described in the following.

- Phase 1: Estimation of the height h_i above the ground reference of each equivalent conductor by the average of the height of all the conductors of the group.
- Phase 2: Estimation of the radius r_i of each equivalent conductor according to the classical analytical formula (5) which gives the inductance of a wire located above an infinite ground plane:

$$r_i = \frac{2h_i}{\exp(2\pi L_{ii\_\text{reduced}}/\mu_0)} \tag{5}$$

- Phase 3: Estimation of the distances d_{ij} between all equivalent conductors according to the classical analytical formula (6) which gives the mutual inductance of two wires i and j located above an infinite ground plane and separated by a distance d_{ij}:

$$d_{ij} = \sqrt{\frac{4h_i h_j}{\exp(4\pi L_{ij\_\text{reduced}}/\mu_0) - 1}} \tag{6}$$

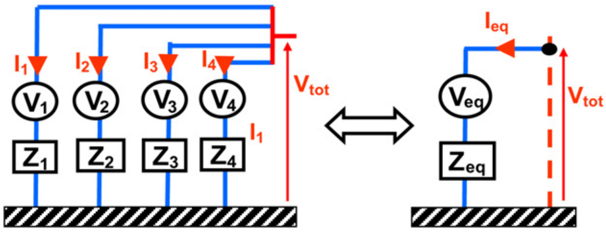

Fig. 1. Termination loads and voltage source network of a 4-conductors configuration and of the corresponding equivalent conductor.

We have to note that even if (5) and (6) are approximate formulas, they still provide good first estimates of the diagonal and off-diagonal inductance terms. In addition, they present the advantage that each term of the matrix can be determined independently of the others.

- Phase 4: Adjustment of the h_i, r_i and d_{ij} parameters determined in the first three phases using a dichotomy optimization realized with exact electrostatic calculations. This phase allows a reduction of the errors involved by using (5) and (6).
- Phase 5: Determination of the thickness of the dielectric coating surrounding each equivalent conductor while avoiding any dielectric coating overlapping.
- Phase 6: Calculation and optimization of the relative permittivity ε_r of the dielectric coating of each equivalent conductor in accordance with the $[C_{\text{reduced}}]$ matrix using an electrostatic calculation.

2.4. *Step 4: Reduced cable-bundle equivalent termination loads*

In the fourth step of the procedure, the termination loads to apply at the ends of all the equivalent conductors are defined by analyzing the termination loads of the reference cable-bundle. At this level, three kinds of termination loads have to be distinguished:

– Case 1: Common-mode loads (which connect conductor ends to the ground reference): the termination load to apply at the end of an equivalent conductor is equal to the loads of all the conductors of the group connected in parallel at the same end.
– Case 2: Differential loads which connect together two conductors belonging to the same group: these kinds of loads are neglected in the model because their effect on the group current is null when we apply the approximations of the method.
– Case 3: Differential loads which connect together two conductors belonging to different groups: in order to define the equivalent load placed between the two equivalent conductors is made by all the loads which link two conductors belonging the two different groups set in parallel.

2.5. *Step 5: Calculation of equivalent voltage sources*

The fifth and last step consists in the determination of the magnitude of the voltage source to apply on each equivalent conductor of the reduced cable harness. Fig. 1 presents the termination networks of a 4-conductor group and the equivalent voltage and equivalent impedance to apply to the corresponding equivalent conductor:

The current I_i of one conductor i belonging to the 4-conductor group can be written in the following form:

$$I_i = \frac{V_{\text{tot}} - V_i}{Z_i} \tag{7}$$

The current I_{eq} on the corresponding equivalent conductor is:

$$I_{\text{eq}} = \frac{V_{\text{tot}} - V_{\text{eq}}}{Z_{\text{eq}}} \tag{8}$$

in which the equivalent termination load Z_{eq} is equal to all the termination loads set in parallel:

$$Z_{\text{eq}} = Z_1 // Z_2 // Z_3 // Z_4 \tag{9}$$

Table 2
Loads and sources applied on each conductor of the reference cable-bundle.

Conductors	Loads		Voltage sources
	End 1 (Ω)	End 2 (Ω)	End 1 (V)
1	24	50	1
2	10	22	3
3	59	38	15
4	63	16	30

Table 3
Loads and sources applied on each equivalent conductor of the reduced cable-bundle.

Equivalent conductor	Loads		Voltage sources
	End 1 (Ω)	End 2 (Ω)	End 1 V
1	24	50	2.4
2	7.5	7.4	22.2

By using (7) and (8), the current of the 4-conductor group which is the sum of the currents of all the conductors of the group can be written as:

$$I_{\mathrm{eq}} = \frac{V_{\mathrm{tot}}}{Z_{\mathrm{eq}}} - \left(\frac{V_1}{Z_1} + \frac{V_2}{Z_2} + \frac{V_3}{Z_3} + \frac{V_4}{Z_4}\right) \tag{10}$$

Consequently, using (8) and (10), the equivalent source voltage V_{eq} can be written in the following form:

$$V_{\mathrm{eq}} = (Z_{\mathrm{eq}})\left(\frac{V_1}{Z_1} + \frac{V_2}{Z_2} + \frac{V_3}{Z_3} + \frac{V_4}{Z_4}\right) \tag{11}$$

These formulas assume that the same waveform (sine wave with different magnitudes) is injected in the frequency domain on the same end of all the groups of conductors. We have to precise that additional tests have shown this phase shift applied on various conductors is not a problem for the method as far as constant amplitude are considered over the whole frequency range (shifted sine waves in time domain).

3. Numerical validation

3.1. Reference and reduced cable-bundle descriptions

For this numerical validation, we have used a reference cable-bundle containing 4 conductors with a radius of 1 mm. This cable-bundle has a length of 1 m and a height of 2 cm compared to an infinite and perfectly conductor ground reference. Each end of the cable is connected to a square metallic bracket (5×5 cm^2).

The termination loads and the voltage sources applied on each conductor of the cable-bundle are contained in Table 2.

All the termination loads of this cable-bundle are lower than the cable-bundle common mode characteristic impedance ($Z_{\mathrm{mc}} = 160\ \Omega$). Thus, in an immunity problem, only one equivalent conductor would be required in the reduced model. However, due to the strong contrast on the magnitude of the voltage sources applied on each conductor, two equivalent conductors are required for the emission problem (the first group contains conductors 1 and 2 and the second group conductors 3 and 4). The termination loads and the voltage source to apply on each equivalent conductor of the reduced cable-bundle are listed in Table 3.

3.2. Results

All the numerical results presented in this paper have been obtained by using the FEKO [4] software which solves the Maxwell equations by using the method of moments (MoM) [5]. Fig. 2 presents a picture of the 3D modeling of the reference cable-bundle according to the $\{x, y, z\}$ Cartesian coordinate system:

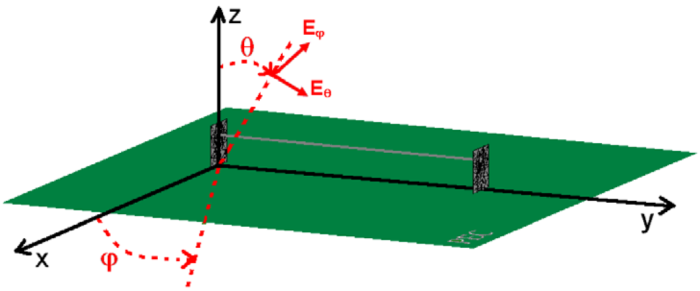

Fig. 2. 3D model of the reference cable-bundle used in the MoM calculation.

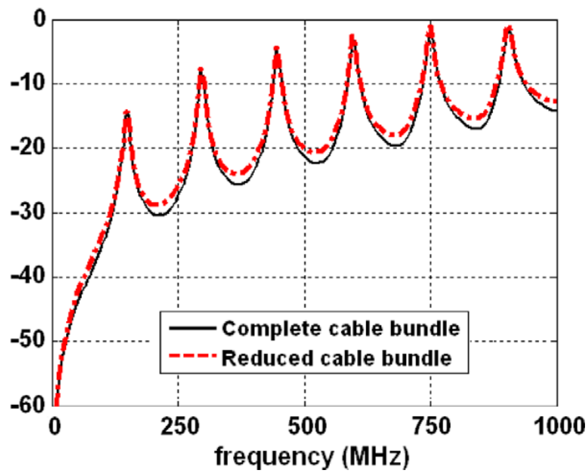

Fig. 3. Total radiated power (in dBm) of both cable-bundle models.

Three complementary numerical validations have been performed on this numerical example to entirely validate the method.

First, the total radiated power of both cable-bundle models (reference and reduced) have been calculated (Fig. 3) in the 1 MHz–1 GHz frequency range. The total radiated power is computed by making the integration of the Poynting vector on the upper-half sphere over the cable.

This first numerical validation shows a quite good agreement between both curves and leads to the conclusion that the method is suited for estimating the total EM radiation of a cable over a ground plane.

Second, the EM radiated diagram of both cable-bundles in the planes $\varphi = 0°$ and $\varphi = 90°$ at the frequency of 1 GHz has been calculated (Fig. 4).

Fig. 4 shows that the electrical far field calculated on both cable-bundles is very close. Thus, the reduction of the cable-bundle complexity induced by the method does not affect the far field radiation.

Third, the modulus of the total electric field radiated by both reference and reduced cable-bundles at test-point $x = 0.5$ m, $y = 0.25$ m and $z = 0.3$ m has been calculated (Fig. 5). The observation point is located at 0.37 m from the closest point of the cable and can therefore be considered in the near field of the cable-bundle.

The agreement between both curves is also very encouraging. This third numerical validation proves on this simple numerical example that the simplified geometry of the reduced model does not affect the accuracy of the field calculation even in the near field region of the cable.

To conclude, all these numerical simulations performed on a simple cable-bundle configuration validate the method in the case of emission problems. Thus, the EM radiation can be determined by a reduced cable-bundle model whatever the position of the test-point is in space.

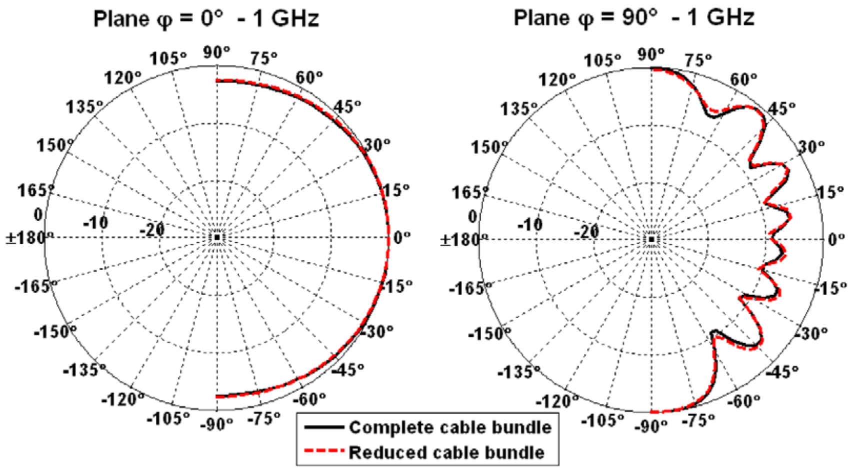

Fig. 4. EM radiation diagram of both cable-bundle models in the planes $\varphi = 0°$ and $\varphi = 90°$ at 1 GHz.

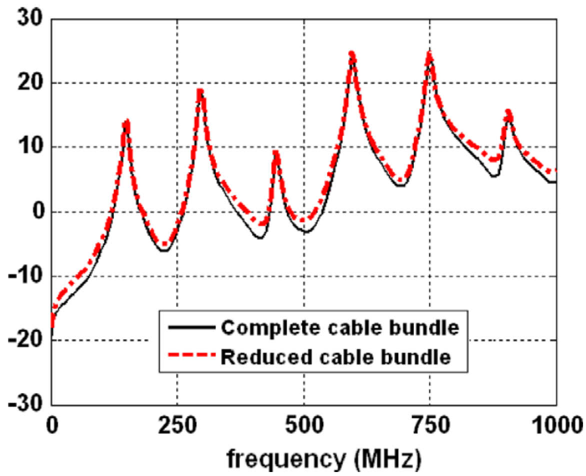

Fig. 5. Electrical field (in dBV/m) emitted by both cable-bundle models at test-point $x = 0.5$ m, $y = 0.25$ m and $z = 0.3$ m.

Table 4
Comparison of the computer needs.

	Reference cable-bundle	Reduced cable-bundle
Total computation time	963 s	385 s
Required memory space	882 Mb	329 Mb

3.3. Reduction of the computer needs

The main objective of the method being to reduce the computer needs required in order to be able to introduce the cable-bundle in a more general 3D model, we compare in Table 4 the total computation time and the memory space required for the MoM modeling of both cable-bundle models on 201 frequency calculation points between 1 MHz and 1 GHz.

Table 4 shows the interest of the method on this simple numerical example: the total computation time and the memory are both divided by a factor 2.5 when using the reduced cable-bundle model. Moreover, the reduction of the computer needs would be larger by using a reference cable-bundle containing more conductors.

Moreover, as in immunity problems, the method can also be used at “low frequencies” by computing the current flowing along the conductors of the reduced cable-bundle thanks to the MTL formalism and simple algorithms can then be used to compute the EM radiation due to the current distribution in ground plane configurations. Thus, the reduction of computation times, negligible on a simple cable-bundle due to the limited computation needs of the MTL, are likely to become significant on very complex cable-bundles such as the ones encountered on real systems.

4. Conclusion

This paper has presented the application of the so-called "equivalent cable-bundle method" [1] to assess the EM radiation of complex cable-bundles on a large frequency range. The method offers a reduction of the complexity of the cable-bundle models by defining a reduced cable-bundle composed of a limited number of equivalent conductors. In the reduced model, the conductors of the reference cable-bundle are grouped together according to their termination loads and the magnitude of the voltage sources applied on them in order to constitute the equivalent conductors of the reduced model. Then the reduced cable-bundle can be used in any type of 3D or MTL modeling instead of the reference cable. The method has been validated numerically on a simple point-to-point cable-link and is ready for being applied in industrial EMC modeling problems involving complex cable-bundles both for EM immunity [1] and emission purposes.

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