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GEOMETRICAL REPRESENTATION AND TRANSMISSION LINE MODELING OF COMPLEX WIRING HARNESSES WITH DIVERSIFIED CONDUCTORS

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ABSTRACT

In this work, geometrical modelling of random wire bundles involving conductors with different geometrical characteristics is addressed. To this end, a polynomial representation is adopted for modelling wire trajectories, whose initial positions are generated by a discrete algorithm based on Graph Theory. An iterative approach is used to generate the proper polynomial functions that satisfy physical constraints. The possibility that the involved wires have different radii is taken into account both in the generation of the initial cross-sections and in the design of an *ad-hoc* anti-overlapping algorithm. Eventually, crosstalk and radiated susceptibility of the generated bundle geometries are investigated by resorting to two different approaches, i.e., transmission line (TL) theory and full-wave solution. Comparison of the obtained results proves the effectiveness and prediction accuracy of the TL-based solution.

1. INTRODUCTION

Complex hand-assembled wiring harnesses are widely exploited in several industrial sectors including aerospace systems [1]-[3] (e.g., Electrical Wiring Interconnection Systems of aircrafts). Such wiring structures are bundles of wires and cables with non-uniform structure (owing to random fluctuations of the conductor trajectories along the bundle longitudinal axis) and electrically long length [4]. This makes the prediction of their performance in terms of electromagnetic compatibility (EMC) as well as the design of proper noise-mitigation strategies challenging tasks for EMC engineers.

To achieve these goals, the preliminary step is to develop suitable geometrical models for the wire bundles, with the conductor trajectories satisfying certain fundamental constraints (e.g., *continuity*, *non-overlap*, and *compactness*, [4]) and retaining realistic shapes. To this end, several methods [4]-[12] have been proposed over the last two decades, based on the assumption that the bundle axis runs approximately parallel to ground while the wires change their relative positions w.r.t. the bundle axis.

These models can be roughly grouped into two categories: a) those resorting to a pre-defined reference cross-section [7], [9], [10], where the conductors can only move across a set of assigned positions within the reference cross-section, and b) those allowing intermediate transitions along the bundle axis [4]-[6], [8], [11], [12]. The methods belonging to the first group offer significant advantages in terms of evaluation of the relevant per-unit-length (p.u.l.) parameter matrices, which can be computed once and for all for the reference cross-section (for instance, through the method of moments [13]), and then re-mapped through suitable transformations. However, the transitions between adjacent sections of the bundle may involve discontinuities as large as the conductor diameter, and this reflects into spurious resonances in the frequency response predicted for the voltages/currents induced at the bundle ends by field-to-wire coupling and/or crosstalk.

The second group of methods has the potential to better represent the conductors' trajectories, since it allows a continuous changing in conductor allocation in the reference cross-sectional plane. In this case, however, the p.u.l. parameter matrices need to be evaluated sequentially (after proper discretization along bundle axis) and this requires an increased computational burden, which anyway does not significantly affect the overall simulation time, especially if a parallel computing approach is adopted. However, most of the methods so far available in the literature do not assure that the wires in the bundle do not overlap (e.g., [8], which considers local instead of global non-overlapping constraints) and/or are tightly packed (e.g., [11], where the wires are far separated) along the whole bundle length.

To overcome the previous limitations, thus providing a realistic description of hand-assembled random wire bundles, a modelling method resorting to continuous polynomial description of wire trajectories has been recently developed in [4]. This method resorts to the approach proposed in [10] to generate reference cross-sections at given positions, as well as to assure minimum-distance wire movements between two adjacent bundle segments. Afterwards, an iterative method is used to interpolate wire path coordinates by high-order polynomial functions and to prevent wire overlapping. This polynomial representation is further extended to handle more complex and realistic wire bundles, e.g., bundles with vertical/horizontal variations, bundles of twisted-wire pairs (TWPs), [12], [14], etc. Despite the achieved effectiveness and flexibility, the implementations so far proposed exploit the underlying assumption that the involved conductors (wires or TWPs) in the bundle have the same outer radius. This assumption is not always verified in practical bundles, where conductors with different geometrical properties (and functions) are often packed together to save space.

This work attempts at overcoming the aforesaid limitation. For the sake of simplicity, hereinafter the term wire is used to denote a conductor in the bundle, and a circular cross-section is assigned to it. Here conductors can be individual wires or more complex wiring structures (such as TWPs, shielded cables or wire bundles). To achieve this goal, the continuous polynomial representation of wire trajectories adopted in [4] is here considered as the starting point, but it is combined with a new formulation of the *compactness* constraint along with a suitable anti-overlapping algorithm. Once the bundle geometry will be created, it will be combined with an efficient prediction technique based on transmission-line (TL) theory [15] to investigate the EMC performance of the harness. The obtained results will be compared versus those from full-wave simulation (taken as the reference solution), where the proposed geometrical model can be easily imported thanks to built-in analytical curve functionalities. In spite of the increased complexity of the wiring harness, the good agreement of the TL-based predictions with full-wave simulation confirms the effectiveness of the proposed modeling approach in terms of generality, accuracy, and computational time.

2. BUNDLE GENERATION

The physical constraints of the wire trajectories in [4] are here adapted to take into account for the presence of wires with different radii. With reference to the coordinate system in Fig. 1, the *non-overlapping* constraint is revised to allow for different wire radii of nearby wires, as

$$r_i + r_j < d_{ij}(z), \; i, j = 1, \ldots, N; \; i < j \tag{1}$$

where r_i, r_j are the external radii of wires i, j, respectively; d_{ij} is the pair-wise distance between the centers of wire i and wire j, which can be analytically calculated according to (1) in [4]; N is the number of wires inside the bundle.

Besides, the *compactness* constraint in [4] is revised to allow for the generation of densely packed bundles, in spite of the presence of wires with different radii. The new constraint is cast as:

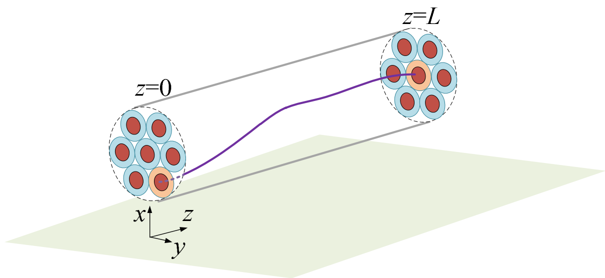

Figure 1. Illustration of a wire bundle and reference coordinate system.

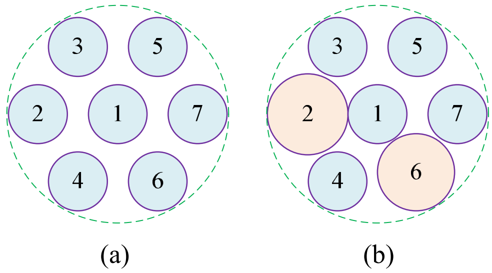

Figure 2. Examples of initial cross-section for a wire bundle. (a): Equal wire radii. (b): Different wire radii.

$$\sqrt{\left[x_i(z) - h\right]^2 + y_i^2} + r_i \le r_0 \tag{2}$$

where (x_i, y_i) are the wire coordinates in the transverse (x, y) plane, z is the longitudinal axis, h is the bundle height, and r_0 is the maximum radius of the circular contour hosting all the N wires in the bundle.

As a starting point to generate the random wire bundles with different wire radii, reference cross-sections should be properly generated along the bundle axis. To this end, the method based on Graph Theory and the concept of *cycle* [4] is used. Unlike in the previous cases [4], [12], where same wire radii were assumed [see Fig. 2(a) for an example of the initial cross-section, i.e., the cross-section at one terminal of the wire bundle], here the possible presence of wires with different radius is considered, leading to a reference cross-section as the one shown in Fig. 2(b). The subsequent cross-sections are generated according to the principle of minimum change. It means that the change in wire position from one given cross-section to an adjacent cross-section can be described by a *cycle*, where movements are limited to positions adjacent to the actual wire position only.

Moreover, an *ad-hoc* anti-overlapping algorithm is designed, which allows enforcing the wire distance to be larger than the summation of the involved wire radii, which can be possibly different. This algorithm is more sophisticated and outperforms the original algorithm proposed in [4]. Indeed, in case of overlapping between two wires, which is more likely to happen in this case due to the presence of different wire radii, the algorithm separates the two overlapping wires by mainly moving

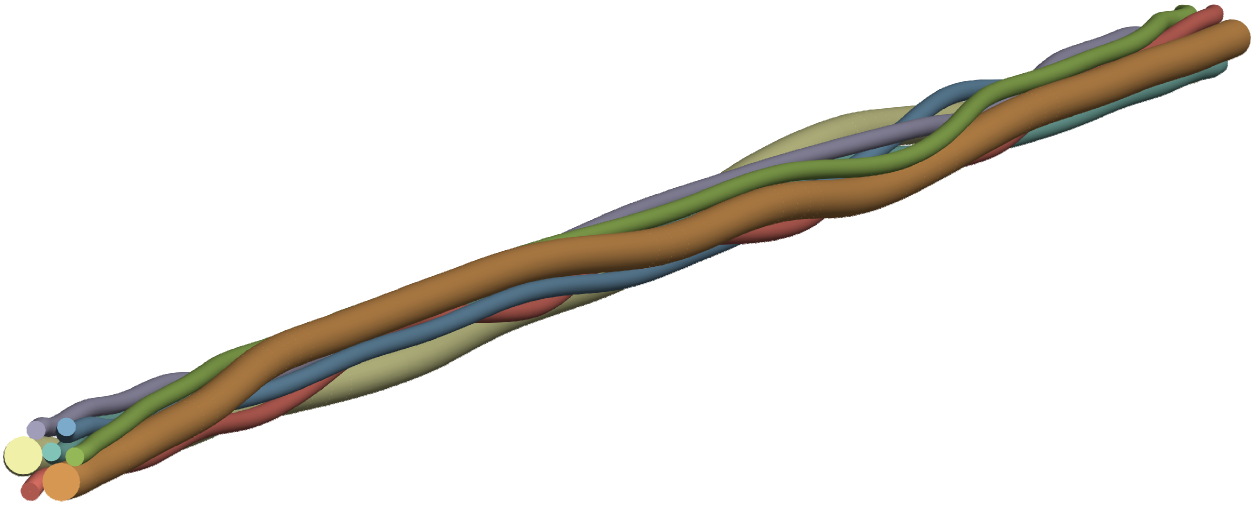

Figure 3. Example of a generated wire bundle with 7 wires and different wire radii.

the smaller wire yet slightly moving the larger wire. This choice is in line with the observation that, in practice, larger wires in a bundle tend to have larger "inertia" and limited movements with respect to smaller wires.

Finally, the bundle with different wire radii and a total axial length of 1 m is generated using the proposed approach, as shown in Fig. 3, where wire #2 and #6 at the initial cross-section have larger radii than the others [see Fig. 2(b)]. This requires a slightly increased generation time w.r.t. the initial case in [4] (where wire radii are uniform) due to increased complexity. The horizontal and vertical coordinates are represented in terms of high-order polynomial functions of the axial position z.

3. VALIDATION EXAMPLES

In this section, examples addressing the prediction of crosstalk and field-to-bundle coupling are presented to show the application of the proposed model in combination with (a) TL-based solution (nonuniform transmission line) and (b) full-wave EM simulation by a commercial solver. For comparison, the voltages induced at the terminations of the bundle under analysis (with 1 m axial length and 5 mm height above the ground) are predicted for the same bundle structure involving wires with different radii.

For the TL-based solution, the structure was discretized into 200 uniform segments equally sampled along the bundle axis, whose p.u.l parameters were evaluated using the MoM-based technique [13]. For full-wave simulation, the polynomial representation of the wire trajectories in three dimensions was imported into a commercial EM solver (Altair FEKO [16]) with the 3-D analytic curve tool, and the voltages and currents induced at the bundle terminations were evaluated. Two test setups, namely, the former to investigate crosstalk, the latter to investigate radiated susceptibility (RS) are considered.

3.1. Crosstalk

For crosstalk prediction, it is assumed that wire #1 [see the initial cross-section in Fig. 2(b)] is driven from the left termination by a voltage source with open-ended voltage amplitude of 1 V. All wires in the bundle are terminated to ground through 150 Ω impedances. For the sake of simplicity, the wires considered in these examples are bare (i.e., the external jacket surrounding the wires is filled in by air) and lossless. However, it is worth noting that these simplifying assumptions do not limit the validity of the proposed approach either for bundle generation or for the TL-based solution here adopted. As a matter of fact, dielectric materials surrounding the wires as well as frequency-dependent effects related to losses (such as skin and proximity effects) can be easily included into the model by suitably evaluating pertinent frequency-dependent p.u.l. parameters.

Predictions of near-end voltages of two wires, i.e., wire #3 (thin wire) and #6 (thick wire), are compared in Fig. 4, where the green curves were obtained by full-wave simulation, and those in dashed red were obtained by TL solution. The good agreement observed up to 2 GHz confirms the effectiveness of the TL solution, despite the strong non-uniformity of the bundle w.r.t. ground (in this example, the distance between the bundle-axis and ground is 5 mm only).

3.2. RS Study

For RS prediction, a uniform plane wave with E-field strength $E_0 = 1$ V/m impinging the bundle with generic incidence and polarization angles is assumed. Without

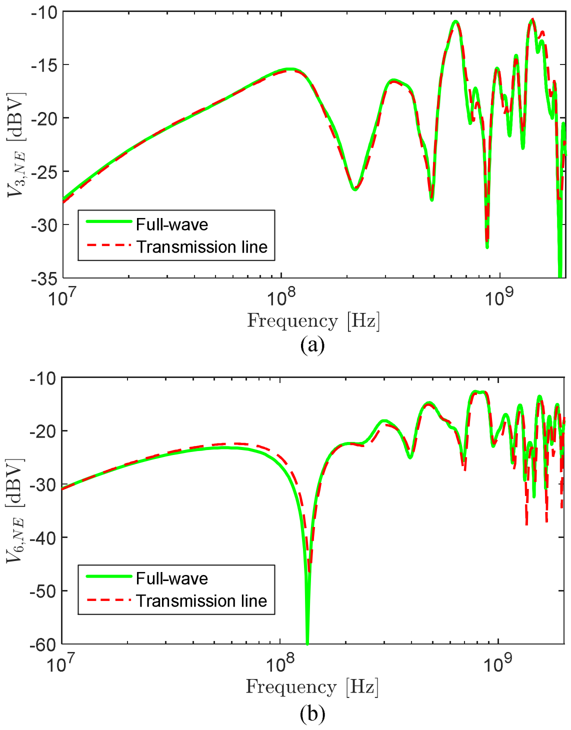

Figure 4. Crosstalk prediction: Voltages induced at the near-end terminations of the (a) thin, and (b) thick wires in the bundle.

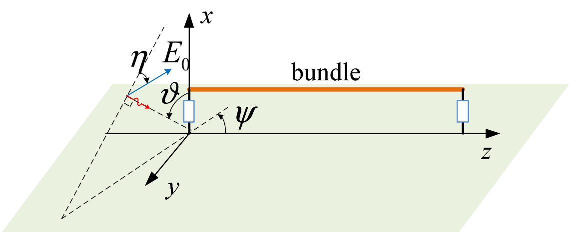

Figure 5. RS setup under analysis.

loss of generality, for the simulation the incidence angles in Fig. 5 were set as: $\vartheta = 50°, \eta = 60°, \psi = 20°$.

The obtained results are compared in Fig. 6. Likewise for crosstalk, also for RS prediction a good agreement is observed between TL-based prediction and full-wave simulation in the entire frequency interval up to 2 GHz.

4. CONCLUSION

In this work, a suitable approach for the generation of hand-assembled random wire bundles involving wires with different radii was presented. The proposed method makes use of analytical curves to represent wire paths along the bundle axis. Moreover, it integrates a set of physical constraints suitably adapted to account for the presence of wires with different radii as well as an *ad-hoc* algorithm, which solves possible overlapping issues by differently perturbing the position of wires with large and small radii.

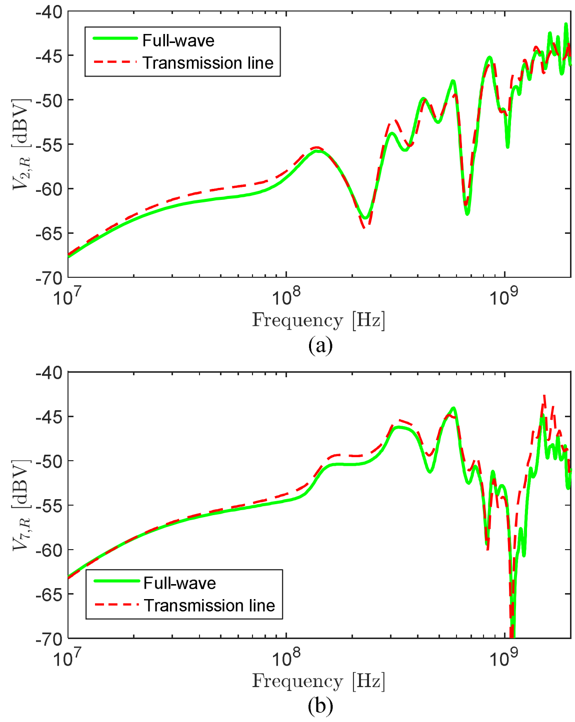

Figure 6. RS prediction: Voltages induced at right terminations of the (a) thick, and (b) thin wires in the bundle.

Based on the generated bundle samples, nonuniform TL solution has been used to predict crosstalk among the wires in the bundle as well as field-to-wire coupling with external EM fields. The predicted voltages and currents induced at the bundle terminal sections have been compared versus those evaluated by a full-wave numerical solver implementing the 3-D geometric representation of the bundle sample under study. In spite of the strong non-uniformity with respect to ground, the good agreement between the predictions obtained by the two methods confirms the accuracy of TL modelling, which can be effectively used to simulate even complex wire bundles thanks to its reduced computational burden w.r.t. full-wave simulation.

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