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Common-Mode Radiation Resulting from Hand-Assembled Cable Bundles on Automotive Platforms

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Abstract—**A statistical cable harness model is developed to account for the random disturbance of the wire positions along hand-assembled bundles. The non-uniform random bundles are modeled as n-cascaded segments of uniform multi-conductor transmission line. At each section, all wire positions are disturbed with random numbers obeying a Gaussian distribution. In addition, a spline interpolation function is used to improve the smoothness of wires winding along the bundle. The common-mode current distribution along the bundle calculated with SPICE is injected into a full-wave tool, e.g., FDTD, as impressed current sources. Thus, the full-vehicle electromagnetic emissions from the automotive harness can be predicted efficiently. The model has been experimentally validated with a controlled laboratory setup.**

Keywords-statistical; random; cable bundles; common-mode current; EMI; automotive EMC

I. Introduction

The common-mode (CM) current along the cable harness, which results from high-speed digital control electronics, as well as power electronics, is a primary contributor to the electromagnetic interference (EMI) on an automotive platform. This undesired EMI may prevent commercial vehicles from satisfying stringent EMC criteria. For modeling a typical hand-assembled cable harness, one of the challenges is that the cable bundles show great variability on the positions of the wires within the bundles because of the random nature of the bundle assembly. This lack of uniformity precludes any rigorous deterministic analysis. Therefore, a statistical approach must be employed to account for the intrinsic random behavior of cable harnesses.

Two cable harness modeling methods have been presented in the literature to model hand-assembled cable harnesses from a statistical point of view. In [1], a Monte Carlo algorithm was introduced. The cable bundle is divided into n uniform segments whose 2D cross-sections are identical, but the positions of the wires are randomly interchanged from segment to segment. The Random Midpoint Displacement algorithm (RMD) is another method [2], [3], [4], which also divides the bundle into n uniform cascaded segments, but describes the positions of a wire along a bundle with a fractal curve. For the Monte Carlo method, the wire positions at each cross-section are determined independently. The smoothness of the wire routing can only be loosely controlled with the total number of segments of the bundle. For the RMD algorithm, the smoothness of the wire routing within the cable bundles is controlled through the fractal dimension and the total number of segments. The RMD method gives better representation of an actual cable harness in terms of smoothness, and it has more flexibility to control the randomness. However, the bundle wires constructed with both methods demonstrated unphysical large discontinuities between adjacent bundle segments because of the nature of the algorithms. The large discontinuities result in unphysical resonances of the CM current along the cable harnesses, which compromises the effectiveness of both models, especially at high frequency. To mitigate the discontinuities of the constructed bundle wires and more physically represent an actual cable harness behavior, a new method, i.e., the Random Displacement Spline Interpolation (RDSI) algorithm, is proposed and developed in this paper. In Section II, the RDSI algorithm is briefly introduced. In Section III, a test setup in a controlled laboratory environment is used to assess the effectiveness of the RDSI cable harness model. Finally, the performance of the RDSI cable harness model is summarized in Section IV.

II. RDSI Algorithm Description

The bundle realization with the Random Displacement Spline Interpolation (RDSI) algorithm is described with one wire construction. Assume the bundle is along the *Z*-axis, and the wire is divided into n uniform segments. The wire position along the bundle can be represented as a set of (x_i, y_i, z_i) coordinates, where i is the 2D cross-section number. The reference point could be anywhere, but it was chosen as the center point of the start end of the bundle herein just for simplicity. The x_i and y_i determine the 2D cross-section position of the wire at the i^{th} segment. The length of each segment is $1/n$ of the length of the bundle. Fig. 1 shows the mechanism of the wire modeling within the bundle using the RDSI algorithm. For simplicity, only x coordinate generation along the *Z*-axis is shown in the figure. The y coordinate generation follows in an identical fashion. To simplify the method at this stage, two assumptions are made in the implementation of the proposed algorithm. First, the diameters of all the wires inside the bundle are the same, so any two wires are interchangeable. Second, the overall geometry of the 2D cross-section of the bundle is invariant along the axial direction, and the positions of the realized wires are allowed only within the pre-defined wire locations. Therefore the evaluation of the per-unit-length L & C matrices needs only to be performed once because of the invariant 2D cross-section. This restriction is not essential, but lifting it significantly increases the computation time. In actual practical cases, this assumption may result in some error. However, when the wires are densely packed, and the number of the wires is up to hundreds, two arbitrary cross sections of a random bundle should be approximately the same. The key point of this model is to determine the mutual spacing between wires.

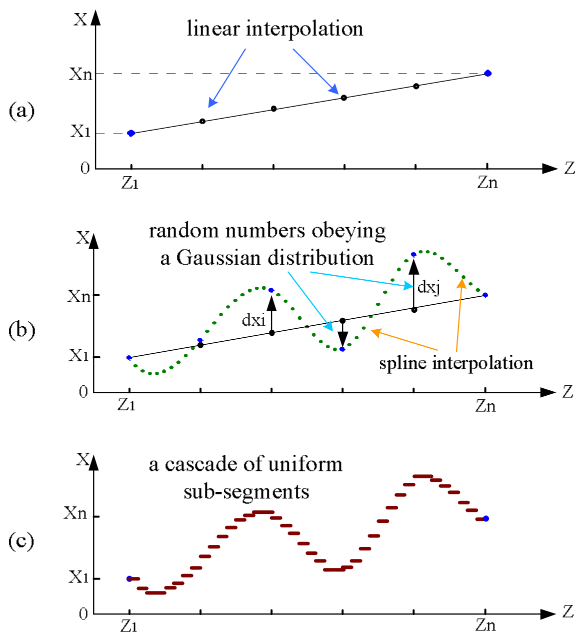


Fig. 1. Schematic representation of wire modeling using the Random Displacement Spline Interpolation (RDSI) algorithm.

There are four steps to construct the wire representation within a bundle.

Step 1: Initial spline coordinate calculation

The wire is first divided into *m* rather long segments, which are referred to as spline segments. The length of each segment is approximately the same as the twist length of the actual cable harnesses under investigation. As shown in Fig. 1 (a), the coordinates of the ends of the segments are calculated using the linear interpolation technique according to the coordinates of two ends of the wire, which can be measured from the connectors at the two ends of the bundle.

Step 2: Spline coordinate randomization

In the second step, random numbers that obey a Gaussian distribution are generated. The final coordinates of the spline segments are the summation of the initial coordinates and the random numbers. Then all spline segments along the sequential line are displaced using the Gaussian distribution. The mean of the Gaussian distribution is zero, so the standard deviation of the random numbers is the key parameter that controls the randomness of the wire positions. This process is shown in Fig. 1 (b).

Step 3: Spline interpolation

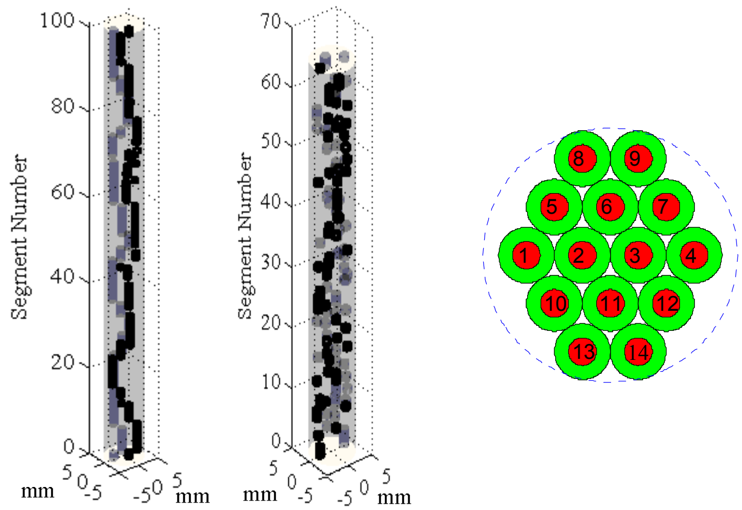
In the third step, the wire is further divided into uniform sub-segments according to the length of the sub-segment specified in the model input file. There are two criteria to determine the length of sub-segments. The first criterion is that it should be equal to or less than 1/10th of the shortest wavelength of interest, which ensure the spatial resolution of the wave with the highest frequency of interest. The second criterion is that one spline segment should have ten or more sub-segments to ensure the continuity of the constructed wire within the bundle. Both criteria need to be satisfied, so the smaller one of the two sub-segment lengths will be used. With coordinates of the spline segments available, the coordinates of the sub-segments of the wire are generated using the piecewise polynomial form of the cubic spline interpolation technique (matlab function spline), as shown in Fig. 1 (c).

Step 4: Fitting the generated wires into the bundle

So far, coordinates of the wire at each cross-section are generated. The last step is to fit the realized wire into the pre-defined locations at each cross-section. The predefined wire locations are used as reference. At the beginning, all the reference positions are unoccupied. Starting with the first wire, the distances between the coordinates of a new wire and all the unoccupied reference locations are calculated and compared. The new wire is placed in the position of the nearest, unoccupied reference location. The taken reference location is then marked as occupied. The iterations continue until the last wire is placed in the final unoccupied reference location, then new 2D cross-sections with identical geometry but different wire positions are generated. In this fashion, the wire is represented as a cascade of short, uniform sub-segments. Because of the nature of the wire representation within the bundle, the new algorithm is further referred to as the Random Displacement Spline Interpolation (RDSI) algorithm for simplicity.

The cubic spline interpolation technique improves the continuity of the constructed wire along its length. The constructed wires are more realistic as compared to the actual hand-assembled cable bundle. To visualize the difference of the bundles constructed with the RDSI and RMD algorithms, two arbitrarily chosen wires within a fourteen-wire bundle are plotted in Fig. 2 (a) and (b). Fig. 2(c) shows the 2D cross-section geometry of the bundle. The large discontinuities between the adjacent sub-segments shown in Fig. 2 (b) are far from the actual behavior of a cable bundle. This unphysical discontinuity leads to a non-negligible discrepancy between the actual bundle length geometry and the corresponding resonances of the CM current along the bundle in the simulations. By contrast, the wires constructed with the RDSI algorithm demonstrate a better transition of wire position variation. The RDSI algorithm gives a more physical representation of actual cable bundles.

After the cable bundle is realized, a 2D quasi-static field solver is used to evaluate the per-unit-length L & C matrices, and a SPICE program is employed to calculate the current on each wire at every segment. The CM current is simply the summation of the current on each wire. Herein a TEM or quasi-TEM mode is implicitly assumed. In a typical case of bundles on an automotive platform, this assumption can be globally satisfied.



(a) RDSI (b) RMD (c) 2D cross-section

Fig. 2. 3D visualization of two wires along the bundle that are constructed with the RDSI and RMD algorithm: (a) RDSI, (b) RMD, and (c) 2D cross-section. Note that for both algorithms, the normalized STDs are 0.5, and the bundle lengths are both two meters long.

III. Experimental Validation

An experimental setup was constructed to assess the effectiveness of the RDSI cable harness model. A photograph of the measurement setup is shown in Fig. 3. The detailed geometry of the setup and the 2D cross-section of the wire bundle are shown in Fig. 4 (a) and Fig. 4 (b), respectively. The two-meter long bundle is composed of fourteen AWG # 20 wires with PVC insulation, and it was placed on a rectangular aluminum plate that is 262 cm long by 120 cm wide. The nominal diameter of the bundle is 8.2 mm, and the average height of the bundle is approximately 2 cm above the aluminum plate. The bundle was connected to two aluminum boxes via two pairs of D-Sub connectors. One end of Wire 2 was connected to an SMA jack inside the source box, and all other ends of the wires were terminated with SMT resistors inside the source and load boxes. The values of the resistors were randomly chosen as low and high impedance combinations with reference to 100 Ω, and they are summarized in TABLE I. Port 1 of a vector network analyzer (HP8753D) was used to feed Wire 2 through the SMA jack, while Port 2 of the vector network analyzer was connected to either a current probe (Fisher F-61), or a lab-made electric field sensor, for the common-mode current and electric field measurements, respectively. Since for the feeding wire (Wire 2), both the feeding impedance (50 Ω) and the load impedance (68 Ω) are low, this setup is current-driven in nature.

The common-mode current was measured at point P1, P2 and P3 as shown in Fig. 4. Point P1 and P2 are two arbitrarily chosen points that can represent the general behavior of the bundle. Point P3 was intentionally chosen as symmetric with respect to the point P1 to investigate the symmetry property of CM current. As shown in Fig. 4, the electric field was measured at point P4, P5 and P6, which were intentionally chosen as gradually further from the bundle. Since the RDSI algorithm is a statistical model, the fourteen-wire, two-meter long cable bundle was randomly re-wrapped sixteen times, and all the measurements were re-performed sixteen times accordingly. The measurement data and the simulation results are compared from a statistical point of view, which are in terms of accumulative maximum and mean values, and the standard deviations.

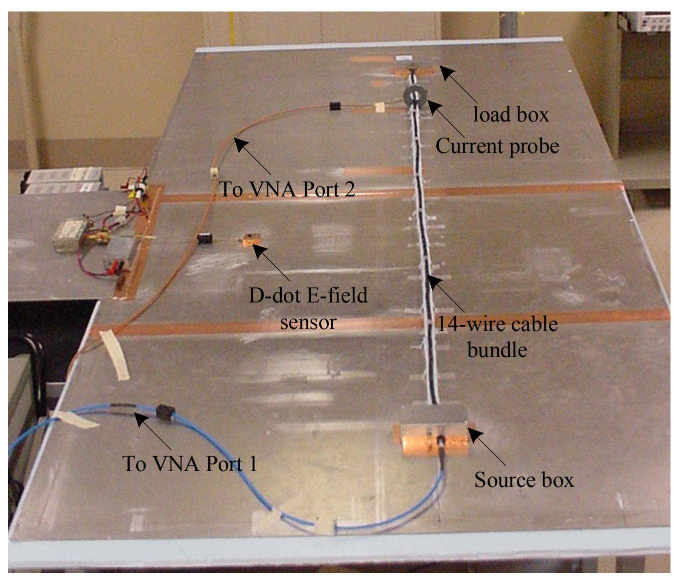
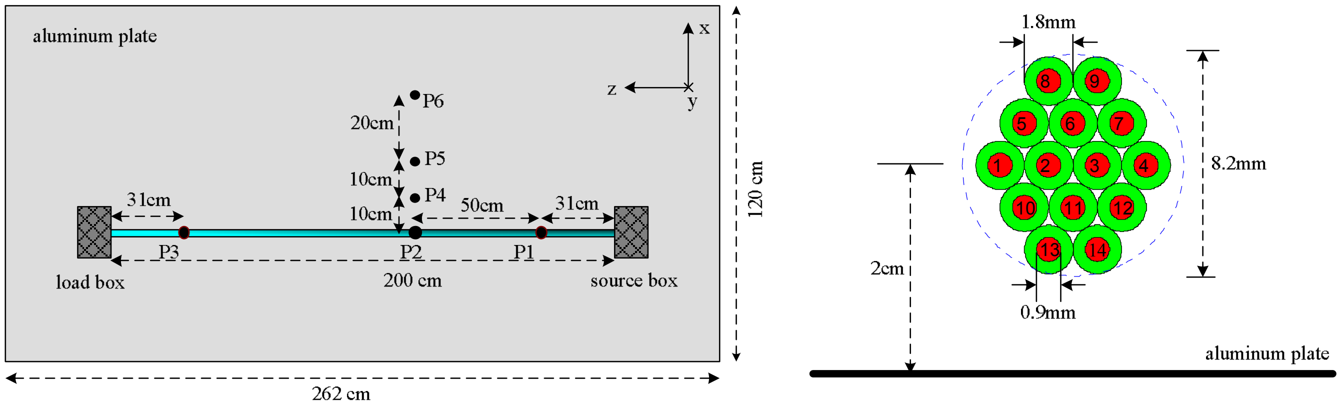


Fig. 3. Photograph of the measurement setup for a fourteen-wire, two-meter long cable harness over a large aluminum plate.



(a) Top view geometry (b) 2D cross-section view

Fig. 4. Schematic of the measurement setup, (a) top view geometry, (b) 2D cross-section view. The CM current was simulated and measured at point P1, P2 and P3, and the electric field was simulated and measured at point P4, P5 and P6.

TABLE I. TERMINATIONS OF THE BUNDLE

	Source end	**Load end**	**Relative impedance* Source - Load**
Wire1-to-GND	996 Ω	10 Ω	High - Low
Wire2-to-GND	Feeding (50 Ω)	68 Ω	Low - Low
Wire3-to-GND	50 Ω	68 Ω	Low - Low
Wire4-to-GND	56 Ω	996 Ω	Low - High
Wire5-to-GND	10 Ω	47 Ω	Low - High
Wire6-to-GND	1 KΩ	15 KΩ	High – High
Wire7-to-GND	56 Ω	1 KΩ	Low - High
Wire8-to-GND	10 Ω	10 Ω	Low - Low
Wire9-to-GND	15 KΩ	47 Ω	High - Low
Wire10-to-GND	47 Ω	10 Ω	Low - Low
Wire11-to-GND	47 Ω	1 KΩ	Low - High
Wire12-to-GND	10 Ω	100 KΩ	Low – High
Wire13-to-GND	996 Ω	10 Ω	High - Low
Wire14-to-GND	56 Ω	10 Ω	Low - Low

* the reference impedance is 100 Ω

TABLE II. MEAN VALUES AND SIGMAS OF THE CM CURRENTS WITH DIFFERENT NUMBER OF SIMULATIONS AT THE FREQUENCY OF 506 MHZ.

Number of Simulations	16	32	64	128
Mean (mA)	2.11	2.07	2.15	2.03
Sigma (mA)	0.76	0.81	0.80	0.91

TABLE III. DIFFERENCE OF THE MEAN VALUES AND SIGMAS WITH RESPECT TO THAT OF 128 SIMULATIONS.

Number of Simulations	16	32	64	128
Difference of mean (dB mA)	0.3	0.2	0.5	0 (ref.)
Difference of sigma (dB mA)	-1.6	-1.0	-1.1	0 (ref.)

For a statistical model, the larger the number of simulations, the better the results that can be achieved. However, for engineering purposes, the number of simulations or measurements should be minimum yet sufficient. To investigate the suitable number of simulations, a total 128 simulations were performed. For the CM current at point P1, the mean values and standard deviations of the probability density function (PDF) are reported in TABLE II. The difference of the mean values and sigmas with respect to that of 128 simulations are reported in TABLE III. The small difference of the mean values and sigmas between 16 simulations and 128 simulations, which are 0.3 dB and –1.6 dB respectively, indicates that sixteen is a suitable number for engineering purposes, even though the mean and variance calculation for such a small number of events is limiting.

Fig. 5 and Fig. 6 show the 16 measured and simulated CM currents at point P1, respectively. The thick curves at the top and bottom in the figures are the accumulative maximum and minimum CM currents among the 16 measured or simulated results. According to the figures, the distributions of the CM currents vary with respect to the frequencies. Generally, the difference between the accumulative maximum and minimum CM current results is 15 B or greater with 16 measurements or simulations. With an increasing frequency, the Q-factor of the CM currents decreases greatly because of the skin effect and the dielectric loss of the PVC material.

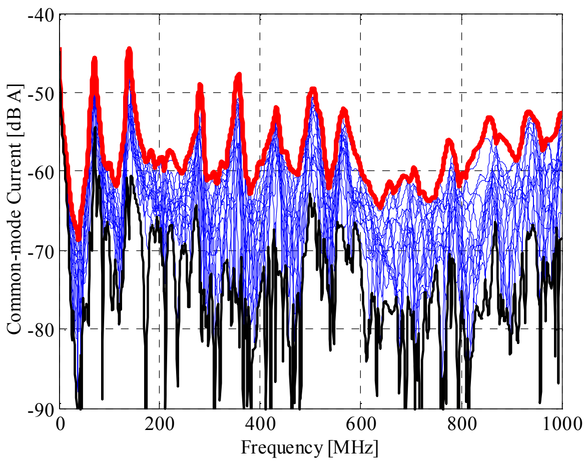


Fig. 5. Amplitufe of the sixteen measured CM currents at point P1.

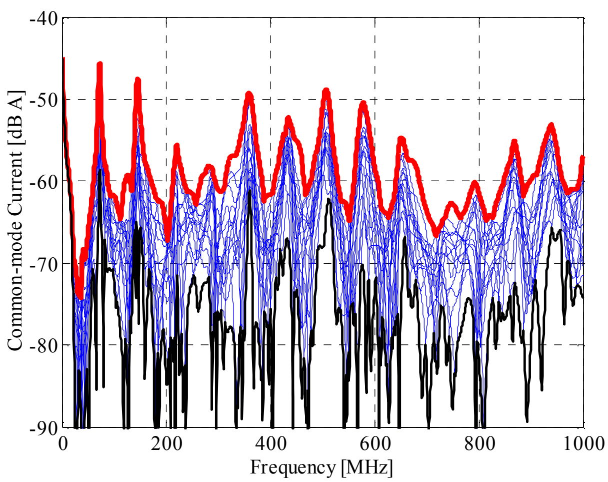


Fig. 6. Amplitufe of the sixteen simulated CM currents at point P1.

The comparison of the measured and simulated maximum and average CM currents among 16 results at point P1 is shown in Fig. 7. The simulation results match the measurement results well, especially for the average CM current. The difference at most frequencies is less than 3 dB. This indicates that the RDSI cable harness model can represent the actual behavior of the hand-assembled cable bundles from a statistical point of view. The small resonant frequency shifts at 280 MHz and 560 MHz are due to the insertion impedance introduced by the current probe. The reasons for the missing resonances at 280 MHz and 630 MHz might be the artifacts introduced by the current probe, and might also be the parasitic effects of the bundle setup, e.g., scattering from the termination boxes and laboratory objects, which are not considered in the model.

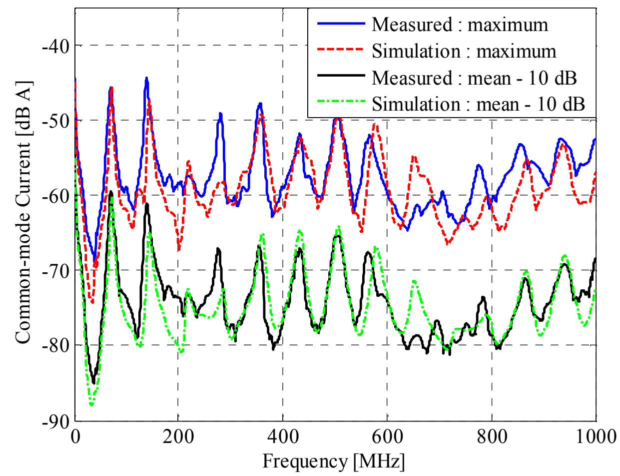


Fig. 7. Comparison of the measured and simulated maximum and average CM current at point P1. Note that both the simulated and measured average CM currents are shifted 10 dB down from the original values for ease of comparison.

One efficient way to predict the system-level EMI resulting from cable harnesses on automotive platforms is to inject the CM current into a full-wave model as impressed current sources [5]. However, since the bundle is placed on a large metal plate, and there are no significant scatters, the free space Green's function combined with image theory [6] is sufficient to predict the electromagnetic emissions. Herein, every CM current filament along the bundle is treated as a current dipole [6]. In this approach, the entire wire bundle is divided into 100 segments, each 2cm long. Because the length of each segment is less than 1/10th of the shortest wavelength of interest, each segment is considered as an infinitesimal dipole, and the current along the segment is approximated as a current filament with constant magnitude and phase, which is the simulation result at the mid-point of the segment.

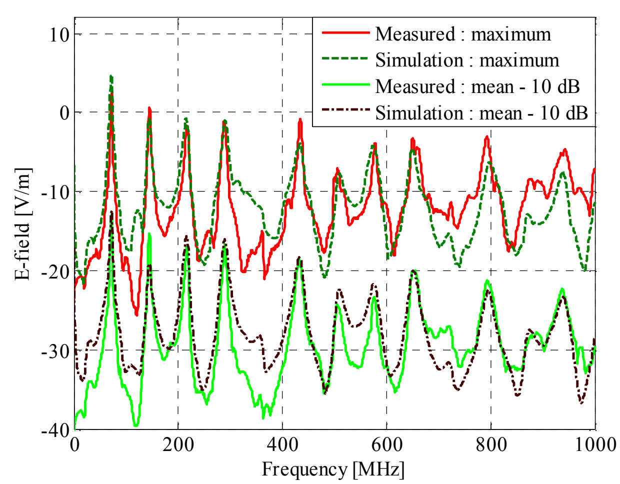


Fig. 8. Comparison of the measured and simulated maximum and average electric field at point P4. Note that both the simulated and measured average E-field data are shifted 10 dB down from the original values for ease of comparison.

The comparison of the measured and predicted electric fields obtained with the free-space Green's function approach at point P4 is shown in Fig. 8. The number of the measurements and simulations is still 16. The difference between the measured and simulated E-fields for the maximum and average results is within 3 dB at most frequencies. This generally good match provides another way to validate the RDSI cable harness model. The remaining difference may be due to two factors. First, the finite number of the simulations and measurements may not be sufficient to achieve a superior match between the simulations and measurements; second, the measurement uncertainties, and scattering from the termination boxes and laboratory objects that are not considered in the free-space Green's function formulas may also contribute to some extent.

IV. CONCLUSION AND DISCUSSION

The good agreement between the simulation results and the measurement data for the CM current and the radiated electric field presented in the previous sections indicate that the proposed RDSI cable harness model is suitable to account for the random behavior of hand-assembled cable bundles from a statistical point of view. With a finite number of simulations, the average or maximum values of the common-mode currents and the standard deviations can be obtained. By injecting the average CM current and the standard deviation information of the CM current into full-wave models, the electromagnetic fields can be computed efficiently within a desired confidence level. The accumulated maximum CM current can be used to predict the electromagnetic emissions for the worst case.

Two model parameters, i.e., the standard deviation of the Gaussian distribution and the spline segment length, are the key parameters that control the randomness of the constructed cable bundles. It is convenient to tune the randomness of the cable bundles by adjusting these two parameters according to the actual cable bundles.

The dielectric loss and the skin effect are two critical effects that have to be considered in the model. These effects have a significant impact on the CM current. They can mitigate the CM current on the order of 10 dB. The fact that the signal loss greatly influences the CM current provides a possible method to mitigate unintentional CM current. However, more signal loss also degrades the useful signal. There is a compromise between mitigating the CM current and maintaining a useful signal.

The artifacts, e.g., wrapping tape, non-ideal terminations, etc., have a non-negligible impact on the simulation results. These effects may reduce the CM current on the order of several dB.

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