Fall 2019

Experimental characterization of common-mode sources for prediction of system level common-mode current on cable harnesses

Sameer Sudha Arun Walunj

EXPERIMENTAL CHARACTERIZATION OF COMMON-MODE SOURCES FOR PREDICTION OF SYSTEM LEVEL COMMON-MODE CURRENT ON CABLE HARNESSES

by

SAMEER SUDHA ARUN WALUNJ

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

in

ELECTRICAL ENGINEERING

2019

Approved by:

Dr. Daryl G. Beetner, Advisor
Dr. Chulsoon Hwang
Dr. Victor Khilkevich

PUBLICATION THESIS OPTION

This thesis consists of the following two articles, formatted in the style used by the Missouri University of Science and Technology:

Paper I: Pages 2-22; Experimental Characterization of the Common-Mode Current Sources in a Cable Harness, has been accepted in 2019 IEEE Symposium on Electromagnetic Compatibility.

Paper II: Pages 23-43; Rapid Measurement-Based Characterization of Common-Mode Sources in Cable Harnesses, will be submitted to 2020 Asia Pacific Electromagnetic Compatibility Symposium.

ABSTRACT

Common-mode current on cable harnesses is often the primary source of radiated emissions below several hundred megahertz. It is difficult, however, to estimate common-mode currents that will occur in a system from component level tests because the common-mode impedances are different in the system. Research presents two methods for using simple component level tests to estimate equivalent common-mode source voltages and source impedances responsible for generating common-mode current. Key to these methods is assuming the harness can be represented with two transmission lines, one terminated with a short and one with an open. Equivalent sources are predicted for those circuits terminated with an open and those terminated with a short. This source information can be used to predict the common-mode currents on harnesses of different lengths or characteristic impedance.

In the first method, source characteristics are found from the magnitude of the common-mode current measured at multiple locations along the harness while varying the component height above the return plane (i.e. by varying the common-mode source impedance). In the second method, a characterization board is used which is connected to the DUT to measure the common-mode source voltages and impedances. Common-mode source measurements are made for groups of pins sorted by known load information, i.e. those pins whose loads are small compared to the characteristic impedance of the transmission line (group 1) and those whose loads are large (group 2).

ACKNOWLEDGMENTS

I would like to express my gratitude to all those who have helped me during this research. Firstly, I would like to thank my advisor, Dr. Daryl Beetner, for giving me the opportunity to work on this project. His valuable insight and suggestions have helped me to overcome many hurdles during this work. I am grateful to him for the advice and guidance he gave me throughout my master's program. I also thank Dr. Beetner for his moral support during my tough times by understanding and encouraging me to focus on my goals. I would like to thank Dr. Hwang and Dr. Khilkevich for being part of my thesis committee and guiding me at every step during my research. This research would not be possible without their continual guidance. I would like to thank Fuwei Ma and Tamar Makharashvili at Missouri University of Science and Technology for their contribution towards this work. I thank Brian Booth and Martin Kerry from John Deere for their valuable guidance and immense support during this study and for providing the hardware which served as a research artifact.

A special thanks to my dearest friend, Lini Alex, whose constant support and encouragement has always been crucial for me. I would like to thank my brother Tushar and sister-in-law Sulekha for always standing by my side and supporting me. Finally, I would like to dedicate this work to my parents, Sudha and Arun Walunj, for their emotional support and unconditional love and sacrifices.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

Table Page

PAPER I

1. INTRODUCTION

The ability to anticipate system-level electromagnetic emissions problems early in the design process is critical to the design of complex modern vehicles. Problems found when the system is being integrated, may be expensive and time-consuming to solve, and solutions may negatively impact design constraints like cost, size, or weight. While prediction of system-level radiated emissions early in the design stage is beneficial, it is challenging because results from component-level tests rarely fully anticipate emissions at the system-level. Differences between the harness configuration in the component-level test and in the system can dramatically change the common-mode currents on the harness and thus the emissions.

The objective of the research is to develop a methodology which uses a few component-level measurements to estimate common-mode currents up to a few hundred megahertz on harnesses of arbitrary length and transmission line characteristics. Estimates are made by assuming that loads can be grouped depending on the size of their impedances and an equivalent circuit can be assigned to each group. The equivalent circuits can be used to estimate common mode currents on harnesses. Research demonstrates two methods to find the equivalent source characteristics of each equivalent common-mode circuit. Results show that the common-mode current can be estimated within a reasonable accuracy.

PAPER

I. EXPERIMENTAL CHARACTERIZATION OF THE COMMON-MODE CURRENT SOURCES IN A CABLE HARNESS

S. Walunj

Department of Electrical Engineering

Missouri University of Science and Technology

Rolla, Missouri 65409–0050

Email: sw4p9@umsystem.edu

ABSTRACT

Common-mode current on cable harnesses is often the primary source of radiated emissions below several hundred megahertz. It is difficult, however, to estimate common-mode currents that will occur in a system from component level tests because the common-mode impedances are different in the system. Here, a method is proposed to use simple component level tests to estimate equivalent common-mode source voltages and source impedances responsible for generating common-mode current. This source information can be used to predict the common-mode currents on harnesses of different lengths or characteristic impedance. The common-mode load impedances are assumed to be approximately open or short compared to the characteristic impedance of the harness. Equivalent sources are predicted for those circuits terminated with an open and those terminated with a short. Source characteristics are found from the magnitude of the common-mode current measured at multiple locations along the harness while varying the component height above the return plane (i.e. by varying the common-mode source impedance). The proposed method was used to predict the common-mode current on multi-wire harnesses of different lengths. The common-mode current was predicted within a few decibels except at frequencies where the harness was resonant during source estimation.

Keywords: equivalent source, cable harness, common-mode current, radiated emissions, prediction.

1. INTRODUCTION

It is better to predict radiated emissions early rather than later in the design process because countermeasures are easier and cheaper to implement if the system does not pass the test [1] - [3]. While components are typically tested for emissions in the very early stages of the system design, their passing the emissions test does not guarantee that the system will also pass [4], [5]. Because the setup used to test the components differs from the system-level setup, the common-mode current on the harness is also different between the two. This difference is a major reason for the uncertainty in predicting system-level radiated emission from component-level measurements. An approach to predict system-level radiated emissions using simple component-level measurements is needed. Such a method could help engineers to plan and build robust systems by detecting and fixing issues early in the design stages.

The objective of the following paper is to develop a method to estimate equivalent sources driving common-mode current on harness bundles. The method should use only a few relatively simple measurements of the magnitude of the common-mode current in a component level test. Once found, these sources can be used to predict the common-mode current on a wide variety of harness configurations. The radiated electromagnetic emissions can be found accurately from simulations once the common-mode currents are known [4]-[10].

The method is based on many of the same concepts as the generalized equivalent cable bundle method [4], [5], [11], [12]. The spatial distribution of common-mode current on a transmission line is determined by the termination impedance. For many common-mode circuits, this termination is much larger or much smaller than the characteristic impedance of the transmission line, and thus approximates an open or short. As such, the many common-mode circuits in a harness can be lumped into a few groups depending on the size of their terminations relative to the characteristic impedance of the transmission line. An equivalent source can be found to approximate the total common-mode current within each group. This approach was developed to reduce simulation complexity by reducing the number of represented circuits. The reduction technique assumes full knowledge of the common-mode circuit associated with each wire in the harness bundle, which may be difficult to find in practice.

The methodology presented in the following paper represents the common-mode current using only a few equivalent sources so that the sources can be characterized using only a few measurements. A similar approach to the one presented here was used in [13], but required accurate measurement of both the magnitude and phase of the common-mode current. Accurate measurement of the phase is tricky, especially when one must know the phase difference between currents for two different harness configurations. The approach in [13] also required measurement of current for two different harness lengths, which may be difficult to obtain due to the difficulty of manufacturing complex harnesses.

The method presented here only requires measurement of the magnitude of the common-mode current, and uses changes in the height of the source above the return plane (i.e. changes in source impedance) to characterize the source rather than changes in harness length. The approach was also extended to allow a least mean square estimate of the source characteristics, which reduces the impact of measurement errors. The methods and formulas for estimating equivalent sources will be presented, along with a validation of the methodology in simulated harness models. Results show the potential of the approach for estimating common-mode currents in a variety of harnesses.

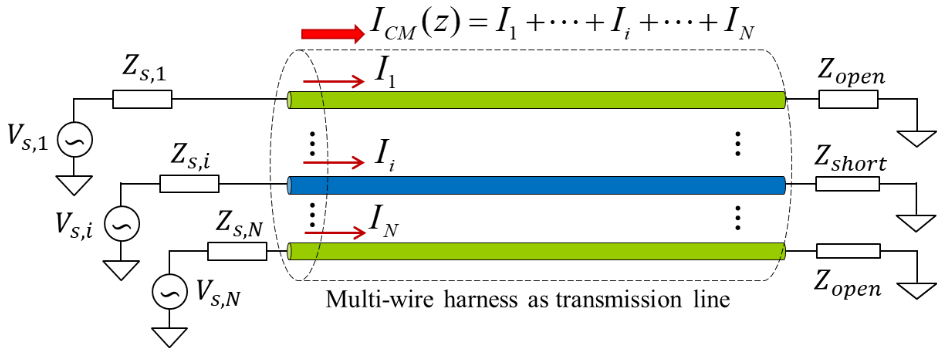
2. EQUIVALENT COMMON-MODE MODEL

During component level tests, the harness is connected between the component and load and placed over a metal return plane. The proposed method is derived from the characteristics of the transmission line formed by the harness and return plane.

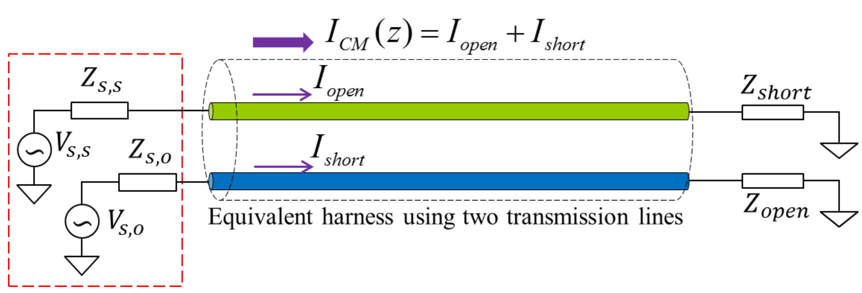
2.1. THE EQUIVALENT CIRCUIT

Each wire in a harness has a source, source impedance and load, as shown in Figure 1a. In many circumstances (and those that generate the largest common-mode currents), the loads are much larger or much smaller than the characteristic impedance of the transmission line, and can be approximated as opens or shorts. This assumption is particularly relevant for capacitive or inductive common-mode terminations, where their impedances are generally much smaller or larger than the characteristic impedance of the harness over a large frequency range.

The collection of common-mode circuits in Figure 1a can be approximated with two equivalent circuits as shown in Figure 1b. One circuit is terminated with an ideal open while the other with an ideal short. The proposed technique calculates the equivalent source voltages and impedances for both equivalent circuits along with the relative phase between the source voltages. The two equivalent sources generate roughly the same common-mode current as the original multi-wire harness.



a



b

Figure 1. Common-mode circuit representing the harness. a) Original multi-wire harness. b) Equivalent two wire system generating approximately the same common-mode current.

2.2. THE EQUIVALENT SOURCE

The steady-state current along the length of a transmission line is given by [14]

$$I(z) = \frac{1-\Gamma_L e^{-j2\beta l} e^{\,j2\beta z}}{1-\Gamma_S \Gamma_L e^{-j2\beta l}} \frac{V_s}{Z_s+Z_c} e^{-j\beta z}, \tag{1}$$

where Γ_L and Γ_S are the reflection coefficients at the load and source, respectively, V_s is the source voltage, Z_s is the source impedance, β is the propagation constant, l is the length of the transmission line, z is the location along the transmission line, and Z_c is the characteristic impedance of the transmission line. This equation can be simplified in form by equating

$$q \equiv \Gamma_L e^{-j2\beta l} \tag{2}$$

and

$$\chi \equiv \frac{V_s}{(1-q)Z_s+(1+q)Z_c} \tag{3}$$

giving

$$I(z) = \chi\left(e^{-j\beta z} - q e^{j\beta z}\right). \tag{4}$$

The total common-mode current, $I_{cm}(z)$, generated by the two equivalent circuits in Figure 1b is the sum of common-mode current generated by the circuit terminated with an open, $I_{open}(z)$, and the current generated by the circuit terminated with a short, $I_{short}(z)$,

$$I_{cm}(z) = I_{open}(z) + I_{short}(z). \tag{5}$$

From (4), the total common-mode current is given by

$$I_{cm}(z) = \chi_o\left(e^{-j\beta z} - q_o e^{j\beta z}\right) + \chi_s\left(e^{-j\beta z} - q_s e^{j\beta z}\right), \tag{6}$$

where χ_o, q_o, χ_s and q_s are coefficients for the equivalent circuits terminated with an open and short respectively.

The magnitude of the common-mode current is determined by χ_o, and χ_s, which are dependent on the source voltage, the characteristic impedance of the transmission line, and the source and load impedances. The characteristics of the source can thus be found from χ_o, and χ_s. To avoid measuring the phase of current, both sides of (6) can be squared to give

$$|I_{cm}(z)|^2 = |\chi_o\left(e^{-j\beta z} - q_o e^{j\beta z}\right) + \chi_s\left(e^{-j\beta z} - q_s e^{j\beta z}\right)|^2. \tag{7}$$

Expressing χ_o and χ_s as

$$\chi_o = a + jb \text{ and } \chi_s = c + jd, \tag{8}$$

(7) can be re-written as

$$\frac{1}{4} \cdot |\mathrm{I}_{cm}(z_i)|^2 = |\chi_o|^2 A_i + |\chi_s|^2 B_i + (bc - ad)C_i, \tag{9}$$

where

$$A_i = sin^2\,\beta\,(z_i - l),\ B_i = cos^2\,\beta\,(z_i - l),\ C_i = sin\,2\,\beta(z_i - l) \tag{10}$$

and $|I_{cm}(z_i)|$ is the measured magnitude of common-mode current at locations z_i along the harness length.

Coefficients $|\chi_o|^2$, $|\chi_s|^2$ and the value of $(bc - ad)$ in (9) can be found from

$$[|\chi_o|^2, |\chi_s|^2, bc - ad]^T = (M^T M)^{-1} M^T N, \tag{11}$$

where

$$N = [n_1, \ldots, n_t]^T, t \geq 3 \tag{12}$$

is a 1 by t vector of currents measured at different locations along the harness length,

$$n_i = \frac{1}{4}|I_{cm}(z_i)|^2, \tag{13}$$

t is the number of measurement locations, and M is given by

$$M = \begin{bmatrix} A_1 & B_1 & C_1 \\ \vdots & \vdots & \vdots \\ A_t & B_t & C_t \end{bmatrix}. \tag{14}$$

At least 3 measurements ($t \geq 3$) are required to find the coefficients in (11). Equation (11) will produce a least-mean-square estimate when more than 3 measurements are used.

Equation (11) determines $|\chi_o|$ and $|\chi_s|$, but the values of $|\chi_o|$ and $|\chi_s|$ are needed for at least three harness configurations to determine the common-mode source voltage and the source impedance. The harness configuration can be changed by changing the harness length [13], but doing so requires that a new harness be built. Here, we investigate adding an impedance in series with the source instead. This method is more straight forward, though has some limitations as will be discussed later.

To add an impedance in series with the source, the component under test can be lifted to produce a parasitic capacitance between the enclosure and the ground plane as shown in Figure 2. The value of the capacitance depends on the height of the component above the reference plane, and can be easily measured. The impedance of the capacitor is defined here as $Z_{cap,m}$, where m specifies the measurement number. At least three measurements of common-mode current along the harness are required for each value of capacitance to define the values of $|\chi_o|$ and $|\chi_s|$. Thus, a minimum of 9 measurements (3 components heights x 3 current measurements/height) are required to characterize the source.

Including this capacitance, (3) can be rewritten for the circuit terminated with an open as

$$\chi_{o,m} \equiv \frac{V_{S,o}}{(1-q_o)(Z_{S,o}+Z_{cap,m})+(1+q_o)Z_c}, \tag{15}$$

where $m = 1, 2, 3$ represents three different capacitance values, and $V_{s,o}$ and $Z_{s,o}$ are the equivalent source voltage and source impedance for the circuits terminated with an open.

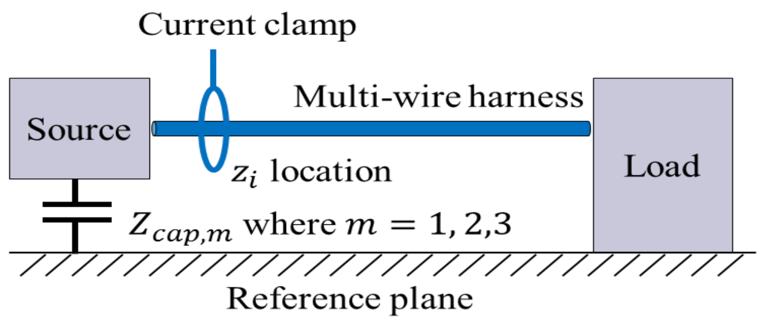


Figure 2. Adding capacitance between component and reference plane.

To solve for the source impedance from (15), denote

$$Z_{\tau,o} \equiv \left(\frac{1+q_o}{1-q_o}\right) Z_c, \tag{16}$$

$$k_{o,1} \equiv \frac{|\chi_{o,1}|}{|\chi_{o,2}|} \equiv \frac{|Z_{s,o}+Z_{cap,2}+Z_{\tau,o}|}{|Z_{s,o}+Z_{cap,1}+Z_{\tau,o}|}, \tag{17}$$

and

$$k_{o,2} \equiv \frac{|\chi_{o,1}|}{|\chi_{o,3}|} \equiv \frac{|Z_{s,o}+Z_{cap,1}+Z_{\tau,o}|}{|Z_{s,o}+Z_{cap,3}+Z_{\tau,o}|}, \tag{18}$$

and denote the source impedance $Z_{s,o}$ as

$$Z_{s,o} = x_o + jy_o - Z_{\tau,o}. \tag{19}$$

Solving (15) - (19) gives

$$y_o = \frac{(k_{o,1}^2-1)Z_{cap,3}^2-(k_{o,2}^2-1)Z_{cap,2}^2+(k_{o,2}^2-k_{o,1}^2)Z_{cap,1}^2}{-2(k_{o,1}^2-1)Z_{cap,3}+2(k_{o,2}^2-1)Z_{cap,2}-2(k_{o,2}^2-k_{o,1}^2)Z_{cap,1}} \tag{20}$$

and

$$x_o = +\sqrt{\frac{(2k_{o,1}^2Z_{cap,1}-2Z_{cap,2})y_o+k_{o,1}^2Z_{cap,1}^2-Z_{cap,2}^2}{(1-k_{o,1}^2)} - y_o^2}. \tag{21}$$

The source voltage is then be found from (15) as

$$\left|V_{s,o}\right| = \left|\chi_{o,3}\right|\left|1 - q_o\right|\left|Z_{s,o} + Z_{cap,3} + Z_{\tau,o}\right|. \tag{22}$$

Similar equations can be used to find the equivalent source impedance, $Z_{s,s}$, and source voltage, $V_{s,s}$, for those circuits terminated with a short.

Equation (22) only finds the magnitude of the source voltage and not the phase. The relative phase between $V_{s,o}$ and $V_{s,s}$ is necessary to predict the correct current distribution. Assuming the phase of $V_{s,s}$ is $0°$ and setting the phase of $V_{s,o}$ as $\theta°$, the relative phase can be found from (22) as

$$\theta = \angle\left(\frac{V_{s,o}}{V_{s,s}}\right) \quad = \angle\left(\frac{\chi_{o,3}}{\chi_{s,3}}\right) + \angle\left(\frac{1 - q_o}{1 - q_s}\right) + \angle\left(\frac{Z_{s,o} + Z_{cap,3} + Z_{\tau,o}}{Z_{s,s} + Z_{cap,3} + Z_{\tau,s}}\right)$$

$$= tan^{-1}\left(\frac{bc-ad}{ac+bd}\right) + \angle(j\tan\beta l) + \angle\left(\frac{x_o+jy_o+Z_{cap,3}}{x_s+jy_s+Z_{cap,3}}\right) \tag{23}$$

where, $bc - ad$ is given by (11) and $ac + bd$ is given by

$$ac + bd = \pm\sqrt{\left|\chi_{o,3}\right|^2 \cdot \left|\chi_{s,3}\right|^2 - (bc - ad)^2}. \tag{24}$$

Parameter $ac + bd$ has two roots. Assuming $T = \left|\frac{(bc-ad)}{(ac+bd)}\right|$ the arctangent can have four solutions: $\arctan(T)$, $\arctan(-T)$, $\arctan(T) - \pi$, $\arctan(-T) + \pi$. Only one solution is correct. The correct value of θ is assumed to be the one which minimizes the error in the predicted common-mode current given by

$$\text{Error} = \sum_{i=1}^{n}\left(\left|I'_{CM}(\theta, z_i)\right| - \left|I_{CM}(z_i)\right|\right)^2, \tag{25}$$

where $I'_{CM}(\theta, z_i)$ is the common-mode current predicted by the equivalent circuit model using one of the possible values of relative phase and $I_{CM}(z)$ is the measured current.

Figure 3 summarizes the procedure used to characterize the common mode sources.

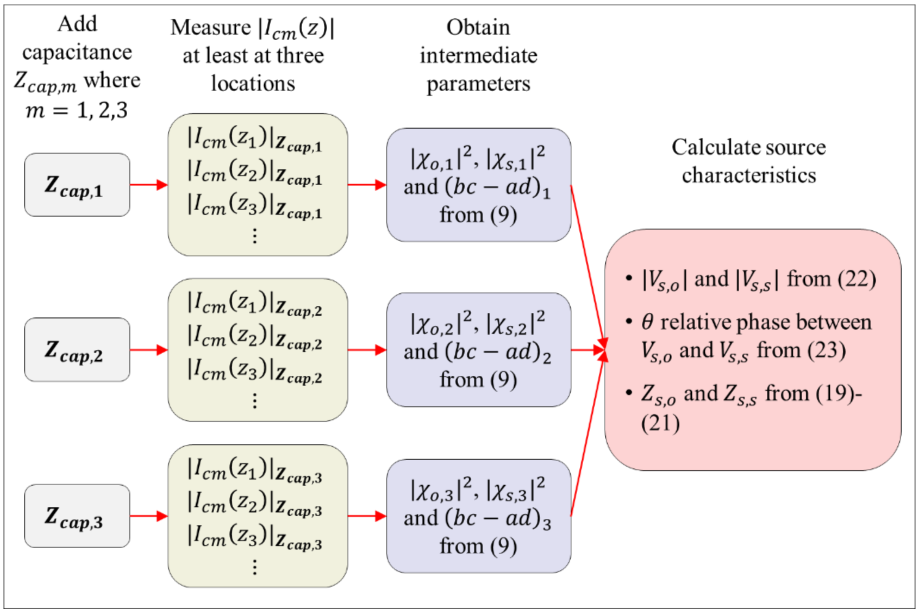


Figure 3. Process for extracting source characteristics from common-mode current measurements.

3. VALIDATION

The proposed methodology was validated through simulation. The test structure was a 1.2 m long multi-conductor harness placed 5 cm above a return plane as shown in Figure 4. The harness consisted of five wires, each having its own source. Two of the five wires were terminated with an ideal open and three were terminated with an ideal short. The source voltages and source and load impedances are shown in Table 1.

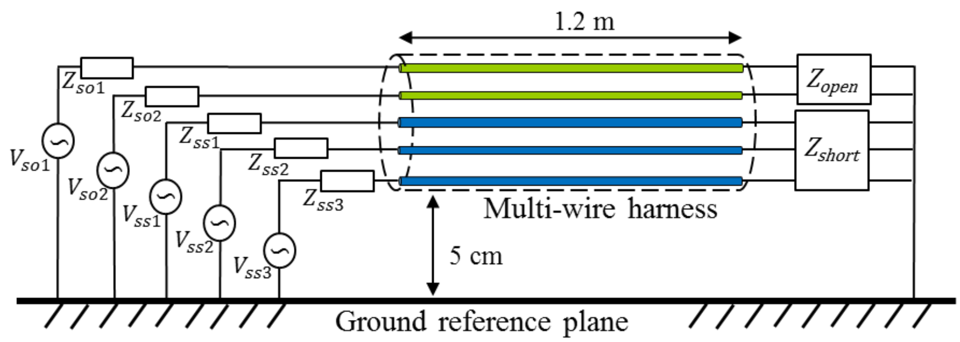


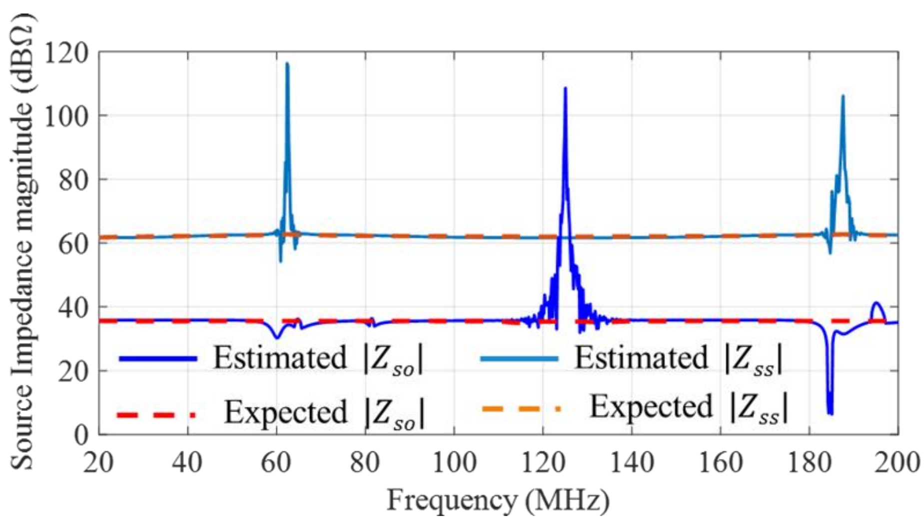
Figure 4. Measurement setup for common-mode current.

Common-mode current on each wire in the harness was obtained from SPICE circuit simulations. The total common-mode current was calculated as the sum of the currents on the wires in the harness. The total common-mode current was found at seven equidistant locations along the harness length from the source to the load. Three different configurations were generated by first placing the source enclosure on the return plane ($Z_{cap}=0$), then "raising" the source to create a 10 pF capacitance and a 70 pF capacitance between the enclosure and return plane.

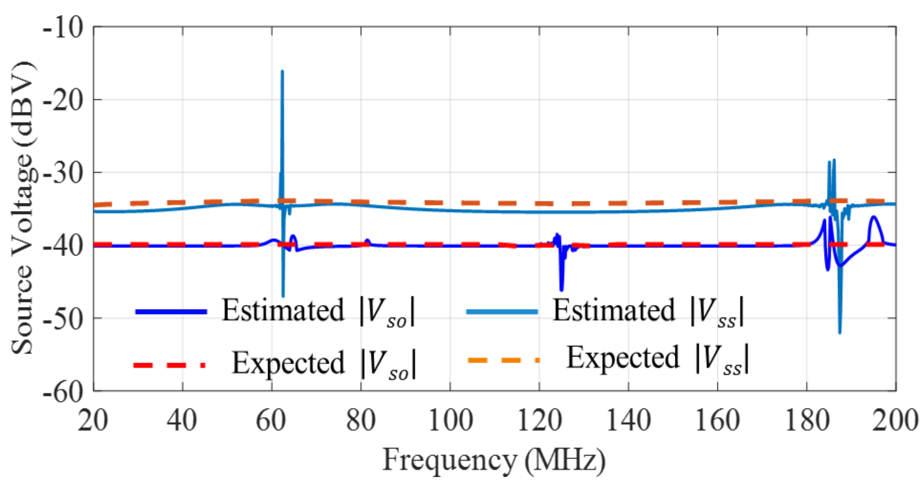
Table 1. Sources and loads in multi-wire harness.

Wire	Source Voltage [mV]	Phase [Degree]	Source Impedance [Ω]	Load Termination
Wire-1	2	0	10+20i	Open
Wire-2	8.1	30	50+40i	Open
Wire-3	5.9	0	1000+100i	Short
Wire-4	10.8	-20	1500+140i	Short
Wire-5	3.5	70	1750+155i	Short

Figure 5 shows the estimated values of the source impedances and the source voltages as a function of frequency from 20-200 MHz. The “expected” values are those that would best represent the current generated by the common mode sources in Table 1 for the tested configurations.



a



b

Figure 5. Estimated and expected values of: a) Magnitude of source impedance, and b) Source voltage.

Agreement between the expected and estimated source parameters are within 3 dB except around 60, 120 and 180 MHz, where the 1.2 m transmission line is a multiple of a quarter wavelength. At these frequencies the impedance looking into the transmission line is an "open" for those circuits terminated with an open or a short (depending on frequency), and produces no common-mode current from which to estimate the source. The estimated source is otherwise roughly constant with frequency, as is expected from the sources and loads in Table 1.

The common-mode current at the near-end of the 1.2 m harness is shown in Figure 6 as a function of frequency for both the original harness and as predicted by the estimated equivalent model. The equivalent model closely predicts the simulated currents (within less than 1 dB). A close prediction for this harness length is expected, since the equivalent circuit was built by "fitting" the current for this harness.

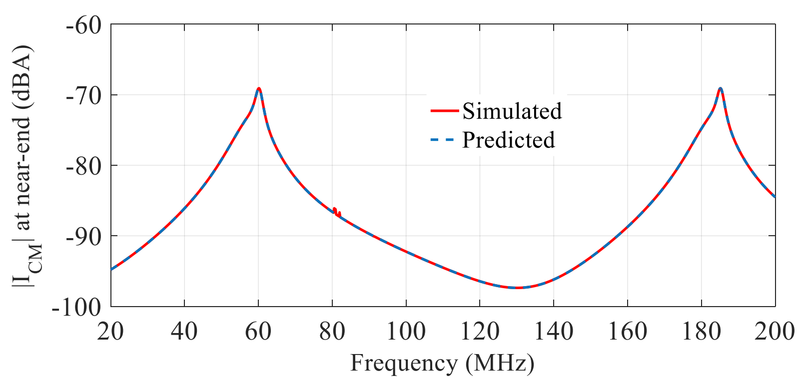
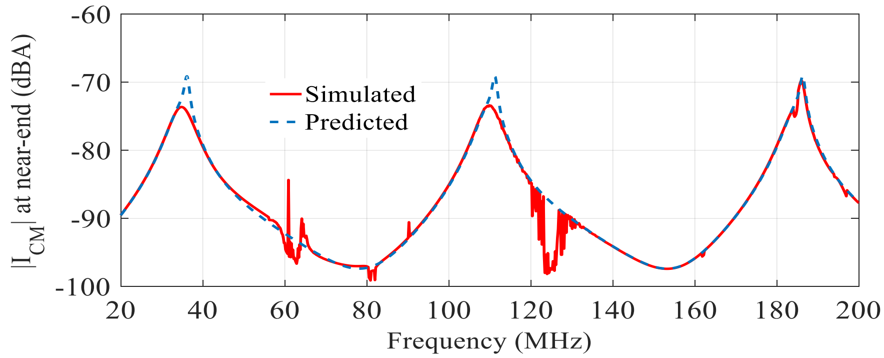
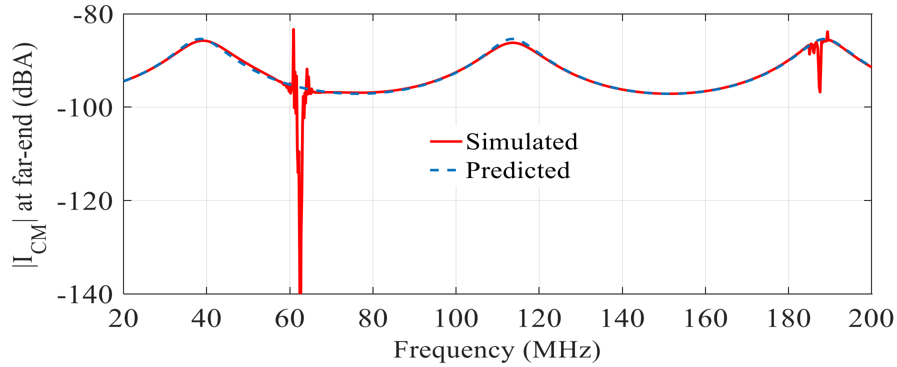


Figure 6. Simulated and predicted common-mode current on a 1.2 m harness.

The sources estimated from current on a 1.2 m harness were also used to predict common-mode currents on a 2.0 m long harness as shown in Figure 7. The predicted currents were within 3 dB of the simulated currents except at roughly 60, 120, and 180 MHz, where the source characteristics could not be estimated correctly.



a



b

Figure 7. Predicted and simulated common-mode current: a) at the near-end b) at the far-end of the 2.0 m harness.

The errors at 60, 120, and 180 MHz are a natural consequence of estimating the equivalent sources from currents on a single harness. The analytic formulations given in (20)-(25) make it possible to estimate the equivalent source using the magnitude of common-mode current, but are only valid for a single harness length. Other analytic formulations for the source that utilize multiple harness lengths different require both the magnitude and phase of the current. If a better estimate of the sources is required, but only the magnitude of current can be measured, the sources could be estimated using (20)-(25) for two harness lengths and then the two estimates combined using a weighted average. The weighted average should maximize the contribution from the harness with a large common-mode current and minimize the contribution with a small common-mode current, since the source can not be measured well when the current is very small. For example, if measurements were made on a 1.2 m and 1.8 m long harness, an improved estimate of the common mode sources could be found from

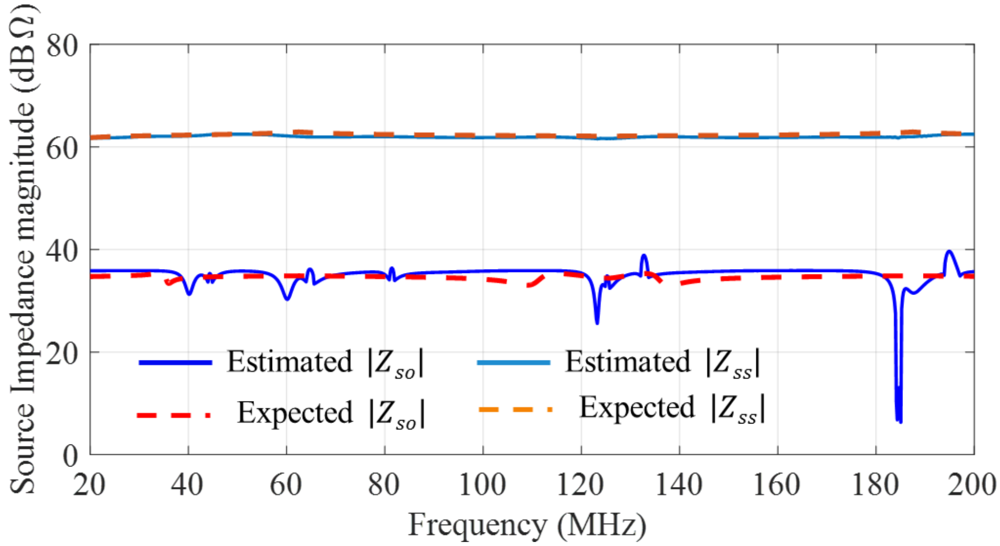
$$Z_{ss,eq} = \frac{I_{12short}}{I_{12short}+I_{18short}} * Z_{ss12} + \frac{I_{18short}}{I_{12short}+I_{18short}} * Z_{ss18} \tag{26}$$

and

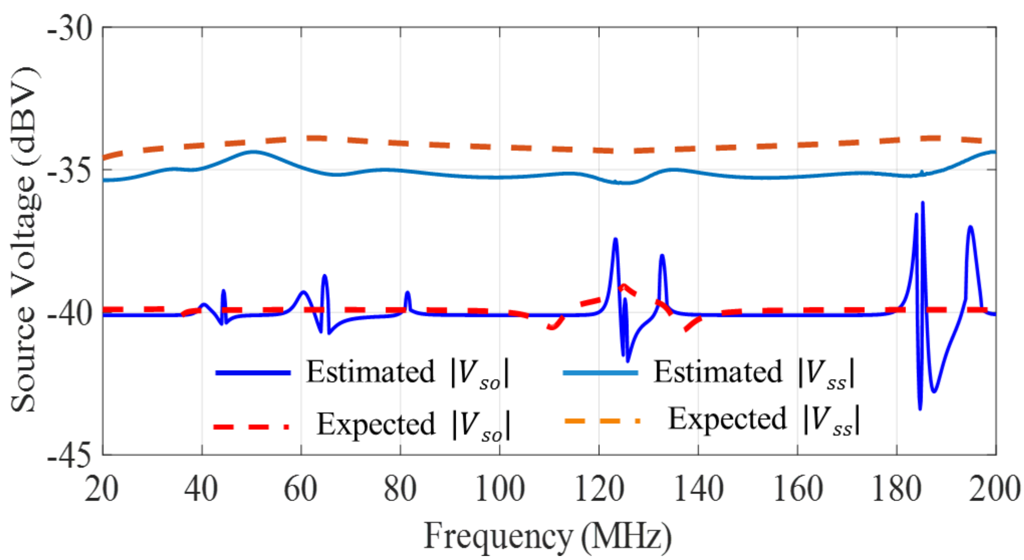
$$V_{ss,eq} = \frac{I_{12short}}{I_{12short}+I_{18short}} * V_{ss12} + \frac{I_{18short}}{I_{12short}+I_{18short}} * V_{ss18} \tag{27}$$

where $Z_{ss,eq}$ and $V_{ss,eq}$ are the equivalent source impedance and source voltage found from the weighted average, $I_{12short}$ and $I_{18short}$ are the currents inferred on the 1.2 m and 1.8 m circuits terminated with a short, respectively, Z_{ss12} and V_{ss12} are the estimated source impedance and voltage for the 1.2 m harness, and Z_{ss18} and V_{ss18} are the estimated source impedance and voltage for the 1.8 m harness.

Values for the source impedances and sources voltages found using the weighted averages in (26)-(27) are shown in Figure 8. The common-mode current found using this source at the near and far end of a 2.0 m harness is shown in Figure 9. While some errors persist at resonant frequencies, the impact of the resonances is substantially mitigated. The predicted currents were within 8 dB of those found from simulation.

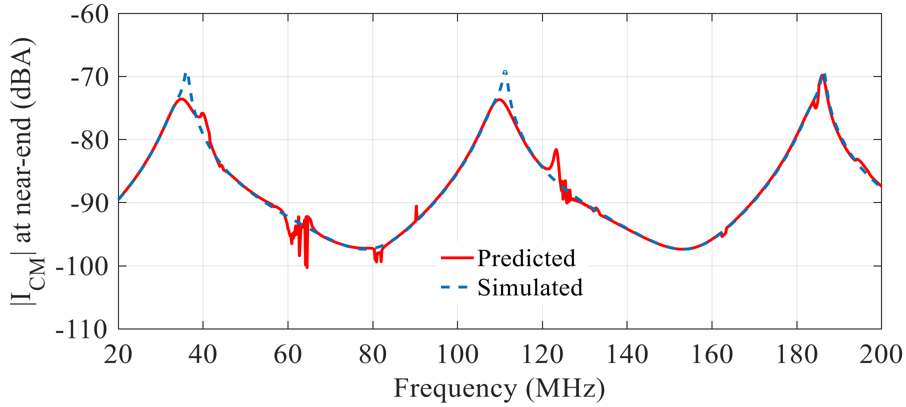


a

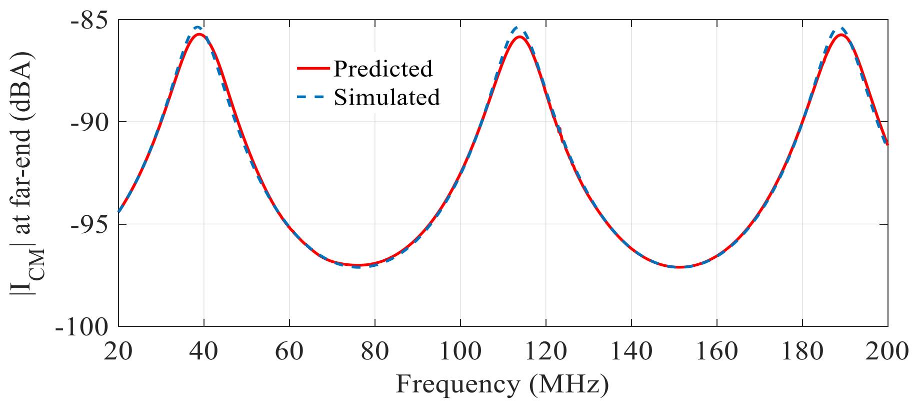


b

Figure 8. Estimated and expected values of: a) the magnitude of the source impedance, and b) source voltage found using a weighted averaging.



a



b

Figure 9. Predicted and simulated common-mode current at: a) the near-end and b) the far-end of the 2.0 m harness.

4. DISCUSSIONS AND CONCLUSIONS

A significant advantage of the proposed technique is that it requires relatively few, relatively simple common-mode current measurements during component-level tests to characterize the common-mode sources. Once know, these common-mode sources can be used to predict common-mode currents generated for a number of other harness configurations, and thus can be used to predict system-level radiated emissions problems early in the design process. Only the magnitude of the common-mode current is required which makes the measurement process much easier and faster. At least nine measurement are required for the technique to work, though additional measurements can improve the prediction accuracy and reduce the impact of measurement errors.

The proposed method varies the height of the source enclosure above the return plane to vary the impedance driven by the common-mode circuit and generate the data needed to estimate the source. Changing the height of the source is relatively easy and it is easy to measure the value of the added impedance. Care must be taken, however, as the added capacitance can cause common impedance coupling between the shorted and open-ended circuits, which is not accounted for in (20)-(25). This limitation should be recognized if using this method to characterize the source. Further work is needed to account for this common-impedance coupling

The proposed technique was shown to work well using simulated data. Further work is needed to validate the technique using real-world measurements of an actual component.

ACKNOWLEDGMENT

This paper is based upon work supported in part by the National Science Foundation under Grant No. IIP-1440110.

REFERENCES

[1] I. P. MacDiarmid, "The role of modelling in electromagnetic compatibility (EMC) design and clearance: a user's viewpoint," IEE Colloquium on Does Electromagnetic Modelling Have a Place in EMC Design, London, UK, pp. 3/1-3/4, 1993.

[2] R. Zamir, V. Bar-Natan and E. Recht, "System level EMC - from theory to practice," 2005 International Symposium on Electromagnetic Compatibility, Chicago, IL, pp. 741-743, Vol. 3, 2005.

[3] J. F. Dawson, A. C. Marvin and C. A. Marshman, "Management of electromagnetic interference at the design stage," IEE Colloquium on Design Management Environments in CAD, London, UK, pp. 311-314, 1991.

[4] G. Andrieu, A. Reineix, X. Bunlon, J -P. Parmantier, L. Koné, and B. Démoulin, “Extension of the “Equivalent Cable Bundle Method” for Modeling Electromagnetic Emissions of Complex Cable Bundles,” IEEE Transactions on Electromagnetic Compatibility, vol. 51, no. 1, pp. 108-118, Feb. 2009.

[5] C. Chen, “Predicting Vehicle-Level Radiated EM1 Emissions Using Module-Level Conducted EMIs and Harness Radiation Efficiencies,” in Proc. of the IEEE International Symposium on Electromagnetic Compatibility, vol. 2, pp. 1146-1151, Aug. 2001.

[6] D. Schneider, S. Tenbohlen, W. Köhler, “Pre-Compliance Test Method for Radiated Emissions of Automotive Components Using Scattering Parameter Transfer Functions,” in Proc. of the IEEE International Symposium on Electromagnetic Compatibility, EMC Europe, Sept. 2012.

[7] J. Jia, D. Rinas, S. Frei, “Predicting the Radiated Emissions of Automotive Systems According to CISPR 25 Using Current Scan Methods,” IEEE Transactions on Electromagnetic Compatibility, vol. 58, no. 2, pp. 409-418, Apr. 2016.

[8] S. Sun, G. Liu, J. L. Drewniak, D. J. Pommerenke, “Hand-Assembled Cable Bundle Modeling for Crosstalk and Common-Mode Radiation Prediction,” IEEE Transactions on Electromagnetic Compatibility, vol. 49, no. 3, pp. 708-718, Aug. 2007.

[9] S. Shinde, "Radiated EMI Estimation From DC–DC Converters with Attached Cables Based on Terminal Equivalent Circuit Modeling," in IEEE Transactions on Electromagnetic Compatibility, vol. 60, no. 6, pp. 1769-1776, Dec. 2018.

[10] G. Li, W Qian, A. Radchenko, J. He, G. Hess, R. Hoeckele, T. Van Doren, D. Pommerenke, D. G. Beetner, "Prediction of Radiated Emissions from Cables Over a Metal Plane Using a SPICE Model," IEEE Transactions on Electromagnetic Compatibility, vol. 57, no. 1, pp. 61-68, Feb. 2015.

[11] Z. Li, Z. J. Shao, J. Ding, Z. Y. Niu and C. Q. Gu, "Extension of the "Equivalent Cable Bundle Method" for Modeling Crosstalk of Complex Cable Bundles," in IEEE Transactions on Electromagnetic Compatibility, vol. 53, no. 4, pp. 1040-1049, Nov. 2011.

[12] G. Andrieu, L. Koné, F. Bocquet, B. Démoulin, and J.-P. Parmantier, "Multiconductor Reduction Technique for Modeling Common-Mode Currents on Cable Bundles at High Frequency for Automotive Applications," IEEE Transactions on Electromagnetic Compatibility, vol. 50, no. 1, pp. 175-184, Feb. 2008.

[13] T. Makharashvili, S. A. Walunj, R. He, B. Booth, K. Martin, C. Hwang, D. G. Beetner, "Prediction of Common Mode Current in Cable Harnesses," in Proc. of the IEEE International Symposium on Electromagnetic Compatibility and IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC), pp. 321-326, May 2018.

[14] C. R. Paul, Introduction to Electromagnetic Compatibility, 2nd ed. John Wiley & Sons, Inc., 2006.

II. RAPID MEASUREMENT-BASED CHARACTERIZATION OF COMMON-MODE SOURCES IN CABLE HARNESSES

S. Walunj

Department of Electrical Engineering

Missouri University of Science and Technology

Rolla, Missouri 65409–0050

Email: sw4p9@umsystem.edu

ABSTRACT

Prediction of common-mode currents in cable harnesses is essential for predicting radiated emissions from automotive systems. Predicting common-mode currents in the system from component-level tests is difficult, however, as the common-mode current changes dramatically form the component setup to the system because the common-mode impedances in the two configurations are different. Characterization of the common-mode sources in the component is essential for prediction of system-level common-mode current. A simple measurement-based approach for characterizing the common-mode sources is proposed which may be used when the common-mode load impedances are known. Common-mode source measurements are made by grouping sources together by their load and measuring the effective source voltage and impedance for the group through a characterization board. The method was validated by characterizing the sources of an engine controller and then predicting common-mode currents on harnesses of different lengths, and thus different load common-mode impedance. The worst error between the

predicted and measured common-mode current for two lengths of a multi-wire harness was less than 10 dB in the 20 MHz to 200 MHz frequency range.

Keywords: cable harness, automotive, system-level radiated emissions, equivalent source, common-mode current.

1. INTRODUCTION

Early prediction of radiated emissions can save time, money and resources [1]-[3]. Individual components are usually tested for radiated emissions problems before they are fitted into the complete system, but passing the component-level tests does not guarantee the system will also clear the radiated emissions requirements [4], [5]. The common-mode currents on the cable harnesses, and thus the associated radiated emissions, can vary significantly between the component and system because the common-mode load impedance may change significantly with changes in the harness configuration. A method is needed to predict the system-level emissions early in the design process using relatively simple component level tests.

Prediction of common-mode currents on cable harnesses has been the subject of numerous previous studies [4]-[11]. Common-mode currents can be predicted if complete information about the system is known [4], [11] but it is a time-consuming process. Moreover, knowing complete information about the system is not practical. In [6] and [7] the common-mode current is predicted reasonably considering the load information is known. Equivalent common-mode source information is found for the group of circuits terminated with impedances larger and smaller than the characteristic impedance of the transmission line (approximating an open and a short respectively). In [6], the equivalent common-mode sources are estimated by changing the length of the harness and measuring the magnitude and phase of the common-mode current on each length. Measuring the phase of the common-mode current on real systems is tricky because the currents are time-varying. The prediction accuracy depends on the source impedances of the dominant drivers of common-mode current. For better accuracy, the source impedances of dominant drivers should be similar. However, the existence of co-dominant drivers with different source impedances is possible in real systems. In [7], the equivalent common-mode sources are estimated using only the magnitude of the common-mode current on the harness when the source is lifted above the ground plane. Lifting the source introduces common impedance coupling between the sources which is not accounted in the formulations.

The objective of the following paper is to develop an experimental technique to efficiently determine the characteristics of equivalent common-mode sources which can reliably predict the common-mode currents on a variety of cable harness configurations. Central to this objective is creating a technique which requires description of only a few sources, rather than source information for every pin and coupling between every pair of pins, which could require thousands of measurements. The number of sources is reduced by grouping them according to their load impedances, which are assumed to be known for every pin. The loads do not have to be exactly the same but can be grouped into relatively broad categories, for example, if their impedance is small or large compared to the characteristic impedance of the transmission line over the frequency range of interest. The source voltages and impedances are measured for these groups along with the coupling impedances between them, by connecting the sources together through a characterization board so that measurements can be made on entire groups at one time. Once determined, the source information may be used to predict the common-mode current based on the harness configurations. Radiated emissions can then be predicted from these common-mode currents through simulations [4], [5], [10], [12]-[15].

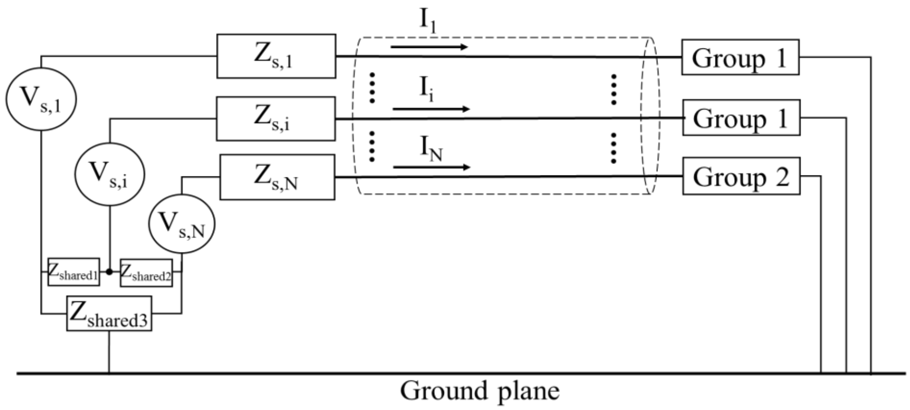
The theory and application of the approach are explained in the following paragraphs. The proposed technique was validated by determining the equivalent sources for a tractor engine controller. Common-mode currents were then predicted on harnesses of two different lengths and compared to measurements. The results show the potential of the technique to predict common-mode current on a variety of harness configurations.

2. THEORY

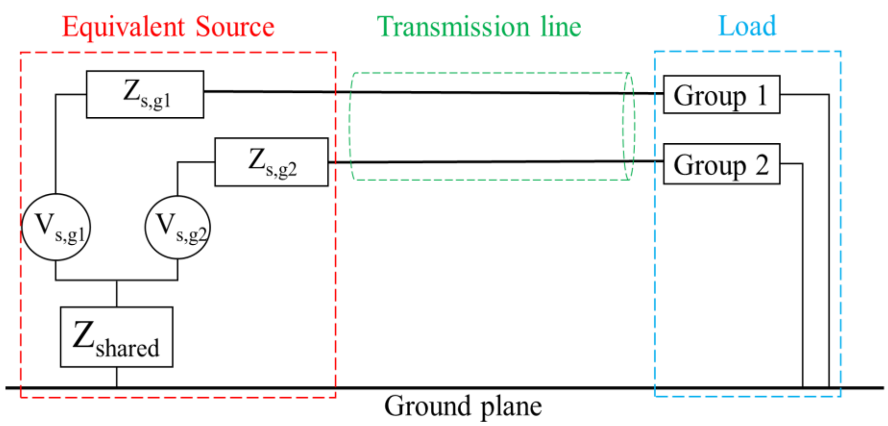
In a typical harness configuration, each wire has a source voltage, source impedance, common coupling impedance and a load as shown in Figure 1a. The common-mode current can be predicted accurately if all the information about the system is known. However, less information about the common-mode circuits is available in practical systems because it is mostly parasitic. It is possible to measure the source characteristics of each circuit but the measurements can get very time consuming because not only the source voltages and impedances of individual circuits is needed, the coupling between all the circuits is needed too. There could be as many as 100 pins in a system, in which case 100 source voltages and impedances are needed along with 4950 coupling impedances which can take unreasonable time to measure. Obtaining the accurate relative phase between the voltage sources would also be not possible due to a large number of circuits.

The spatial distribution of currents along the length of the transmission line depends on the impedance of the load compared to the characteristic impedance of the transmission line. Loads that are much smaller or much larger than the transmission line give roughly the same spatial distribution of currents. To simplify the complexity of a harness with a large number of common-mode circuits, an 'equivalent cable bundle method' is proposed in [4], [5], [11], and [16] where a large number of circuits in a harness are represented by an equivalent circuit depending on the source and load impedances. The proposed method is based on the similar concept. Here, the common-mode circuits are grouped depending on the size of the load impedances and hence only the load information is needed. Circuits terminated with similar load impedances are grouped together and equivalent source information is found through measurements for the equivalent circuits. The equivalent source model of a complex harness is shown in Figure 1b.

Wires in the harness shown in Figure 1a are terminated with two types of loads i.e. 'Group 1' and 'Group 2'. The equivalent circuit contains two circuits terminated with these two loads for which the source information needs to be measured. Vs,g1, Vsg2, Zs,g1 and Zs,g2 are the equivalent source voltages and impedances for circuits terminated with loads 'Group 1' and 'Group 2' respectively. Zshared is the common impedance between the two equivalent circuits representing the coupling. One huge advantage in grouping the circuits is that the number of sources and coupling impedances that needs to be characterized are greatly reduced as seen in Figure 1. The example shown in Figure 1 has two groups of loads, in practical circuits, there could be more than two groups e.g. loads that are much larger, smaller and equal to the characteristic impedance of the transmission line.



a



b

Figure 1. Common-mode circuit representing the harness: a) Original multi-wire harness. b) Equivalent two-wire system.

Once the termination loads are known, the pins on the system are grouped depending on the termination impedances. Source characteristics are measured for the group of pins sorted by the termination impedances. A characterization board is used to measure the equivalent source information for the groups. The characterization board is designed to short all the pins in the same group so that the equivalent sources can be measured for each group. It is fitted on the device under test (DUT) very close to the pins during measurements. Measurements are done using RF connectors soldered for each group on the characterization board. The equivalent sources are then used to estimate the common-mode current on a model of the equivalent transmission line.

The method is validated on a real system and the results are discussed in the upcoming sections. The system under test will be discussed first where the pins are grouped depending on the load terminations. The characterization board and equivalent source measurement procedure will then be discussed. Finally, the common-mode prediction results and improvements will be discussed.

3. DEVICE UNDER TEST

The DUT used for validation of this method is an engine controller with 7 active pins. 5 pins are used to power the controller with a DC power supply and the remaining 2 pins are used for data sensing. The DUT is powered up through a standard Line Impedance Stabilization Network (LISN) using a cable harness laid 5 cm above the ground plane as shown in Figure 2. The impedance offered by the LISN for the wires which are used to power up the DUT is 50 ohms each. Therefore the common-mode load impedance for this group of wires is 25 Ohms being parallel with each other. This is much lower than the characteristic impedance of the harness which is approximately 300 Ohms. The data pins are left open at the load because typically the data sensor outputs are small capacitances offering high impedances at frequencies below a few hundred megahertz. Keeping them open is also helpful for this validation as it forms another set of pins that can be grouped as being terminated with impedance much higher than the characteristic impedance of the transmission line. This way two groups of load terminations for this system are formed, i.e. group 1 with 25 Ohms offered by the LISN and group 2 with a parasitic capacitance of 5-15 pF at the open termination.

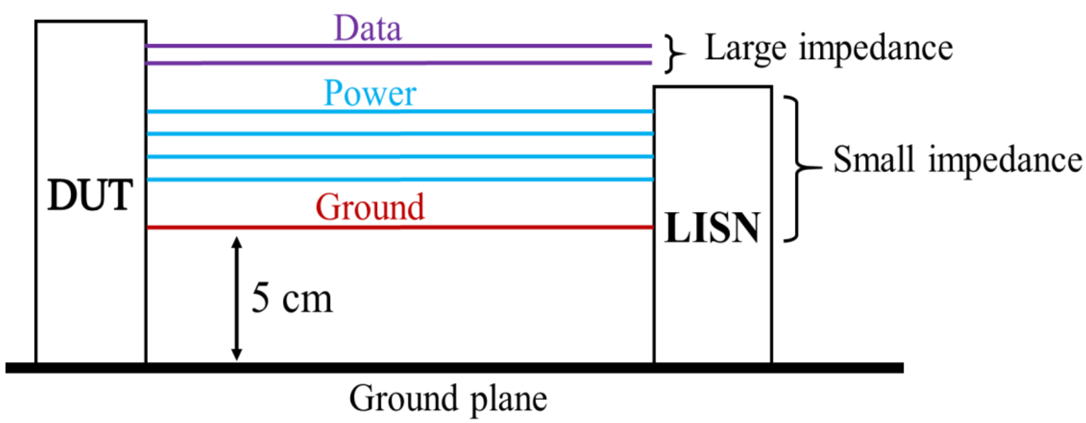
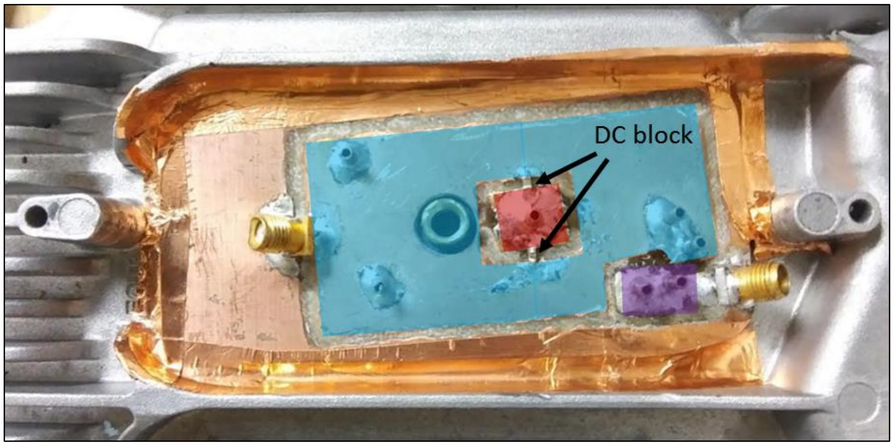


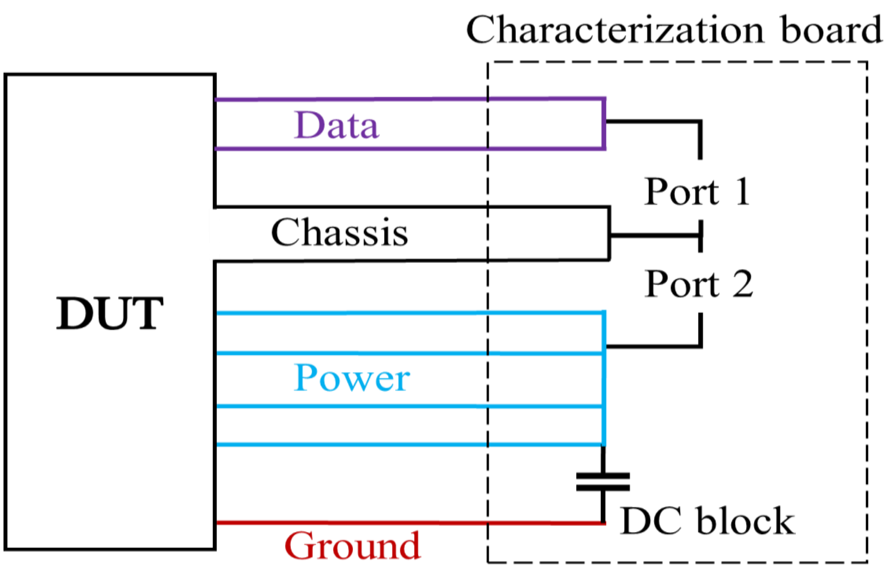
Figure 2. Grouping of the wires in the cable harness.

4. CHARACTERIZATION BOARD

A self-made characterization board is used for preliminary validation of this method as shown in Figure 3a. Figure 3b shows the circuit diagram of the board. The board is designed to short the pins corresponding to group 1 and group 2. In group 1, two DC blocking capacitors are soldered between power and ground such that they are shorted at the frequency of source characterization while providing an open at DC to power up the DUT. RF connectors are soldered for each group for measurement of source characteristics.



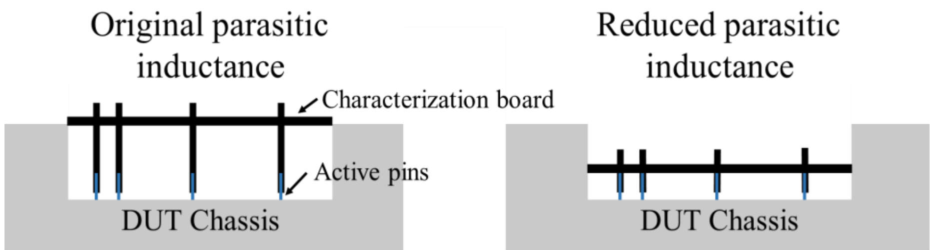
a



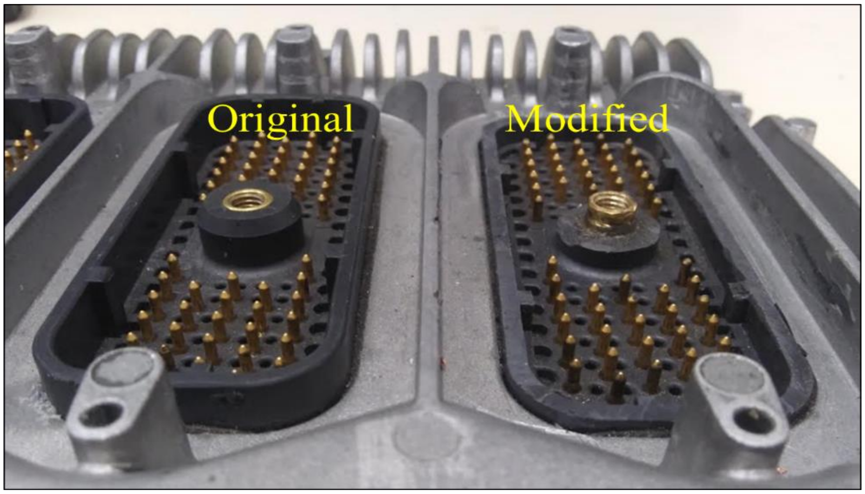
b

Figure 3. a) Characterization board mounted on the DUT. b) Circuit diagram of the characterization board.

The characterization board is fitted on top of the DUT for measurements. Placement of the characterization board close to the pins on the DUT is important to minimize the parasitic inductance introduced by the connecting pins as shown in the cross-sectional view in Figure 4a. This parasitic impedance can affect the measurement of equivalent source impedance and can also introduce unnecessary resonances in the measured source characteristics.



a



b

Figure 4. a) Minimizing parasitic inductance. b) Modified DUT connector.

On the DUT, a plastic sleeve around the connector obstructing the characterization board from being placed close to the pins was removed so that the board fits as close to the pins as possible. Figure 4b shows the original connector with the plastic sleeve and modified connector when the sleeve was removed.

5. COMMON-MODE SOURCE CHARACTERIZATION

The equivalent source impedances were measured using a network analyzer at the two RF ports available on the characterization board. For the system under consideration, three impedances were needed to be measured i.e. the equivalent source impedance of the two circuits and the coupling impedance between them. Two port S-parameter measurements were performed and then converted to Z-parameters. The common impedance between the two ports measured by the network analyzer (Z_{21}) represents the common impedance coupling between the two circuits. The coupling impedance (Z_{21}) was subtracted from the impedances seen looking into each circuit (Z_{11} and Z_{22}) to obtain the equivalent source impedance for the two circuits.

The equivalent source voltages were measured in time-domain using two channels of an oscilloscope as shown in Figure 5. Corrections in the measured source voltages were needed since the two circuits were coupled. Corrections were incorporated by circuit analysis and by calculating the contribution of the current from one circuit to the other through the coupling impedance.

The equivalent source voltages were calculated by

$$\begin{bmatrix} V_{s,g1} \\ V_{s,g2} \end{bmatrix} = \begin{bmatrix} A_x & -B_x \\ -A_y & B_y \end{bmatrix}^{-1} \begin{bmatrix} V_x \\ V_y \end{bmatrix}, \tag{1}$$

where

$$A_x = \frac{(Z_{shared} + Z_{s,g2} + R_{osc}) * R_{osc}}{(Z_{s,g1} + R_{osc}) * (Z_{shared} + Z_{s,g2} + R_{osc}) + (V_{s,g2} + R_{osc}) * Z_{shared}},$$

$$B_x = \frac{Z_{shared} * R_{osc}}{(Z_{s,g2} + R_{osc}) * (Z_{shared} + Z_{s,g1} + R_{osc}) + (V_{s,g1} + R_{osc}) * Z_{shared}},$$

$$A_y = \frac{Z_{shared} * R_{osc}}{(Z_{s,g1} + R_{osc}) * (Z_{shared} + Z_{s,g2} + R_{osc}) + (V_{s,g2} + R_{osc}) * Z_{shared}},$$

$$B_y = \frac{(Z_{shared} + Z_{s,g1} + R_{osc}) * R_{osc}}{(Z_{s,g2} + R_{osc}) * (Z_{shared} + Z_{s,g1} + R_{osc}) + (V_{s,g1} + R_{osc}) * Z_{shared}}.$$

V_x and V_y are the voltages measured by the oscilloscope for circuits terminated with group 1 and group 2 respectively. R_{osc} is the input impedance of the oscilloscope.

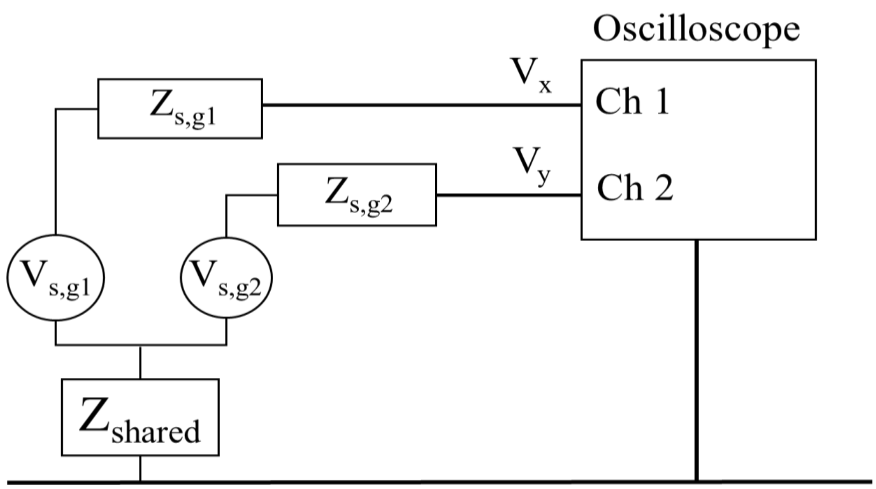


Figure 5. Equivalent source voltage measurement setup

The relative phase between the two equivalent circuits is needed for common-mode current prediction. The relative phase was calculated from the fast fourier transform of the time domain voltages measured for each equivalent circuit. Due to the time-varying signals from the DUT the equivalent source voltages needed to be measured simultaneously on the oscilloscope channels for accurate phase measurement. Only two oscilloscope channels were required because two types of load impedances exist in the system i.e. impedances much larger and much smaller than the characteristic impedance of the harness. The number of oscilloscope channels required for equivalent voltage measurement is the same as the number of groups. The phase of the circuit terminated with group 1 was assumed as 0 degree and the relative phase of the circuit terminated with group 2 was calculated by fast fourier transform.

The source voltages measured on the DUT are time-varying resulting in the different frequency spectrum for voltages measured at different times. To capture the peak voltages at all frequency points, the source voltages were measured multiple times at different time instances. The common-mode current was predicted for each set of measurement and then the peak current among these at all frequencies were compared with the measured peak common-mode current. 15-20 voltage measurements were found enough to find the peak common-mode current throughout the frequency range of interest.

6. PREDICTION OF COMMON-MODE CURRENT

To validate the technique, the measured source characteristics were used to predict the common-mode current on a harness and were compared against the true common-mode current found from measurements. The cable harness consists of 7 wires which were placed 5 cm above a large ground plane forming a transmission line connected to the DUT at one end and a LISN at the other end as shown in Figure 6. As discussed previously in section III, two data wires were left open at the LISN end of the harness and five were terminated through a low impedance to the ground plane by the LISN.

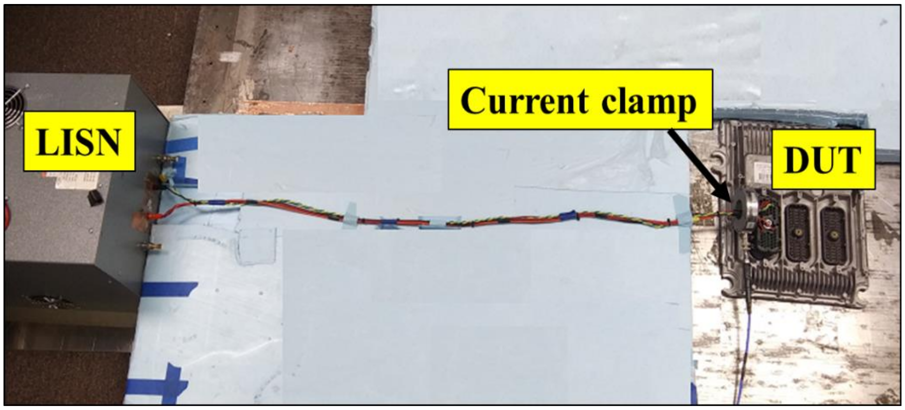


Figure 6. Measurement setup for common-mode current.

The DUT was powered by a DC power supply through the LISN. Two different lengths of cable harnesses, 1 m, and 2 m were used for validation. The common-mode current was measured at three locations: near the source, at the middle and near the load.

Common-mode current on the harness was measured using FCC F-61 RF current clamp. A low noise amplifier, ZFL-1000- LN+ was used to improve the signal-to-noise ratio because the magnitude of the common-mode current on the harness was low and was comparable to the noise floor of the measuring instrument. The common-mode current was measured on an R&S FSV30 spectrum analyzer with 100 kHz resolution bandwidth. The spectrum analyzer was set to provide optimal measurement sensitivity i.e. the RF attenuation was kept 0 dB and the pre-amplifier was turned on. To measure the peak common-mode current across the frequency range, max-hold trace was used on the analyzer.

The common-mode current was predicted in a circuit simulator using the equivalent source model shown in Figure 1b. The 7-wire cable harness was modeled as equivalent two-wire transmission line using the ‘equivalent cable bundle’ approximation described in

Section II. The two-wire transmission line was modeled in the circuit simulator by using approximately the same cross-sectional geometry as in the original cable harness i.e. the two wires were placed 5 cm above the ground plane separated by 2 mm to 10 mm distance from each other. The wires in the cable harness were insulated with thick insulation of approximately 1 mm and hence the minimum separation was kept as 2 mm. The maximum separation between the wires was found to be up to 10 mm due to random twisting along the length. The separation between the wires controls the coupling between them and the height above the ground plane controls the characteristic impedance.

As discussed in the previous section, the equivalent source voltages were measured multiple times due to the time-varying signal from the DUT. Common-mode current was predicted for each measured voltage and the maximum envelope among the predicted currents was compared with the worst-case current measured on the real system.

7. RESULTS

The peak common-mode current comparison between the measured and predicted current on the DUT is shown in Figure 7. Prediction results are shown for the realistic loads, i.e. 25 Ohm of the LISN and the parasitic capacitance of 5-15 pF of the open termination and for idealistic loads, i.e. an ideal short termination and an ideal open termination. Results with idealistic loads are compared because in few practical circuits, the real load impedances may not be accessible to measure but may approximately be larger, smaller or equal to the characteristic impedance of the cable harness.

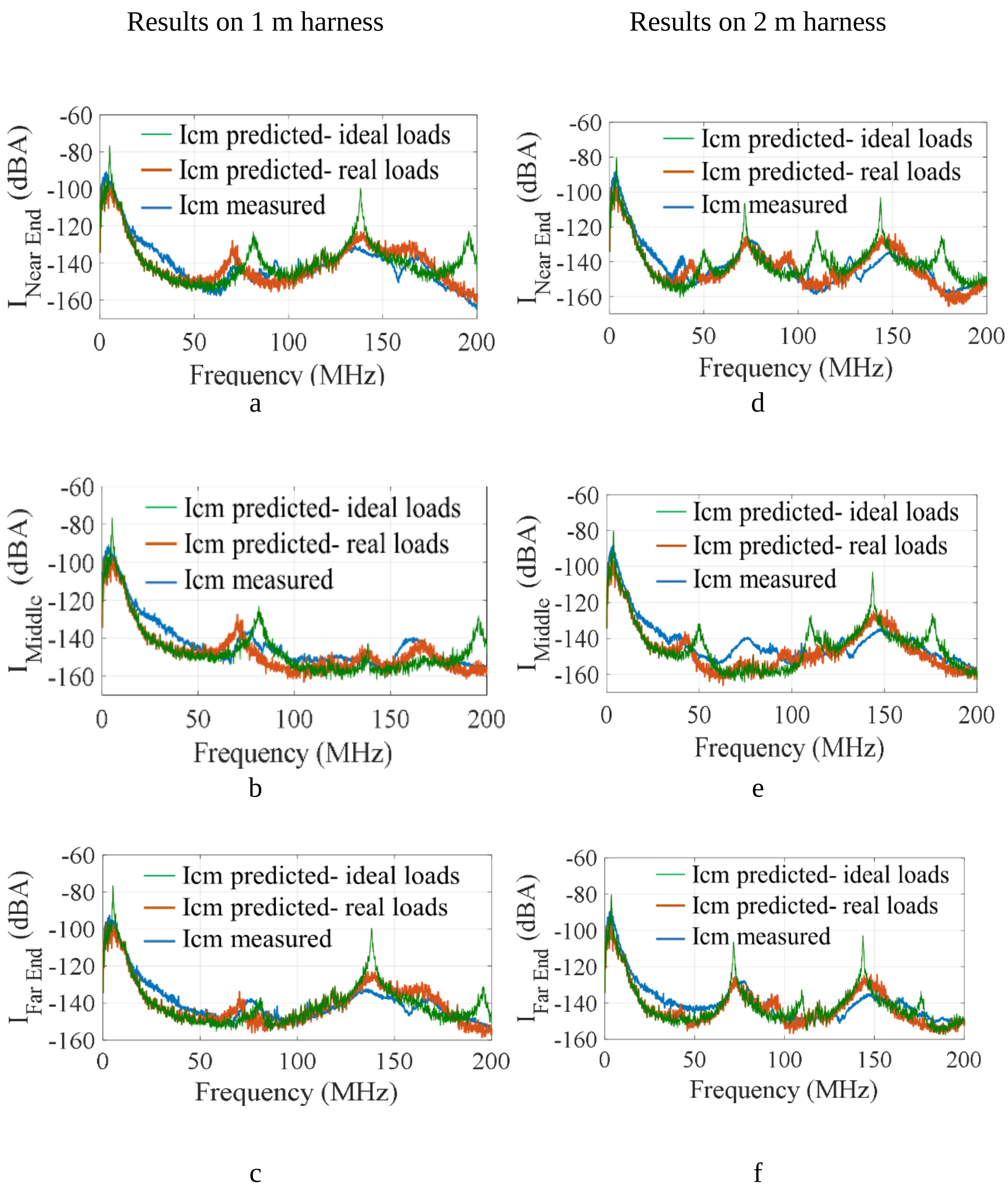


Figure 7. Common-mode current on: a) 1 m harness near the source. b) 1 m harness at the center of harness length. c) 1 m harness near the load. d) 2 m harness near the source. e) 2 m harness at the center of harness length. f) 2 m harness near the load.

The RMS error between the predicted and measured common-mode current is calculated by

$$Error_{rms} = \sqrt{\frac{\sum_{t=1}^{T}(Ip_t - Im_t)^2}{T}}, \tag{2}$$

where Ip_t is the predicted common-mode current, Im_t is the measured common-mode current and T is the total number of frequency points.

The worst RMS error calculated by (2) among the three locations for 1m and 2m long harnesses with realistic loads is 6.35 dB and 7.40 dB respectively and that with idealistic loads is 9.53 dB and 9.91 dB respectively.

8. DISCUSSIONS AND CONCLUSIONS

Information about the load impedances is essential for this technique so that many circuits in the system can be grouped into a few equivalent circuits and the number of sources that need to be characterized are significantly reduced as explained in Section II. This reduces the measurement time and efforts significantly.

The measurements performed in this work assumes two groups of load terminations i.e. terminations which are much smaller and much larger than the characteristic impedance of the transmission line. This is a reasonable assumption as many practical load terminations are inductive or capacitive hence offering either much smaller or much larger impedances at frequencies below few hundred megahertz. At higher frequencies, this assumption starts to fall apart as the impedance of an inductor start to increase and impedance of a capacitor start to decrease over frequency. This is the reason for the mismatch between the measured common-mode current and the predicted current with ideal loads in Figure 7. More than two groups of load impedance can exist in other practical cases e.g. a matched load. However, large or small impedances are typically important for radiated emissions as matched terminations do not introduce resonances.

A handmade characterization board is used for the measurements in the presented work. A well-fabricated board with less parasitic is expected to reduce the error between the predicted and measured common-mode current.

An approximate model of the equivalent transmission line based on the cross-sectional geometry of the original harness is used for prediction in this work. A more accurate model of the equivalent transmission line can be used for prediction using the 'equivalent cable bundle method' explained in [4], [5], [11], and [16]. Since a large number of wires are represented by only a few equivalent wires, a better transmission line model should represent the coupling between the wires more accurately. The model used in this study is only approximate and only mimics the geometrical dimensions of the original harness. However, the results show that the coupling between the wires in this generic model is still captured with reasonable accuracy.

The loads used for prediction, i.e. LISN impedance for group 1 and parasitic capacitance for group 2 are only expected values and are not measured. Using measured loads can result in lesser errors in predicted common-mode current than approximate loads.

Limitation of this method is that the information about the load impedances must be known in order to group the common-mode circuits and to reduce the measurement efforts. Another limitation is that different characterization boards are required for different devices because the pin map for the devices will not be the same. However, fabrication of the characterization board for different circuits is not difficult as it is only used to group/short the pins.

The method demonstrates that after characterizing the equivalent sources, the common-mode current can be predicted for a wide range of system configurations. Once the common-mode current is found, system-level radiated emissions can be predicted.

ACKNOWLEDGMENT

This paper is based upon work supported in part by the National Science Foundation under Grant No. IIP-1440110.

REFERENCES

[1] I. P. MacDiarmid, "The role of modelling in electromagnetic compatibility (EMC) design and clearance: a user's viewpoint," IEE Colloquium on Does Electromagnetic Modelling Have a Place in EMC Design, London, UK, pp. 3/1-3/4, 1993.

[2] R. Zamir, V. Bar-Natan and E. Recht, "System level EMC - from theory to practice," 2005 International Symposium on Electromagnetic Compatibility, Chicago, IL, pp. 741-743, Vol. 3, 2005.

[3] J. F. Dawson, A. C. Marvin and C. A. Marshman, "Management of electromagnetic interference at the design stage," IEE Colloquium on Design Management Environments in CAD, London, UK, pp. 311-314, 1991.

[4] G. Andrieu, A. Reineix, X. Bunlon, J -P. Parmantier, L. Koné, and B. Démoulin, “Extension of the “Equivalent Cable Bundle Method” for Modeling Electromagnetic Emissions of Complex Cable Bundles,” IEEE Transactions on Electromagnetic Compatibility, vol. 51, no. 1, pp. 108-118, Feb. 2009.

[5] C. Chen, “Predicting Vehicle-Level Radiated EM1 Emissions Using Module-Level Conducted EMIs and Harness Radiation Efficiencies,” in Proc. of the IEEE International Symposium on Electromagnetic Compatibility, vol. 2, pp. 1146-1151, Aug. 2001.

[6] T. Makharashvili, S. A. Walunj, R. He, B. Booth, K. Martin, C. Hwang, D. G. Beetner, “Prediction of Common Mode Current in Cable Harnesses,” in Proc. of the IEEE International Symposium on Electromagnetic Compatibility and IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC), pp. 321-326, May 2018.

[7] S. Walunj, F. Ma, T. Makharashvili, R. He, B. Booth, M. Kerry, C. Hwang, D. Beetner, “Experimental Characterization of the Common-mode Current Sources in a Cable Harness,” 2019 IEEE Symposium on Electromagnetic Compatibility, Signal & Power Integrity (EMC, SI & PI), Orleans, LA, USA, 2019.

[8] Geping Liu, D. J. Pommerenke, J. L. Drewniak, R. W. Kautz and Chingchi Chen, "Anticipating vehicle-level EMI using a multi-step approach," 2003 IEEE Symposium on Electromagnetic Compatibility. Symposium Record (Cat. No.03CH37446), Boston, MA, USA, 2003, pp. 419-424 vol.1.

[9] D. Schneider, M. Bottcher, B. Schoch, S. Hurst, S. Tenbohlen, W. Kohler, “Transfer Functions and Current Distribution Algorithm for the Calculation of Radiated Emissions of Automotive Components,” in Proc. IEEE International Symposium on Electromagnetic Compatibility, 2013, pp. 443–448.

[10] J. Jia, D. Rinas, S. Frei, “Predicting the Radiated Emissions of Automotive Systems According to CISPR 25 Using Current Scan Methods,” IEEE Transactions on Electromagnetic Compatibility, vol. 58, no. 2, pp. 409-418, Apr. 2016.

[11] G. Andrieu, L. Kone, F. Bocquet, B. Demoulin and J. P. Parmantier, “Multiconductor Reduction Technique for Modeling Common-Mode Currents on Cable Bundles at High Frequency for Automotive Applications,” IEEE Transactions on Electromagnetic Compatibility, vol. 50, no. 1, pp. 175– 184, 2008.

[12] D. Schneider, S. Tenbohlen, W. Köhler, “Pre-Compliance Test Method for Radiated Emissions of Automotive Components Using Scattering Parameter Transfer Functions,” in Proc. of the IEEE International Symposium on Electromagnetic Compatibility, EMC Europe, Sept. 2012.

[13] S. Sun, G. Liu, J. L. Drewniak, D. J. Pommerenke, “Hand-Assembled Cable Bundle Modeling for Crosstalk and Common-Mode Radiation Prediction,” IEEE Transactions on Electromagnetic Compatibility, vol. 49, no. 3, pp. 708-718, Aug. 2007.

[14] S. Shinde, "Radiated EMI Estimation From DC–DC Converters with Attached Cables Based on Terminal Equivalent Circuit Modeling," in IEEE Transactions on Electromagnetic Compatibility, vol. 60, no. 6, pp. 1769-1776, Dec. 2018.

[15] G. Li, W. Qian, A. Radchenko, J. He, G. Hess, R. Hoeckele, T. Van Doren, D. Pommerenke, D. G. Beetner, “Prediction of Radiated Emissions from Cables Over a Metal Plane Using a SPICE Model,” IEEE Transactions on Electromagnetic Compatibility, vol. 57, no. 1, pp. 61-68, Feb. 2015.

[16] Z. Li, Z. J. Shao, J. Ding, Z. Y. Niu and C. Q. Gu, "Extension of the “Equivalent Cable Bundle Method” for Modeling Crosstalk of Complex Cable Bundles," in IEEE Transactions on Electromagnetic Compatibility, vol. 53, no. 4, pp. 1040-1049, Nov. 2011.

SECTION

2. SUMMARY AND CONCLUSIONS

The research presents two methods to characterize the common mode currents in a harness bundle, using a few simple measurements at the component level. This characterization can be used to predict the common mode current on harnesses of arbitrary lengths even if the characteristic impedance of the harness changes. Once the common mode current is known, there are a variety of techniques that can be used to estimate the system-level radiated emissions.

The major advantage of the approach is that the measurement efforts that are needed to predict the common-mode current are greatly reduced. The advantages and limitations of each method is discussed in detail in previous section.

VITA

Sameer Sudha Arun Walunj earned his Bachelor of Science in Electronics and Telecommunication Engineering from Mumbai University, India in 2013. After completion of his bachelor's degree, he worked as a Research Scientist at the Society for Applied Microwave Electronics Engineering and Research, Mumbai, India for 3 Years. As a graduate student in the Electrical Engineering Department at Missouri University of Science and Technology, he worked as a Graduate Research Assistant under Dr. Daryl Beetner from December 2016 until August 2019. He received his Master of Science in Electrical Engineering from Missouri University of Science and Technology in December 2019.