Direct Measurement and Representation of Common-mode Sources in Cable Harnesses

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***Abstract*—Predicting common-mode currents in cable harnesses is essential for predicting radiated emissions early in the design process. Using component-level tests to predict system-level emissions is difficult, however, as the common-mode current seen in the component-level test may differ dramatically from that seen in the system. A component-level measurement-based approach for characterizing common-mode sources is proposed here which may be used to predict common-mode currents for a variety of harness configurations. Common-mode source measurements were made by grouping sources together by the size of the loads they drive and measuring the effective common-mode source voltage and impedance for the group through a characterization board. Common-mode currents were predicted using these sources and transmission line models of the harness. The method was validated by characterizing sources in an engine controller from 20 MHz to 200 MHz and then predicting common-mode currents on harnesses of a variety of lengths, and thus for different common-mode impedances looking into the harness. The worst error between the predicted and measured common-mode current was less than 7 dB in the 20 MHz to 200 MHz frequency range.**

***Keywords*—cable harness, automotive, system-level radiated emissions, equivalent source, common-mode current**

I. Introduction

Early prediction of radiated emissions problems in automotive systems can save time, money and resources [1]. Individual components are usually tested for emissions problems before they are placed within the complete system, but passing component-level tests does not guarantee the system will also pass emissions requirements. Method are needed which allow accurate prediction of system-level emissions early in the design process using relatively simple component-level tests.

Predicting emissions requires accurate knowledge of common-mode currents on cable harnesses [2]-[8]. Differential-mode current also adds to the emissions but not as significantly as its common-mode counterpart. Common-mode currents are often found through measurements. They can be predicted if complete information about the common-mode characteristics of the system is known [5]-[7], but this information is rarely available.

One approach for predicting radiated emissions is to insert a measurement of the common-mode current made at the component level into the system-level simulation [2]-[4]. This approach works poorly, however, because the common-mode current may change dramatically from one setup to another. The current changes with the common-mode impedance seen looking into the harness, which is a function not only of the load but also of the harness length, return plane configuration, and more. Characterizing the common-mode source and source-impedance can overcome this problem [7], but estimating only a single source is not sufficient [8]-[10]. For example, consider the case where the common-mode termination for some circuits is an open and for other circuits is a short. Whether the source sees an open or a short looking into the transmission line formed by the harness will depend on the length of the harness, which means that the dominant sources (driving the shorts or opens) also depends on the harness length.

The objective of the following paper is to develop an experimental technique to efficiently measure equivalent common-mode sources from component-level tests, and to use these sources to predict the common-mode currents on cable harnesses of different configurations. To keep the process practical, the number of measurements must be minimized, which also means minimizing the number of source descriptions. The number of sources is reduced by grouping circuits according to their common-mode loads, which are assumed to be known. The source voltages and impedances are measured for these groups using a characterization board which allows measurements to be made among entire groups at one time. The resulting source information may be used to predict common-mode currents for a variety of harness configurations. These common-mode currents could then be used to predict radiated emissions in a full-wave simulation model.

II. Theory

A typical representation of the common-mode circuit for a harness of N wires is illustrated in Fig. 1a. Each circuit has a common-mode source voltage, source impedance, and load, and is connected to their loads through a harness, which can be represented as a multiconductor transmission line. Coupling exists between the circuits both in the source and along the transmission line. For illustration, this coupling is only shown simply in the figure. Coupling can also exist in the load, though this coupling is typically less important and is ignored for the case considered here. While it is possible to measure the common-mode characteristics of every circuit within the harness, this characterization is rarely practical because of the large number of measurements required. A 100-pin harness, for example, would require more than 5000 measurements to fully characterize.

The measurement process can be simplified by grouping common-mode sources according to their loads [8]-[10]. The spatial distribution of currents along a transmission line depends on the relative size of the load compared to the

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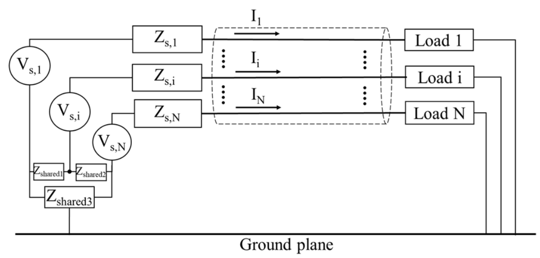
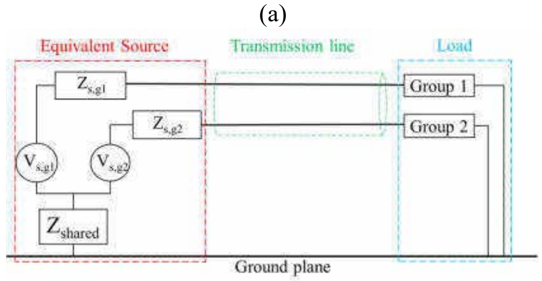
characteristic impedance of the transmission line. Loads that are much smaller or much larger than the characteristic impedance will create roughly the same spatial distribution of currents. As a result, loads do not have to be exactly the same size to be placed into the same group, which allows the possibility of forming only a few groups of loads. The common-mode loads are also more likely to be known than the common-mode sources, and may be repeated regularly throughout a design (e.g. when loads feed similar inputs or see similar filter capacitors or ferrites). Fig. 1b shows an example equivalent circuit representation for the circuit in Fig. 1a, assuming loads can be approximated in two groups. Characterization of the equivalent source voltages, $V_{s,g1}$, V_{sg2}, equivalent source impedances, $Z_{s,g1}$ and $Z_{s,g2}$, and the shared common-mode impedances between these circuits, Z_{shared}, can be performed using a characterization board which groups these circuits together as part of the measurement.



(a)



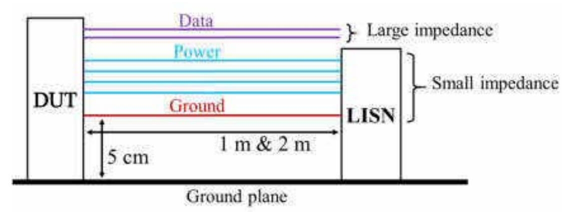
(b)

Fig. 1. Common-mode circuit representing the harness (a) Original multi-wire harness; (b) Equivalent two-wire system.

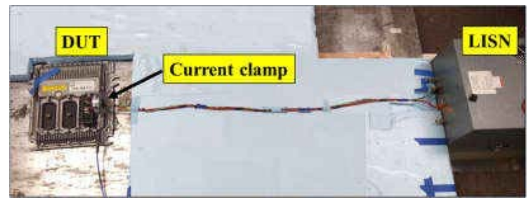
III. Experimental Characterization

To show the feasibility of this approach, equivalent sources were characterized for a simple 7-wire harness connected to an engine controller as indicated in Fig. 2. Five pins are associated with DC power or return and two are used for data. The Power and return pins were connected to a Line Impedance Stabilization Network (LISN) at the far end of the harness, with a common-mode load of 25 ohms. The data pins were left open at the load to approximate the small input capacitance associated with a digital input gate. The power and return pins were lumped into one equivalent circuit (with termination much smaller than the transmission line impedance), and the data pins were lumped into a second equivalent circuit (with termination much larger than the transmission line impedance).

A characterization board was used to measure the equivalent source voltages and impedances for the two equivalent circuits, as illustrated in Fig. 3. The board was designed to "short" the pins at high frequencies in each group, allowing the entire group of pins to be accessed using a single RF connector. DC blocking capacitors were used to isolate pins, to prevent DC connections between Vdd and Vss. The characterization board was fitted into the connectors of the DUT to minimize the impact of the parasitic inductance of the connector on the source characterization. The return plane of the board was connected to the chassis with copper tape.



(a)



(b)

Fig. 2. The approach was tested with a 7-wire harness connected to an engine controller: (a) diagram and (b) picture of experimental setup.

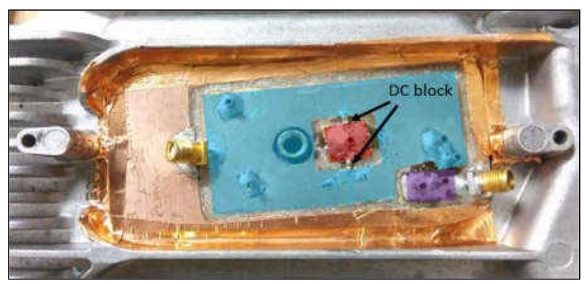


Fig. 3. Characterization board mounted into connector.

Two-port network analyzer measurements were used to determine the equivalent source impedances, $Z_{s,g1}$, $Z_{s,g2}$, and Z_{shared}. Measurements were performed with the engine controller turned on using a battery source and short wires. Effect of this battery and external wires was not considered in the calculation of the source because the impedance offered by the battery is much larger than the impedance looking into the source. The equivalent source voltages $V_{s,g1}$ and $V_{s,g2}$ were measured using an oscilloscope to allow capture of both the magnitude and the relative phases of the sources. The magnitude and phase was found with the fast-Fourier transform. The phase of $V_{s,g1}$ was set to zero. To eliminate the influence of the source impedances, source voltages were found using the equation:

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

where

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

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

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

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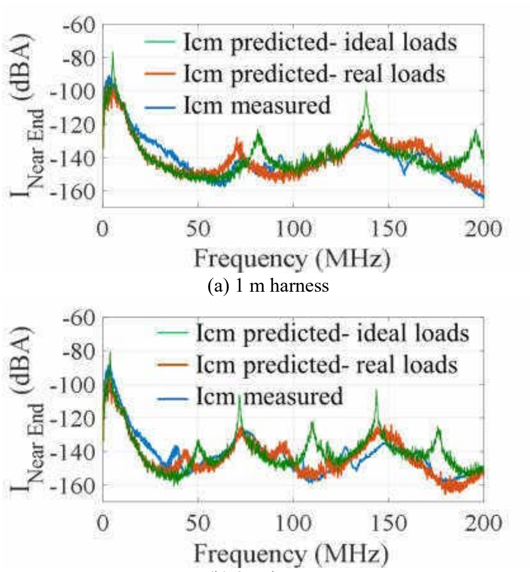
$$B_y = \frac{(Z_{shared} + Z_{s,g1} + R_{osc}) * R_{osc}}{(Z_{s,g2} + R_{osc}) * (Z_{shared} + Z_{s,g1} + R_{osc}) + (Z_{s,g1} + R_{osc}) * Z_{shared}},$$

R_{osc} is the input impedance of the oscilloscope, and V_x and V_y are the voltages measured by the oscilloscope for equivalent circuits 1 and 2, respectively. Equation 1 is derived by solving the Thevenin equivalent source in Fig. 1b when connected to the oscilloscope. To capture the peak current, the source voltages were measured over 15-20 separate sweeps of the oscilloscope. Common-mode current was predicted for each measurement and the peak current at each frequency among all measurements was compared to the peak current measured with a spectrum analyzer.

Measured and predicted common-mode current from 20-200 MHz were compared for the harness in Fig. 2. Measurements were made with a common-mode current clamp and a spectrum analyzer set to a 100 kHz resolution bandwidth and max-hold. Common-mode currents were predicted in ADS using the equivalent circuit in Fig. 1. The equivalent common-mode sources were connected to a two-wire coupled transmission line. The transmission line was modeled in ADS as being 5 cm above the ground plane with wires separated by 2-10 mm from one another. The loads were set to the impedance of the LISN or the capacitive termination of the data lines.



(a) 1 m harness

(b) 2 m harness

Fig. 4. Comparison of predicted and measured common-mode currents at the near ends of 1 m and 2 m long harnesses.

IV. Results

Fig. 4 shows a comparison between the measured and predicted common-mode currents. Predicted results are shown both for the "true" loads (25 ohm for the LISN and 5-15 pF for the data lines), and for ideal loads approximating a short or an open. Results with shorts or opens are considered to show the accuracy of the approach when the real load impedances are not known but might be reasonably approximated as much larger or smaller than the characteristic impedance of the cable harness. Results are shown at location near to the source for both a 1m and 2 m long harness. The RMS error was less than 3.5 dB for the 1 m harness and less than 5.6 dB for the 2 m harnesses when using realistic loads. The error was 4.9 dB and 6.5 dB, respectively, when using ideal loads. While the RMS error was reasonable for the case with shorted or open-ended loads, the predicted current at resonances were (not surprisingly) significantly overestimated.

V. Discussions and Conclusions

By grouping circuits by their termination, the number of measurements required to characterize the common-mode sources is reduced dramatically. Information about the size of the common-mode loads is required, however, at least approximately. For the system tested here, the approach was able to predict the measured common-mode current within less than 7 dB for more than one harness configuration. This level of accuracy is more than sufficient to determine where potential problems may occur in future system-level tests.

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