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Effect of Ground Proximity on Common-mode Currents in Wire Harnesses

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Abstract

Common-mode currents are the most significant source of radiated emissions from wire harnesses. Differential-mode signals are converted to common-mode currents whenever the electrical balance of the wire harness changes. Wire harnesses may experience a change in their electrical balance when the distance from the wire harness to the ground structure changes. This paper explores the effect of ground proximity on the induced common-mode currents in wire harnesses.

1. Introduction

Common-mode currents play a key role in unintentional radiated emissions. Clayton Paul [1] and many others have demonstrated that common-mode currents radiate much more effectively than differential-mode currents. Conversion from differential mode to common mode occurs when there is a change in the electrical balance of a transmission line. The key to preventing differential-mode signals from inducing common-mode currents is maintaining the same level of electrical balance or imbalance all the way from the signal source to the signal termination.

An imbalance difference model describing how differential- to common-mode conversion occurs resulting in radiated emissions was first introduced by Watanabe et al. [2], [3]. It was later rigorously derived and validated by Niu et al. [4]. Niu demonstrated that imbalance difference calculations are exact provided that the imbalance factor, h, represents the actual ratio of currents on the two transmission line conductors excited by a common-mode source.

In [5], the author demonstrates that placing extra ground on the other side of a signal trace in a printed circuit board reduce the radiation emissions. This paper provided insight about the importance of ground proximity, without directly referencing electrical imbalance.

Changyi Su et al. [6] demonstrated how to apply the imbalance difference model to the analysis of radiation from circuit boards due signal trace terminations. Several other authors have also demonstrated useful ways of applying the imbalance difference method to estimate the radiated emissions from circuit board geometries [7]–[12]. Tetshushi Watanabe et al. [13], [14] estimate radiated emissions due to the common-mode currents caused by a signal line in the vicinity of the ground plane edge on a PCB.

These papers showed that ground proximity and asymmetric geometries affect electrical balance changes resulting in common-mode currents.

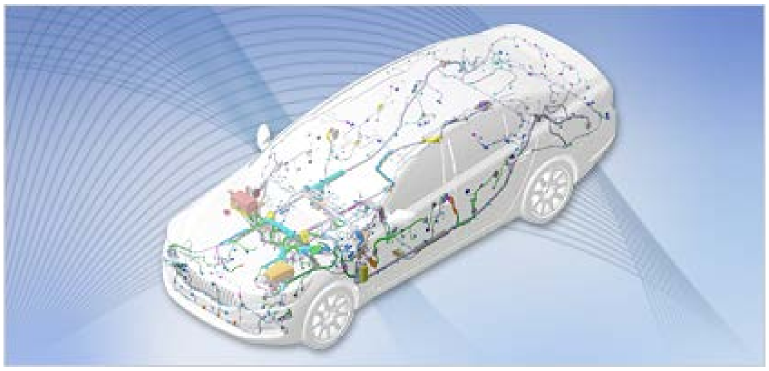


Fig. 1. Wire harnesses in an automobile.

It is common practice to use wire harnesses to carry electronic signals in metallic structures such as automobiles as shown in Fig. 1. The relative location of wires change as they move through the harness, some wires may peel off and go in a different direction from other wires in the harness. Sometimes the harness is run in close proximity to the frame of the car, other times it's routed away from the frame. In other words, for any intentional or unintentional currents flowing on the wires in the harness and returning on the frame, automotive wire harnesses can experience significant changes in electrical balance. The wire harnesses typically have ground wires designed to provide a return path for high-frequency currents and reduce radiated emissions. However, the electrical balance of harness that have ground wires is still affected by changes in the proximity of the wire harness to the frame.

This paper explores the impact of wire harness proximity to ground on the generation of common-mode currents. Section 2 explains how to calculate the common-mode voltage from the differential-mode voltage for a given transmission line and describes a test setup for evaluating the effect of changes in the harness-to-frame proximity. Section 3 discusses the test results and validates the results using the imbalance difference method. Finally, the conclusions of the study are summarized in Section 4.

2. Wire Harness Geometry under Study

2.1 Conversion to common-mode voltage from differential-mode voltage

It is common to send differential signals through twisted wire pairs in a wiring harness. For example, controller area network (CAN) is a network widely used in the automotive industry. The CAN signaling is differential but common-mode currents flow on CAN wire pairs [15]. These common-mode currents don't result in significant radiated emissions if they return on another wire in the harness or in the nearby vehicle frame. However, antenna-mode currents that flow in one direction on all conductors play a key role for radiated emissions. The antenna-mode currents are result of changes in the imbalance of the harness structure [16]. The test set-up is designed to explore the effect that changes in the proximity of the vehicle frame have on the imbalance and therefore the antenna-mode currents.

The wire harness in the test set up has three wires as shown in Fig. 2. Two of the wires are a twisted wire pair. Both wires in the pair carry current in the same direction, representing the unintentional common-mode current generated by a differential signal source such as a CAN transceiver. The third wire is a ground wire that serves as a return path for the currents flowing on the twisted wire pair. Any change in the imbalance factor observed by the signal currents propagating down the wire pair and returning on the ground wire will result in a voltage that drives antenna-mode current onto the structure [2, 4]. The driving voltage will be,

$$V_{AM} = \Delta h \times V_{CM} \tag{1}$$

where V_{AM} is the common-mode voltage driving the structure, Δh is the change in the imbalance factor, and V_{CM} is the common-mode voltage on the twisted wire pair [16].

2.2 Description of the test setup

The geometry and cross-sectional view of the wire harness under study are illustrated in Fig. 2.

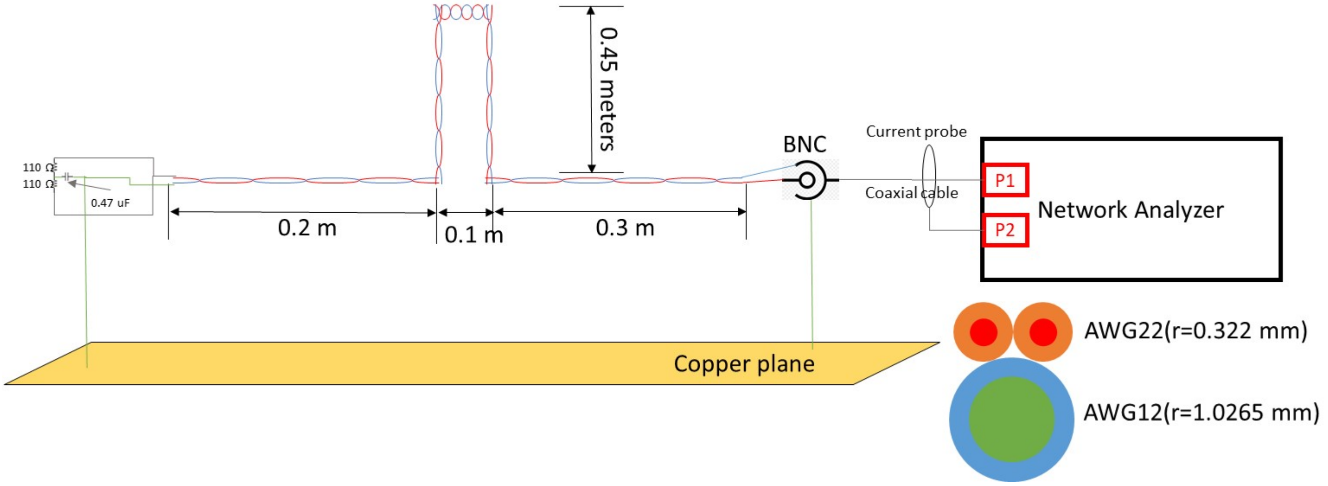
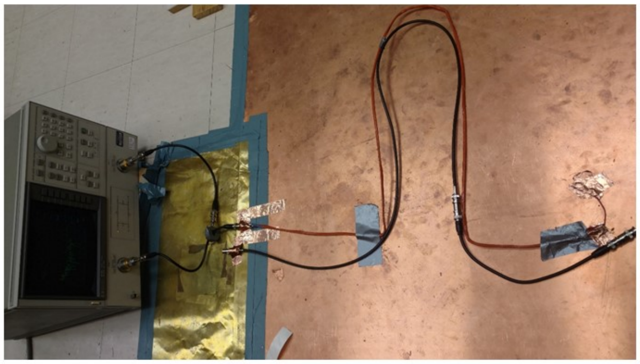


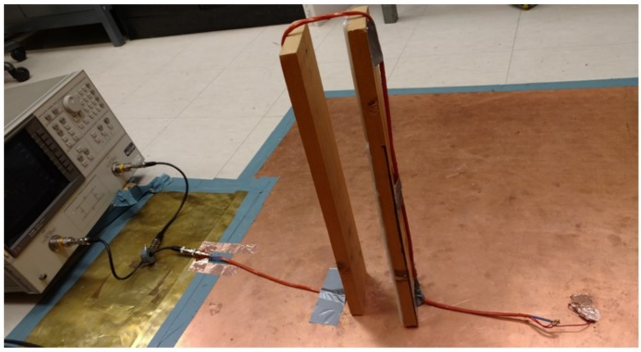
Fig. 2. Schematic view of the test environment and wire harness geometry.

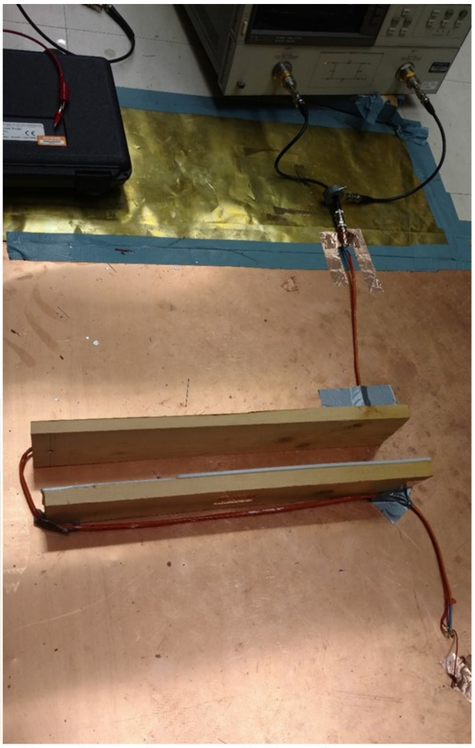
A network analyzer drives a signal down a coaxial cable. The analyzer and the cable are perfectly unbalanced (i.e. h=0). The network analyzer signal sweeps in frequency from 50 MHz to 450 MHz. The coaxial cable drives a wire harness. The center conductor of the coaxial cable connects simultaneously to both wires in a twisted wire pair. The shield of the coaxial cable connects to a larger “ground” wire in the harness. The analyzer signal simulates a common-mode current being driven on the twisted wire pair and returning on “ground” or other wires in the harness. A current probe is used to measure the antenna-mode current induced on the coaxial cable.

The twisted wire pair consists of two AWG22 wires. The “ground” wire is AWG12. The cross-sectional areas of wires are 0.326 mm^2 for each of the AWG22 wires and 3.31 mm^{2}for the ground wire. The wire insulation is polyvinyl chloride ($\varepsilon_r = 3$). The wire harness was carefully made to maintain the same cross-section geometry from one end to the other. A copper plane was placed underneath the wire harness and the coaxial cable. A split termination load (two 110-ohm resistors to ground) was used to terminate the twisted wire pair at the load end. The CM impedance of the termination was 55 ohms in order to nearly match the CM impedances of the wire harness and the coaxial cable. The ground plane was connected to the ground wire at the both ends so the current could return either on the ground wire or the ground plane



(a) Noise floor measurement using a coaxial cable





(b) Bending wires vertically respect to the copper plane (c)Bending wires parallel to the copper plane

Fig. 3. Test setup for each bending configuration.

Three configurations were tested, as shown in Fig. 3. To determine the level of common-mode current on the coaxial cable due to ambient noise sources, wire harness was replaced with an equal length of coaxial cable as shown in Fig. 3(a). In this configuration, there is no imbalance change and no reflected voltage at the load, because the cable is terminated by the matched impedance.

The other two configurations include the wire harness illustrated in Fig. 2. In both of these configurations, the wire harness extends for 30 cm, makes a 90-degree turn, extends another 45 cm, turns back to the original direction and extends another 10 cm, turns 90 degrees again and back-tracks to its original axis, then extends another 30 cm to the termination. In one configuration, Fig. 3c, the harness maintains a constant proximity to the ground plane. In the other configuration, Fig. 3b, the harness starts and ends near the ground plane, but loses proximity to the plane in the middle.

3. Results and Discussion

The common-mode characteristic impedance of the wire harness was calculated using a 2D field solver. It varied depending on the harness proximity to the plane from 46 ohms to 56 ohms. Using the same 2D field solver, the imbalance factors were calculated. When the harness is in close proximity to the plane, the imbalance factor is $h = 0.0305$. When the harness is 45 cm above the plane, the imbalance factor is $h = 0.3863$.

The change in the imbalance factor at the interface between the coaxial cable and wire harness equals the imbalance factor of the wire harness. When the wire harness maintains its proximity to the plane, this is the only source of antenna-mode current driving the coaxial cable.

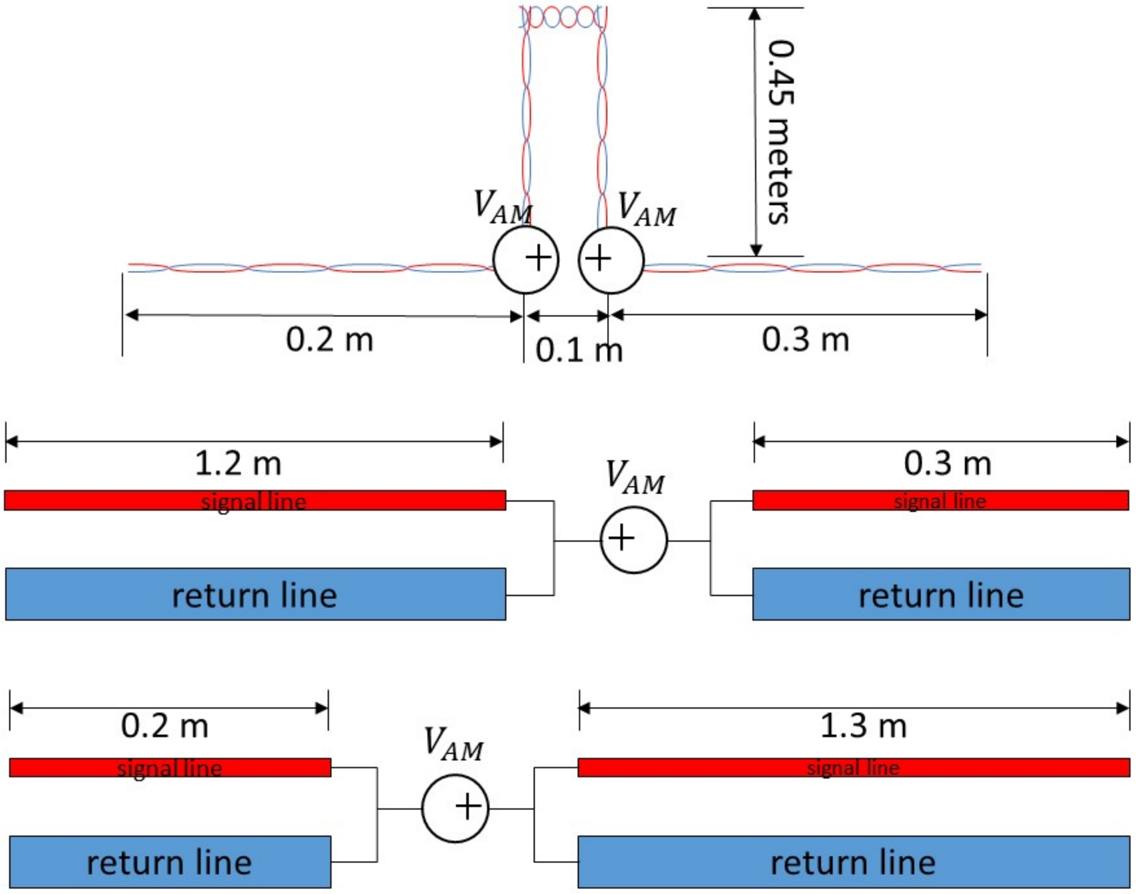


Fig. 4. Common-mode excitation on the vertically bended wire harness.

When the harness loses its proximity to the plane then gets it back again, two more sources of antenna-mode current with opposite polarities are created as shown in Fig. 4. The amplitude of the antenna-mode current due to the voltages at the two vertical bends is not easily calculated because the antenna is a complex geometry that includes the coaxial cable, network analyzer, etc. However, analyzing the average input impedance at the each voltage source allows one to estimate the average antenna-mode current due to the combination of the two sources.

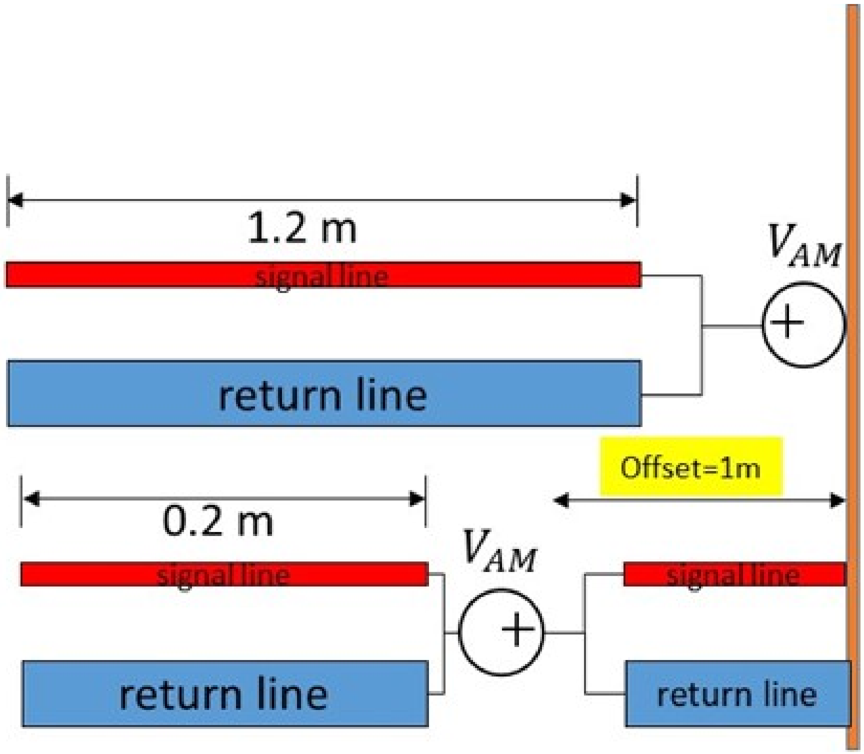


Fig. 5. The quarter-wave monopole antenna modelling.

In Fig. 5, the right half of the wire harness, coaxial cable, network analyzer and building ground structure are represented by an infinite ground plane. The source at the first bend drives the left half of the harness relative to this plane. The second source is offset from the first, closer to the end of the structure.

The offset position (z) is 1 meter from the center of the monopole and the length of the monopole (l) is 1.2 meters. On average, the input impedance of the second source is higher than the input impedance of the first source, because of its proximity to the end of the harness. To estimate the relative input impedance of the voltage sources, a full-wave simulation is performed by FEKO.

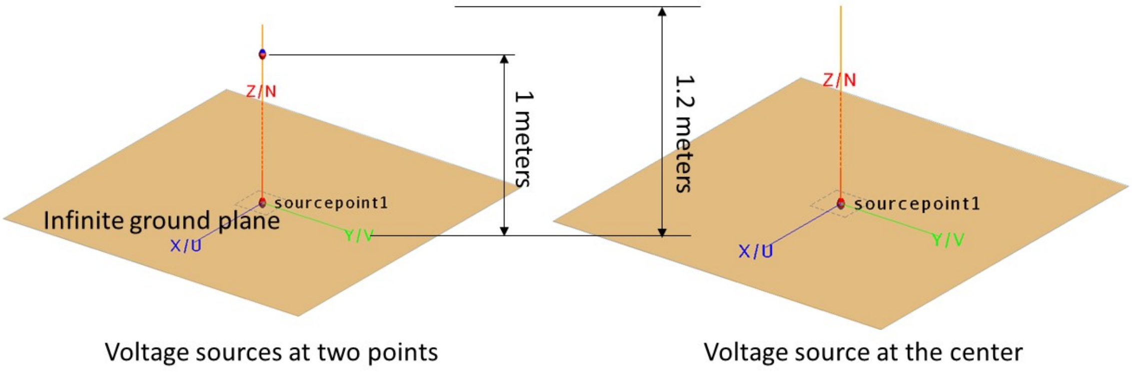


Fig. 6. Full-wave simulation configuration.

The full-wave simulation test setup is shown in Fig. 6. The monopole antenna has two voltage sources, one at the center of the monopole antenna and one that is 1 meter away from the center. The second voltage source is 180 degrees out of phase with the first one.

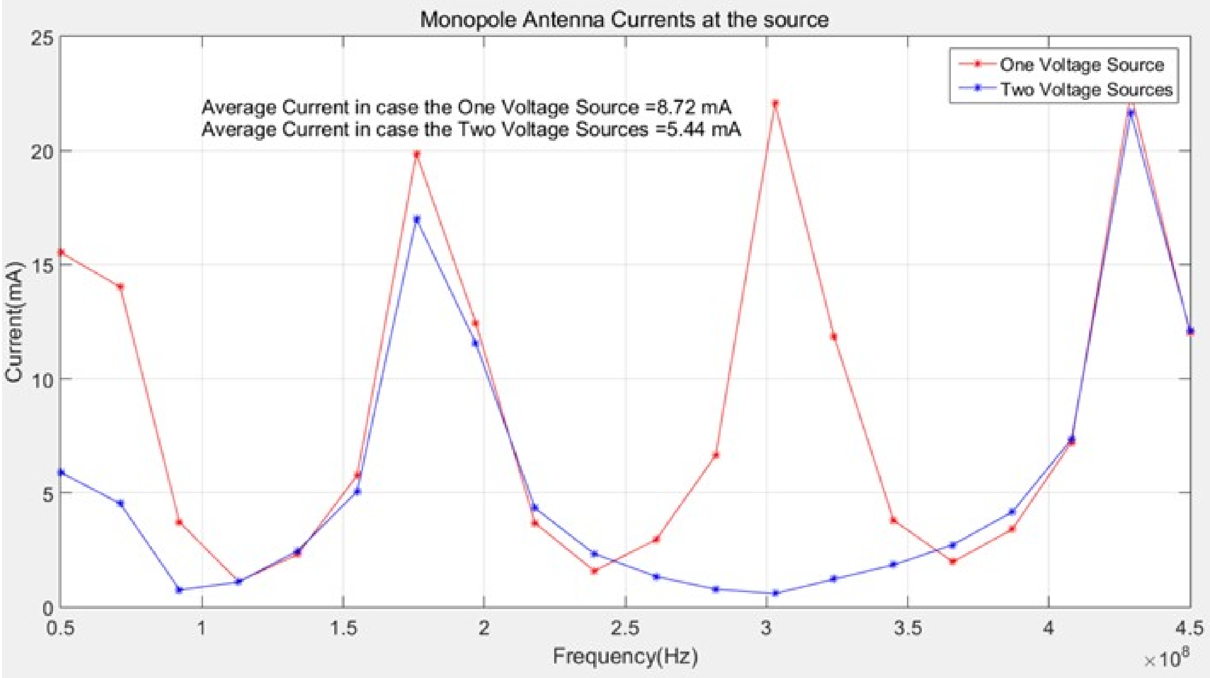


Fig. 7. FEKO results for the antenna-mode currents at the lower voltage source.

The calculated antenna-mode current magnitude at the lower source position is plotted in Fig. 7. The red curve is the current on the wire with only the lower source active. The blue curve is the current with both sources active.

The magnitude of the current with both sources averaged over this frequency range is 5.44 mA (74.7 dB(μA). The average value of the current with only the lower source is 8.72 mA (78.8 dB(μA). Therefore, we expect the average antenna-mode current from the two vertical bends in our test set-up to be approximately 4 dB lower than the average current that would be induced by the first bend only.

Therefore when the harness is lying flat over the ground plane, we expect to see only one antenna-mode source (at the junction of the coax to the harness). That source has an amplitude of

$$\begin{aligned} & h_{coax} = 0 \\ & \Delta h_{\|} = 0.0305 \\ & V_{AM\|} = \Delta h_{\|} \times V_{CM} \end{aligned} \tag{3.2}$$

where V_{CM} is the amplitude of the common-mode voltage at input to the harness. The imbalance factor of the coaxial cable (h_{coax}) is zero because the cable is perfectly unbalanced. The imbalance factor difference at the interface with coaxial cable to the wire harness is then the imbalance factor of the wire harnesses bended parallel ($h_{\|} = 0.0305$).

With the harness raised vertically above the ground plane as shown in Fig. 3b, two additional antenna-mode sources are introduced. The average amplitude of these sources together is,

$$\begin{aligned} & \Delta h_{\|} = 0.0305 \\ & \Delta h_{\perp} = 0.3558 \\ & V_{AM\perp} = (\Delta h_{\perp} - \Delta h_{\|})V_{CM} = 0.325 V_{CM} \quad \leftarrow \quad \text{first source} \\ & V_{AM2\perp} = \frac{5.44\,\text{mA}}{8.72\,\text{mA}} V_{AM\perp} = 0.203 V_{CM} \quad \leftarrow \quad \text{both sources} \end{aligned} \tag{3.3}$$

The imbalance factor difference for the wire harness bended vertically ($\Delta h_{\perp}$) can be calculated by the difference between the imbalance factors for the vertical bended and the parallel bended wire harness ($h_{\|} = 0.0305, h_{\perp} = 0.3863$). Noting that the antenna-mode voltage generated by the two vertical bends is much higher than the antenna-mode voltage generated by the coax-to-harness transition.

$$20\log\left(\frac{V_{AM\,2_{\perp}}}{V_{AM\|}}\right)=20\log\left(\frac{0.203V_{CM}}{0.0305V_{CM}}\right)=16.5\ \text{dB} \tag{3.4}$$

Therefore, the magnitude of the antenna-mode current for the configuration with the two vertical bends should be about 15 – 18 dB higher than the magnitude of the current on the harness that maintains its proximity to the ground plane.

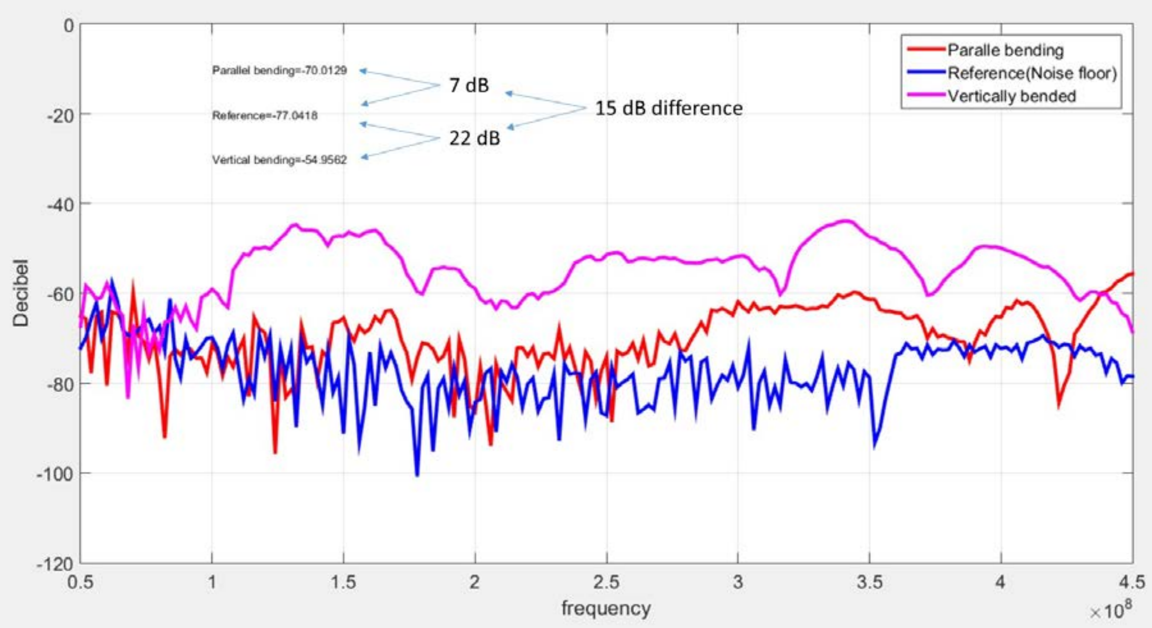


Fig. 8. Comparison of the common-mode currents with the vertical bending and with the parallel bending to the copper plane.

The antenna-mode current measurements are plotted in Fig. 8. As expected, the ratio of common-mode currents is around 15 dB. Although there are some fluctuations due to the resonances of the antenna structure affecting the input impedance at the two source locations, the results show that the calculation of the average increase in the antenna-mode currents is consistent with the change in the imbalance factor.

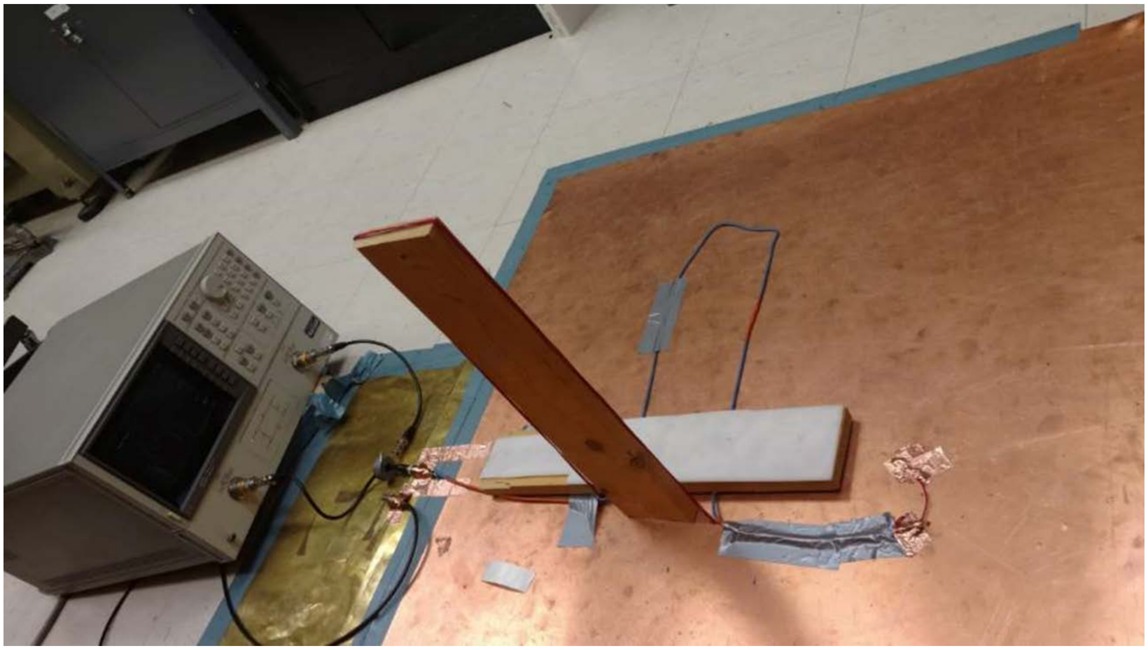


Fig. 9. Test set-up for the detached twin wire pair from the ground wire.

Although the harness lost proximity to the ground plane, the twisted pair was always in close proximity to the ground wire. A second test was conducted to examine the consequences of losing proximity to all ground conductors. This test setup is shown in Fig. 9. In this setup, the ground wire stays on the ground plane even when the twisted wire pair is routed away from the plane. This situation is a common occurrence in automobiles, because the signals carried on twisted wire pairs are generally considered to be independent of ground.

The common-mode currents are measured at the same location and the load is terminated by the same load as the previous setup. The imbalance factor for the detached twisted wire pair (TWP) is one because the transmission line is perfectly unbalanced (the total common-mode currents flows in the signal line only). In this case, the strength of the two mode conversion sources is higher, because the change in the imbalance factor is higher. On average, the source amplitudes are increased by

$$\begin{aligned} V_{AM2\perp} &= 0.203V_{CM} \\ \Delta h_{Detach\_TWP} &= 0.9695 \end{aligned} \tag{3.5}$$

where $V_{AM2\perp}$ is the antenna mode voltage with the harness raised vertically above the ground plane calculated already in (3.3). Δh_{Detach_TWP} is the imbalance factor difference between the twist wire pair (the imbalance factor for the twisted wire pair 45 cm above a plane $h_{Detach\_TWP} = 1$) and parallel bending wire harness (the imbalance factor for the parallel bended wire harness $h_{\parallel} = 0.0305$). The imbalance factor experience the difference between them because the ground wire is stayed as like the wire harness is bended parallel to the ground. Therefore, the induced antenna mode voltage for the detached twisted wire pair can be calculated as same as calculated in (3.3) and (3.4):

$$\begin{aligned} V_{Detach\_TWP} &= (\Delta h_{Detach\_TWP} - \Delta h_{\parallel})V_{CM} = 0.94V_{CM} \leftarrow \text{ first source} \\ V_{Detach\_TWP2} &= \frac{5.44\text{ mA}}{8.72\text{ mA}} V_{Detach\_TWP} = 0.59V_{CM} \quad \leftarrow \text{ both sources} \end{aligned} \tag{3.6}$$

where V_{Detach_TWP2} is the induced antenna mode voltage for the detached twisted wire pair represented by the amplitude of the common-mode voltage at input to the harness (V_{CM}).

$$20\log\left(\frac{V_{Detach\_TWP2}}{V_{AM2\perp}}\right) = 20\log\left(\frac{0.59V_{CM}}{0.203V_{CM}}\right) = 9.3 \text{ dB} \tag{3.7}$$

Therefore, the magnitude of the antenna-mode current for the configuration with the twisted wire pair should be about 8 – 10 dB higher than the magnitude of the current on the harness that bends vertically.

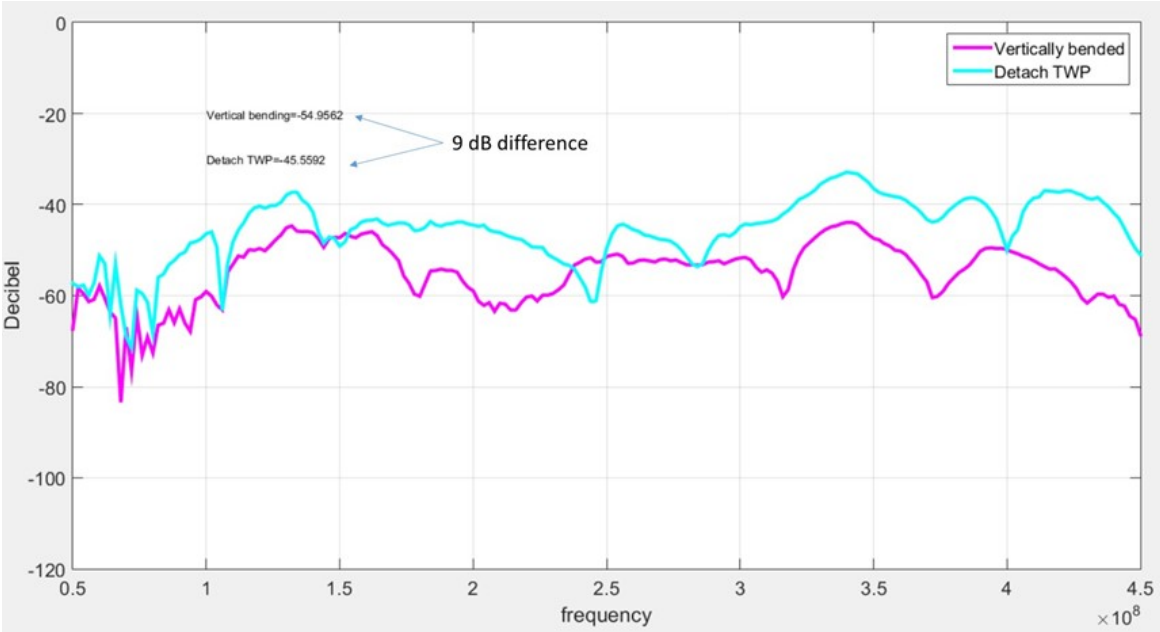


Fig. 10. Effect of losing the ground wire from the signal wires.

The measured results are plotted in Fig. 10. The pink line is the antenna-mode current measured when the ground wire is routed with the twisted wire pair. The cyan line is the antenna-mode current when the TWP loses proximity to the ground wire. The average difference of the common-mode currents is approximately 9 decibels (close to the 9.3 dB calculated value).

4. Conclusion

In this paper, the effect of ground proximity on antenna-mode currents induced in wire harnesses was studied. Conversion to antenna-mode currents occurs when there is a change in the electrical balance. Automotive wire harnesses experience changes in the imbalance factor depending on the distance from the wire harness to the ground structure. Even when a ground wire is routed along with a CAN bus wire pair, significant antenna-mode currents are created when the proximity to the ground structure changes. The antenna-mode currents can be estimated using the imbalance difference method based on changes in the electrical balance of the structure.

References

[1] C. R. Paul, *Introduction to Electromagnetic Compatibility*, vol. 184. John Wiley & Sons, 2006.
[2] T. Watanabe, O. Wada, T. Miyashita, and R. Koga, "Common-mode-current generation caused

by difference of unbalance of transmission lines on a printed circuit board with narrow ground pattern," *IEICE Trans. Commun.*, vol. 83, no. 3, pp. 593–599, 2000.

[3] T. Watanabe, H. Fujihara, O. Wada, R. Koga, and Y. Kami, "A prediction method of common-mode excitation on a printed circuit board having a signal trace near the ground edge," *IEICE Trans. Commun.*, vol. 87, no. 8, pp. 2327–2334, 2004.

[4] L. Niu and T. H. Hubing, "Rigorous Derivation of Imbalance Difference Theory for Modeling Radiated Emission Problems," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 5, pp. 1021–1026, 2015.

[5] C. R. Paul, "Effect of Interspersed Grounds on Radiated Emissions", in *Handbook of Electromagnetic Compatibility*. Academic Press, pp985–987, 2013.

[6] C. Su and T. H. Hubing, "Calculating Radiated Emissions Due to I / O Line Coupling on Printed Circuit Boards Using the Imbalance Difference Method," *IEEE Trans. Electromagn. Compat.*, vol. 54, no. 1, pp. 212–217, 2012.

[7] H. Kwak and T. H. Hubing, "Investigation of the imbalance difference model and its application to various circuit board and cable geometries," in *Electromagnetic Compatibility (EMC), 2012 IEEE International Symposium on*, 2012, pp. 273–278.

[8] Y. Toyota, K. Iokibe, and L. R. Koga, "Mode conversion caused by discontinuity in transmission line: From viewpoint of imbalance factor and modal characteristic impedance," *EDAPS 2013 - 2013 IEEE Electr. Des. Adv. Packag. Syst. Symp.*, pp. 52–55, 2013.

[9] T. Hubing and L. Niu, "Application of the Imbalance Difference Method to the EMC Design of Automotive ECUs," in *Electromagnetic Compatibility, Tokyo (EMC'14/Tokyo), 2014 International Symposium on*, pp. 453–456, 2014.

[10] Y. Toyota, S. Kan, and K. Iokibe, "Modal Equivalent Circuit of Bend Discontinuity in Differential Transmission Lines," in *Electromagnetic Compatibility, Tokyo (EMC'14/Tokyo), 2014 International Symposium on*, vol. 1, no. c, pp. 117–120, 2014.

[11] H. W. Shim and T. H. Hubing, "Model for estimating radiated emissions from a printed circuit board with attached cables due to voltage-driven sources," *IEEE Trans. Electromagn. Compat.*, vol. 47, no. 4, pp. 899–907, 2005.

[12] Y. Toyota, T. Matsushima, K. Iokibe, R. Koga, and T. Watanabe, "Experimental validation of imbalance difference model to estimate common-mode excitation in PCBs," *2008 IEEE Int. Symp. Electromagn. Compat.*, pp. 1–6, 2008.

[13] R. K. Tetsushi Watanabe, Hiroshi Fujihara, Osami Wadaz, Akihiro Namba, Yoshitaka Toyotazn, "High-speed Common-Mode Prediction Method for PCBs Having a Signal Line Close to the Ground Edge," *IEEE Int. Symp. Electromagn. Compat.*, vol. 1, no. 2, pp. 28–33, 2003.

[14] T. Watanabe, O. Wada, Y. Toyota, and R. Koga, "Estimation of common-mode EMI caused by a signal line in the vicinity of ground edge on a PCB," *IEEE Int. Symp. Electromagn. Compat.*, vol. 1, pp. 113–118, 2002.

[15] J. Ahn and T. H. Hubing, "Evaluation of the Common Mode Voltage Generated by Different CAN Transceivers," *Clemson Veh. Electron. Lab. Technical Rep. CVEL-18-068*, 2018.

[16] J. Ahn and T. H. Hubing, "Application of Imbalance Difference Method to the EMC Design of Automotive Wire Harnesses," *Clemson Veh. Electron. Lab. Technical Rep. CVEL-18-072*, 2018.