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Application of the Imbalance Difference Method to the EMC Design of Automotive ECUs

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Abstract—**Controlling the common-mode currents induced on wiring harnesses plays an important role in meeting automotive electromagnetic compatibility requirements. For high-frequency signals, the key to controlling these common-mode currents is maintaining the same electrical balance in the harness that was present on the circuit board. When routing differential signals such as LVDS or CAN signals, designers are generally careful to maintain the balance in the differential signal pair. However, driver skew and other sources of common-mode current in these routing pairs makes it equally important to maintain the balance of the wire pair and system ground relative to distant objects. This paper employs the imbalance difference method to demonstrate the importance of maintaining the electrical balance of the common-mode currents that return on system ground. These examples should help engineers to make better decisions regarding the optimum harness configuration for a given automotive system.**

Keywords—EMC; imbalance; common-mode; differential-mode; wiring harness; cable; radiated emissions

I. INTRODUCTION

Circuit designers are generally very careful to maintain electrical balance when routing differential-mode signals, such as CAN or LVDS signals, in an automotive component or system. They recognize that any electrical imbalance in the circuit will result in the conversion of some of the differential-mode signal to common-mode noise. Unfortunately, they rarely pay the same level of attention to electrical balance when routing these signals between circuit boards on a cable or wiring harness. This can be a significant source of radiated emissions in automotive systems.

In order to understand what electrical balance is and why it is so important, it is first necessary to establish consistent definitions for *electrical balance* and *common-mode current*. Clayton Paul [1] and many others have demonstrated that common-mode currents radiate much more effectively than differential-mode currents. However the common-mode currents that are efficient radiation sources are the currents that flow in one direction in a bundle of conductors and return to their source through displacement current or through some distant conductor that is not part of the bundle. This is not the same as the common-mode currents that flow in a differential signal circuit, which generally return on the same board or in the same wire harness.

To illustrate this, refer to the two traces over a plane in Fig. 1. The traces represent an LVDS transmission line routed on a circuit board. In an ideal LVDS signal routed on these traces, I_1 would equal $-I_2$ and the common-mode component of the signal would be,

$$I_{\text{LVDS-TRANSMISSION LINE}} = I_1 + I_2 = 0 \ . \tag{1}$$

Unfortunately, LVDS drivers are not ideal and LVDS signals generally have a common-mode component. This common-mode component is often due to driver skew or other factors that are beyond the direct control of the circuit designer. The common-mode component of the current flows in the same direction on both traces and returns on the ground plane. While this is generally undesirable, it does not necessarily result in radiated emissions. From an emissions perspective, it is the sum of the currents on all conductors that is important. In this case,

$$I_{\text{CM-ANTENNA}} = I_1 + I_2 + I_{\text{PLANE}} = 0 \ . \tag{2}$$

So common-mode currents flowing in a differential circuit are not themselves a source of significant radiated emissions. Radiated emissions are much more likely to result when there is a component of the current that flows in the same direction on all three of the conductors in Fig. 1. It can be convenient to refer to this mode of propagation as the "antenna mode" in order to distinguish this definition of common mode from the multi-wire transmission line definition of common mode.

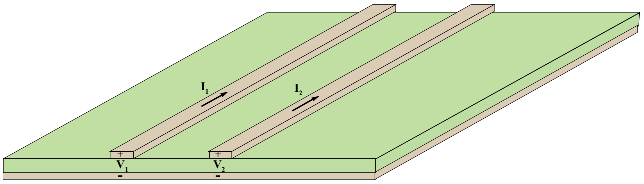

Fig. 1. Two circuit board traces over a plane.

In other words, we can reserve the use of the term *common-mode current* to refer to the currents returning on a local ground in a multi-wire transmission line; and use the term *antenna-mode current* to refer to the current that propagates in

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the same direction on all conductors without a nearby return path.

Circuit designers generally recognize the importance of maintaining electrical balance to prevent differential-mode signals from becoming common-mode noise. However, they often neglect to consider how the common-mode noise is converted to antenna-mode emissions. Watanabe et al. [2-5] and others have demonstrated that preventing these transmission-line currents from being converted to antenna-mode currents is also a matter of preserving electrical balance.

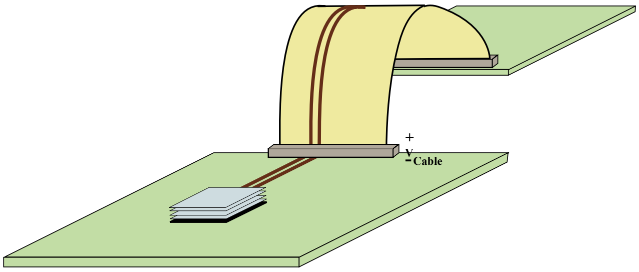

Fig. 2. LVDS board-ribbon-cable interface.

This can be illustrated using the example in Fig. 2. A differential LVDS signal is routed on a circuit board using two identical traces over a ground plane. On the ribbon cable, the LVDS signal is routed on two parallel wires. A cross-section of the signal traces on the circuit board is shown in Fig. 3. A cross-section of the signal traces in the ribbon cable in shown in Fig. 4. In Fig. 4, the two center wires carry the LVDS signal and the two outer wires are connected to the circuit board's ground plane.

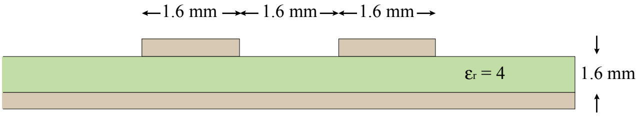

Fig. 3. Cross-sectional view of LVDS routing on board.

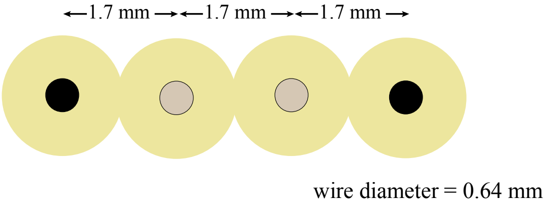

Fig. 4. Cross-sectional view of LVDS routing on ribbon cable.

Watanabe [2] demonstrated that for TEM propagation on a transmission line consisting of two signal conductors and a ground conductor, differential-mode propagation and common-mode propagation are independent and orthogonal provided the following definitions of differential-mode and common-mode are applied,

$$\begin{aligned} V_{CM} &= hV_1 + (1-h)V_2 \\ V_{DM} &= V_1 - V_2 \\ I_{DM} &= (1-h)I_1 - hI_2 \\ I_{CM} &= I_1 + I_2 \end{aligned} \qquad (3)$$

where h is the "current division factor" or "imbalance factor." The imbalance factor is the defined as,

$$h = \frac{C_{1G}}{C_{1G} + C_{2G}} \qquad (4)$$

where C_{1G} and C_{2G} are the capacitances of each conductor to ground as indicated in Fig. 5. In a homogeneous medium, the imbalance factor can also be expressed as a ratio of partial inductances.

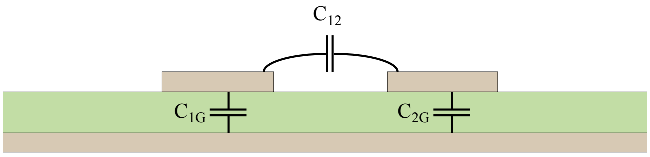

Fig. 5. Mutual capacitance and capacitances to ground.

When the two signal conductors have the same geometrical relationship to ground (i.e. C_{1G} equals C_{2G}), h = 0.5. In this case, the transmission line is perfectly balanced. If the capacitance to ground of one conductor is different from the capacitance to ground of the other conductor, h does not equal 0.5 and the transmission line is unbalanced.

Differential-mode signal currents are converted to common-mode noise currents when the signal encounters a change in the imbalance factor. In the LVDS example (Figs. 2-4), the imbalance factor is 0.5 on the board because both traces have the same relationship to the ground plane. The imbalance factor in the ribbon cable is also 0.5. Even though the signal and ground conductors in the ribbon cable are very different from the signal and ground conductors on the board, balance is maintained across the interface, and we would not expect any differential-mode to common-mode conversion to take place.

II. ANTENNA MODE

While there was no differential-to-common-mode conversion at the interface in the LVDS example, we still expect to see common-mode currents due to the driver skew. The common-mode current flows out on both signal conductors and returns on the ground wires/plane. From a radiated emissions perspective, this is a differential-mode signal, because the net current flowing on all conductors is zero.

Several authors [e.g. 2-7] have shown that the definitions for differential-mode voltage and differential- and common-mode current in (3) can be applied to systems where the ground is far from the current-carrying conductors. In particular, we can move the ground reference to infinity and still calculate the

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imbalance factor using (4). Changes in the imbalance factor result in the conversion of common-mode currents in our LVDS example to antenna-mode currents that result in radiated emissions.

More specifically, any change in the imbalance factor (ground at infinity) that occurs between the board and the cable in Fig. 2 will result in a voltage that drives the cable relative to the board. The amplitude of that voltage will be,

$$V_{AM} = \Delta h \times V_{CM} \qquad (5)$$

where V_{AM} is the antenna-mode voltage (V_{CABLE} in Fig. 2), Δh is the change in the imbalance factor, and V_{CM} is the common-mode voltage on the LVDS transmission line.

A. LVDS Example

Using (5), we can readily calculate the voltage that drives the ribbon cable relative to the circuit board in our LVDS example. First we need to know Δh, so we must calculate the imbalance factor on both the board and the ribbon cable with a ground reference at infinity. The capacitances of each conductor to infinity were calculated using the 2D electric field solver, ATLC2. Since ATLC2 does not directly calculate capacitance matrices for multi-conductor configurations, three simulations were run to determine the capacitance from each node (Conductor 1, Conductor 2 and infinity) relative to the other two. The capacitances of each set of conductors to infinity (C_1 and C_2) were calculated from these results as indicated in the second column of Table I. C_{12} is the mutual capacitance between Conductor 1 and Conductor 2.

On the circuit board, Conductor 1 is the trace pair and Conductor 2 is the plane. As indicated in Table 1, the capacitance of the trace pair to infinity in this example is 1.6 pF/m, while the capacitance of the plane to infinity is 51.5 pF/m. Applying (4), the imbalance factor is 0.03. In other words, like virtually all trace-over-plane structures, this structure is very unbalanced.

TABLE I. IMBALANCE FACTOR CALCULATIONS FOR LVDS EXAMPLE.

		Ribbon cable	PCB
Values from ATLC2	C_1+C_{12}	79.6 pF/m	142.0 pF/m
	C_2+C_{12}	102.8 pF/m	192.0 pF/m
	C_1+C_2	68.2 pF/m	53.2 pF/m
Calculated	C_1	22.5 pF/m	1.6 pF/m
	C_2	45.7 pF/m	51.6 pF/m
	h	0.33	0.030
	Δh	0.3	

The ribbon cable cross-section in Fig. 4 appears to be more balanced than the circuit board. We would expect the capacitance of the inner two wires to infinity, C_1, to be close to the capacitance of the outer two wires, C_2. In fact, the calculations in Table 2 support this. The capacitance of the inner wires to infinity is 22.5 pF/m and the capacitance of the outer wires to infinity is 45.7 pF/m. Applying (4), the imbalance factor of the ribbon cable is 0.33.

The change in the imbalance factor that occurs at the board-cable interface is 0.33 – 0.3 = 0.30. Applying (5), we see that the antenna-mode voltage is 0.3 times the common-mode voltage on the LVDS transmission line. This voltage drives the ribbon cable relative to the board as indicated in Fig. 6.

In most automotive systems, as little as 1 mV between two conductors of non-negligible size will result in a failure to meet radiated emissions requirements. So with the board-cable configuration in Fig. 2, just a few millivolts of common-mode voltage due to driver skew in the LVDS signal is likely to present a problem. That problem could be easily avoided by matching the imbalance factor on the board to the imbalance factor in the cable. For LVDS signals, it is usually better to decrease the imbalance factor of the cable rather than attempting to increase the level of balance on the board.

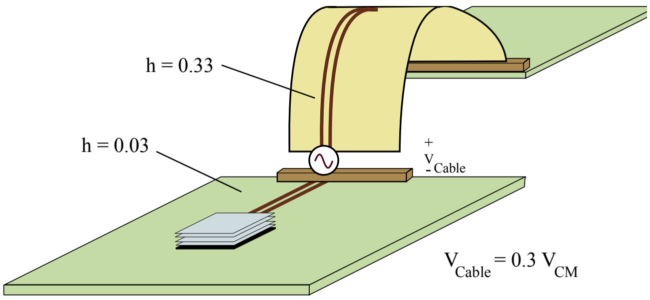

Fig. 6. Imbalance factors associated with the board and ribbon cable.

Often multiple LVDS signals will be transmitted over the same ribbon cable. An example of this is the automotive display interface shown in Fig. 7. When more than one signal share the same interface, the voltage driving the interface is the vector sum of the antenna mode voltages calculated for each signal.

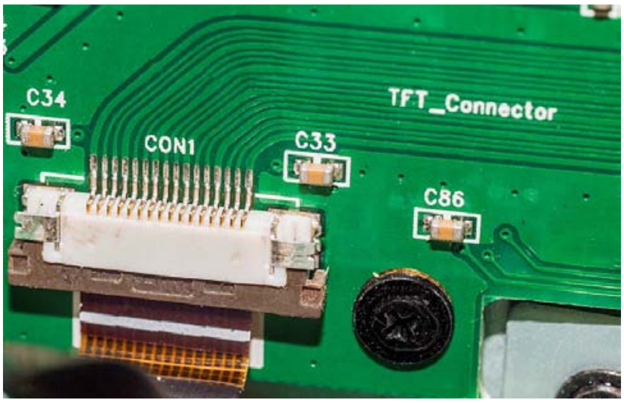

Fig. 7. Automotive display driver interface employing LVDS signals.

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B. *CAN Example*

Another type of differential signal commonly found in automotive systems is CAN communications. CAN signals are typically routed on the circuit board using parallel traces with a cross-section similar to the one in Fig. 3. CAN signals are much lower in frequency than LVDS signals, but they are usually routed on much longer cables, so they can still be the source of radiated emissions problems.

Fig. 8 shows a representative cross-section of a CAN twisted-wire pair in a wire harness with six additional wires. The diameter of the copper wire is 1 mm and the diameter of the insulation is 2 mm. The relative permittivity of the insulation is 4. Conductor 1 is the twisted-wire pair and Conductor 2 is the remaining wires in the bundle. The imbalance factor associated with common-mode currents flowing on the wire pair in this configuration is 0.0773 as indicated in Table II.

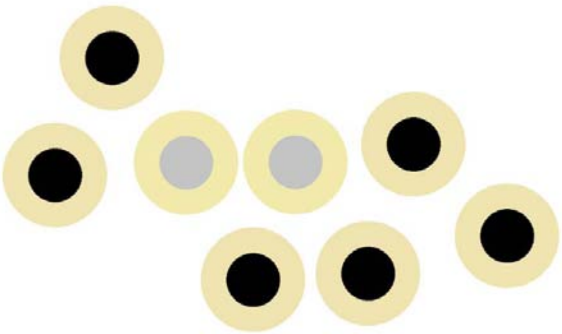

Fig. 8. Cross-sectional view of possible CAN routing in a wire harness.

TABLE II. IMBALANCE FACTOR CALCULATIONS FOR CAN EXAMPLE.

		CAN Cable	PCB
Values from ATLC2	C_1+C_{12}	100.47 pF/m	142.0 pF/m
	C_2+C_{12}	167.95pF/m	192.0 pF/m
	C_1+C_2	79.82 pF/m	53.2 pF/m
Calculated	C_1	6.17 pF/m	1.6 pF/m
	C_2	73.65pF/m	51.6 pF/m
	h	0.077	0.030
	Δh	0.047	

This example illustrates that a wire pair surrounded by wires referenced to the ground plane of the board can result in an imbalance factor that is small and more closely matches that of the board. With fewer wires surrounding the CAN signal pair, the imbalance factor rises and the common-mode currents on the CAN bus drive the wire harness relative to the board more effectively. In the limit where all of the other wires are missing (i.e. the CAN wires are the only wires in the harness) the imbalance factor is equal to one. In this case Δh is nearly equal to one and, according to (5), the common-mode voltage on the CAN bus is approximately equal to the antenna mode voltage. In other words, nearly all of the common-mode voltage on the CAN bus drives the cable relative to the board.

III. CONCLUSION

In automotive designs, noise coupled to the wiring harnesses is often a significant factor affecting radiated emissions. Automotive system designers often pay close attention to the electrical balance relative to system ground when routing differential signals such as LVDS and CAN signals. However, the common-mode components of these signals due to driver skew can become a radiated emissions problem when designers neglect to maintain the electrical balance of the signal conductors relative to infinity. In many cases, maintaining the balance relative to infinity is relatively easy to do, and it can make a big difference in the radiated emissions from automotive components.

REFERENCES

[1] Clayton R. Paul, *Introduction to Electromagnetic Compatibility, 2nd ed.*, Chapter 8, John Wiley and Sons, 2006.

[2] Tetsushi Watanabe, Osami Wada, Takuya Miyashita, and Ryuji 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. E83-B, no. 3, pp. 593-599, March 2000.

[3] Tetsushi Watanabe, Hiroshi Fujihara, Osami Wada and Ryuji Koga, "A prediction method of common-mode excitation on a printed circuit board having a signal trace near the ground edge," *IEICE Trans. Commun.*, vol. E87-B, no. 8, pp. 2327-2334, Aug. 2004.

[4] Tohlu Matsushima, Tetsushi Watanabe, Yoshitaka Toyota, Ryuji Koga and Osami Wada, "Increase of common-mode radiation due to guard trace voltage and determination of effective via-location," *IEICE Trans. Commun.*, vol. E92-B, no. 6, pp. 1929-1936, Jun. 2009.

[5] Tohlu Matsushima, Tetsushi Watanabe, Yoshitaka Toyota, Ryuji Koga and Osami Wada, "Evaluation of EMI reduction effect of guard traces based on imbalance difference method," *IEICE Trans. Commun.*, vol. E92-B, no. 6, pp. 2193-2200, Jun. 2009.

[6] C. Su and T. Hubing, "Imbalance difference model for common-mode radiation from printed circuit boards," *IEEE Trans. on Electromagnetic Compatibility*, vol. 53, no. 1, Feb. 2011, pp. 150-156.

[7] H. Kwak and T. Hubing, "Investigation of the Imbalance Difference Model and its Application to Various Circuit Board and Cable Geometries," *Proc. of the 2012 IEEE International Symposium on Electromagnetic Compatibility*, Pittsburgh, PA, USA, Aug. 2012.

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