特集 Estimation of Inverter EM Noise Propagation in Network Communication through Wire Harnesses*

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The electro-magnetic noise generated by an HV inverter can cause significant side-effects when it interferes with automotive LAN communications. This paper provides a calculation method to estimate the spectrum of the noise propagating through the wire harnesses by modeling LAN wire harnesses as uniform multi-conductor transmission lines and ECUs as S-parameter elements. Applying this model to a test bench with actual automotive ECUs, the consistency of the calculation and actual measurement can be evaluated. The calculated noise spectrum peaks agree with the measured noise spectrum peaks with a tolerance of 6dB in the frequency range below 20MHz.

Key words: Electromagnetic compatibility, Hybrid electric vehicles, Modeling, Simulation

1．INTRODUCTION

Recently, automobiles are being equipped with an increasing number of ECUs (Electronic Control Units) connected over automotive LANs (Local Area Networks). Since they are now indispensable to automobile operations, electro-magnetic noise generated by inverter switching in hybrid systems can be a significant side-effect when it interferes with LAN communications.

Currently, tens of signal lines are bound in a bundle and routed through the interior of automobiles. Since signal lines from ECUs controlling a hybrid system are often contaminated with electro-magnetic noise generated by inverter switching, LAN signal lines are affected by this noise through inter-harness EM coupling when they are bound together in a bundle. Since separate routing increases wiring costs considerably, it is important to assess whether communication lines should be routed separately to avoid EM noise, or can be bound in a bundle with hybrid controller ECU lines.

Several international standards[1)2)] or their local counterparts are available to evaluate ECUs' immunity robustness in presence of EM coupling noise.[3)] However, the test results complying with these standards are not useful to make separate-routing assessment since it requires evaluation on changing harness length while the standards are designed for specific predefined test configurations only. To make the required evaluation possible, we constructed a unique wire harness test bench to simulate the wire harnesses in automotive vehicles with changing the harness length.[4)]

In order to reduce the time and costs for actual measurements in the test bench, it is desirable to estimate the noise propagation by calculation. In general, a bundle of wire harnesses without branching or fluctuation in the distance to the ground can be modeled as uniform multi-conductor transmission lines and the voltage propagation can be calculated when the terminal conditions are given.[5)-8)] In our previous study, we developed our own equations to calculate the noise voltage propagation in the test bench when the noise source is a voltage source and the terminal elements are restricted to discrete resistors or inductors only and evaluated the accuracy of the calculation method.[4)]

In this paper, we extend our calculation method to handle arbitrary terminal conditions expressed in S-parameters so that it can calculate the noise voltage propagation with actual ECUs attached as the terminal elements. Using a noise-source with a known voltage spectrum, we compare the measured noise spectrums at the noise receptor side with their calculated values and evaluate the accuracy of the calculations.

2．TEST BENCH CONFIGURATIONS

A circuit image of the test bench is shown in **Fig. 1**. In this diagram, the noise source is the ECU in the lower left, and this noise travels through the single line harness. The noise is transferred to the LAN twisted pair harness via an electro-magnetic coupling and received by the upper right LAN receiver ECU.
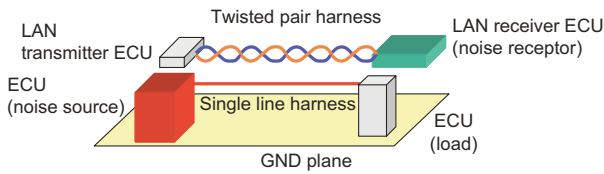
Fig. 1 Test bench circuit image
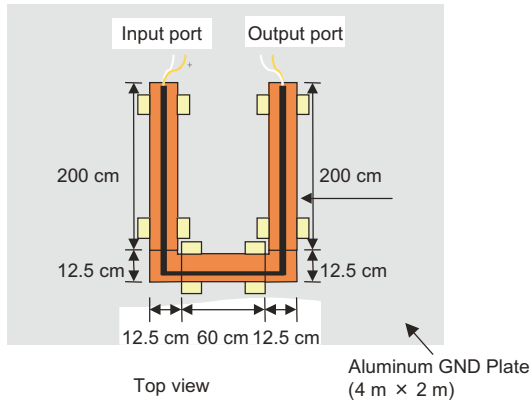
Fig. 2 Test bench physical layout

(a) Wire harnesses on ground plane

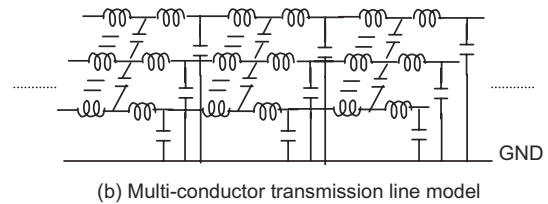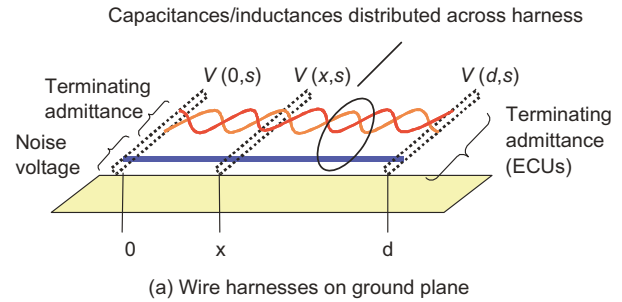(b) Multi-conductor transmission line model

Fig. 3 Wire harness model

as a pseudo noise source is measured and converted into a frequency domain using FFT.

Using this data, we are able to obtain the noise spectrum at the receptor ECU by solving Telegrapher's equations for the multi-conductor transmission lines at each frequency point.[6] The general solution for the noise voltage in the wire harness is as follows.[4]

$$V(x, s) = P_v \big(diag[\exp(-Td_j \cdot s \cdot x)]C_1(s) + diag[\exp(Td_j \cdot s \cdot x)]C_2(s) \big)$$

Here, $V(x,s)$ is the Laplace transform of the noise voltage vector at position x as shown in **Fig. 3(a)**, Pv is the projection matrix that converts the propagation mode voltages into the actual voltages, Tdj is the propagation time per meter for each propagation mode, 'diag' denotes a diagonal matrix whose j-th element is shown in parentheses, and C_1 and C_2 are constant vectors fixed by solving the boundary conditions at both terminals of the wire harness.

The boundary conditions at both the left and right terminals are specified in the form of admittance matrices as follows. The admittance matrix for the left terminal LAN transmitter ECU is Y_{e1T}, and the admittance matrix for the right terminal LAN receiver ECU and the load ECU combined is Y_{e2}. Y_{e1T} and Y_{e2} are frequency dependent matrices calculated from the measured S-parameters of the ECUs using the S-matrix to Y-matrix relationship:

$Y = Y_0 (I - S) (I + S)^{-1}$, where Y_0 is the inverse of the characteristic impedance and I is the identity matrix.

If we assume that the noise voltage is measured as $E_n(s)$, the constant vectors C_1 and C_2 are solved as follows:

The test bench configuration is shown in **Fig. 2**. The entire bench is mounted on a 4×2 m aluminum ground plate used to simulate the car body. The wire harness is placed on plastic rails to form a U-shape. At the upper left side of the TOP VIEW, the harness has an input port connected to the noise source ECU and LAN transmitter ECU, while at the upper right side, it has an output port connected to the LAN receiver ECU and load ECU.

3. MODELING AND CALCULATION METHOD

The wire harnesses can be modeled as uniform multi-conductor transmission lines as shown in **Fig. 3**.[4)-8)] When 'x' indicates the distance from the left terminal, the voltage vector at position 'x' is shown as $V(x,s)$ in **Fig. 3(a)**. Here, 's' shows that 'V' is processed in the frequency domain. Capacitances and inductances are distributed across the harness conductors as shown in **Fig. 3(b)**.

The distributed inductance and capacitance parameters of the transmission lines are measured with the open/short method. The 2-port S-parameters of the LAN ECUs and single-port S-parameter of the load ECU are also measured to model them. The output signal from the signal generator

$C_1 = (K - M \text{ diag}[\exp(-\gamma_j(s)\,d)](M_3 + I)^{-1} (M_3 - I) \text{ diag}[\exp(-\gamma_j(s)\,d)]\,)^{-1} V_{0A}(0, s)$

$C_2 = (M - K \text{ diag}[\exp(\gamma_j(s)\,d)](M_3 + I)^{-1} (M_3 - I) \text{ diag}[\exp(\gamma_j(s)\,d)]\,)^{-1} V_{0A}(0, s)$

Here, d denotes the length of the harnesses and

$$K = \begin{bmatrix} Y_{e1T} P_{VT} - P_{CT} \\ P_{VA} \end{bmatrix}$$

$$M = \begin{bmatrix} Y_{e1T} P_{VT} + P_{CT} \\ P_{VA} \end{bmatrix}$$

$$V_{0A}(s) = \begin{bmatrix} 0 \\ E_n(s) \end{bmatrix}$$

$Pc = (sL)^{-1} Pv\, \Gamma(s)$

$\Gamma(s) = \text{diag}[\,\gamma_j(s)\,]$

$M_3 = P_c^{-1} Y_{e2} P_v$

$\gamma_j(s) = s\, Tdj.$

'T' denotes that it concerns the terminating admittances at the left terminals, and 'A' denotes that it concerns the noise voltage at the left terminals.

By solving these equations at each sample frequency point, the frequency spectrum for the noise voltage propagated to the LAN receiver ECU can be given as the upper two elements in the voltage vector $V(d, s)$.

These equations also give us an insight into understanding the mechanism behind noise propagation, which is, since the noise propagates as mode voltages, the analysis of the transmission mode and mode conversion at terminals is important.

4．MEASURED CHARACTERISTICS OF THE TARGET COMPONENTS

The characteristics of a bundle of sample twisted-pair lines and noise source single line are shown in **Fig. 4** as distributed inductance and capacitance matrices. These are

		Twisted pair		Single line	
	Twisted	726.1	407.5	331.5	
L=	pair	407.5	730.9	332.3	(nH/m)
	Single line	331.5	332.3	728.5	

		Twisted pair		Single line	
	Twisted	57.3	-32.9	-14.7	
C=	pair	-32.9	57.9	-14.9	(pF/m)
	Single line	-14.7	-14.9	43.0	

Fig. 4　Characteristics of a bundle of sample twisted-pair lines and single line

measured using the open/short method.[9] The upper two rows and left two columns indicate the distributed L or C values for the LAN twisted pair lines, and the lowermost row and rightmost column indicate those for the noise source single line.

The measured characteristics of some sample target ECUs are as follows. Here, three ECUs from a particular hybrid vehicle product are used as LAN transmitter ECUs and LAN receiver ECU in the test bench. Normally, two ECUs at both ends of the LAN have internal terminator circuits to make the input differential impedance close to that of the LAN harness characteristic impedance and thus reduce the ringing effects. Since the internal terminator significantly alters the input impedance of ECU LAN ports, one of the sample ECUs is selected to have internal terminators. The 2-port S parameters of each ECU's LAN ports are measured with the ground plate as a common ground. The S parameters after mixed mode conversion are shown in **Fig. 5**. The mixed mode conversion is used to clarify the mode characteristics used in the calculation method introduced above.[10)-12]

5．MEASUREMENT AND CALCULATION RESULTS

The noise measurement and calculation results are as follows. The target harnesses and ECUs are the same as those used in the previous section. The harness length is 3 m, and the input/output signal voltage is measured for pseudo noise input of 1MHz duty 5% pulse. The sample results are shown below for two conditions, with and without an internal terminator for the transmitter ECU.

5.1　Transmitter ECU with internal terminator

The input/output signal voltage waveforms are shown in **Fig. 6**. In **Fig. 7**, the estimation of the noise spectrum at the receptor is calculated using the method shown in the previous section and compared with the measured noise spectrum calculated directly from the time domain signal in **Fig. 6**.

As the figure shows, the estimated spectrum peaks match the measured spectrum peaks with an accuracy of 6 dB within the frequency range below 20 MHz. Above 20 MHz, however, the peak level difference between the estimation and measurement exceeds 10 dB at certain points.
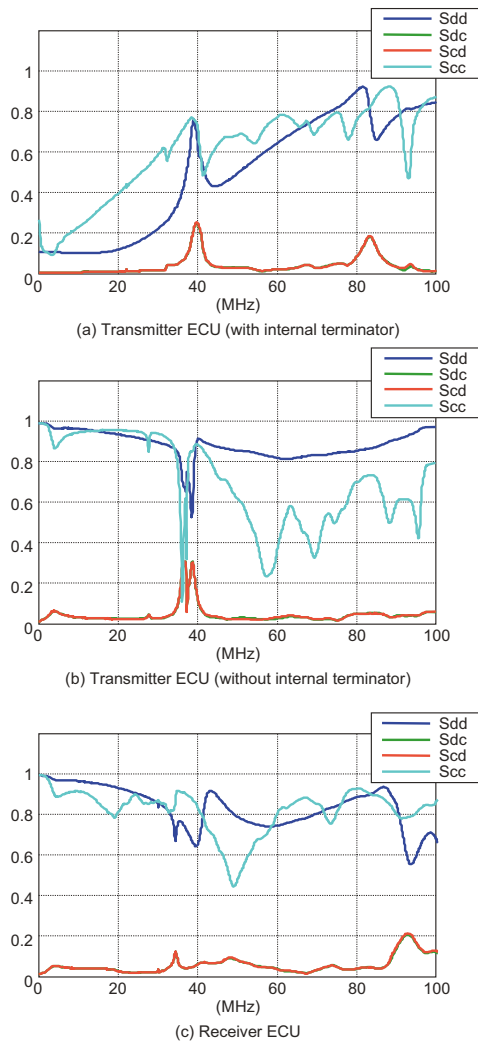
(a) Transmitter ECU (with internal terminator)

(b) Transmitter ECU (without internal terminator)

(c) Receiver ECU

Fig. 5　Mixed mode S-parameters of the sample ECUs

1. Pseudo noise input (5 V/div)
2. Receptor common mode (5 V/div)
3. Receptor differential mode (200 mV/div)

Fig. 6　Input (transmitter ECU)/output (receiver ECU) signals in the time domain

(a) Differential mode

(b) Common mode

Fig. 7　Comparison of estimated and measured propagated noise spectrums

5.2　Transmitter ECU without internal terminator

The input/output signal voltage waveforms are shown in **Fig. 8**. As indicated in the previous subsection, the estimation of the noise spectrum at the receptor is compared with the measured noise spectrum in **Fig. 9**.

Although the signal waveforms in the time domain and the spectrum shapes are considerably different from those in the previous subsection, the estimated spectrum peaks still match the measured spectrum peaks with an accuracy of 6dB within the frequency range below 20 MHz.

6．CONCLUSION

In this paper, we have modeled wire harnesses on a test bench as uniform multi-conductor transmission lines and their term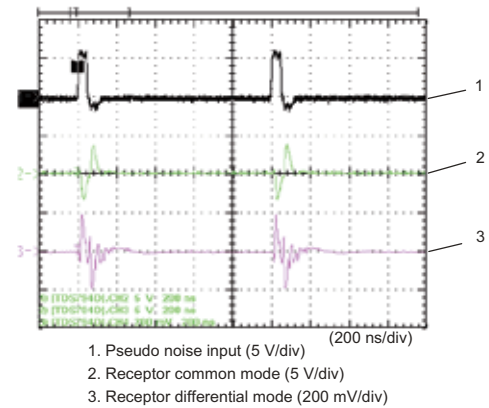inal elements as S-parameter elements. Using these modelings, we have developed a calculation method through which it is possible to estimate the spectrum of the noise propagating through the wire harnesses. Applying this model to the test bench with actual automotive ECUs, we have evaluated the consistency of the calculation and actual measurement. The calculated noise spectrum peaks agree with the measured noise spectrum peaks with a tolerance of 6 dB within the frequency range below 20 MHz. For those hybrid vehicles whose inverter noise falls within this frequency range, the devised calculation method is capable of adequately estimating the inverter noise propagating through the wire harnesses to the LAN communication
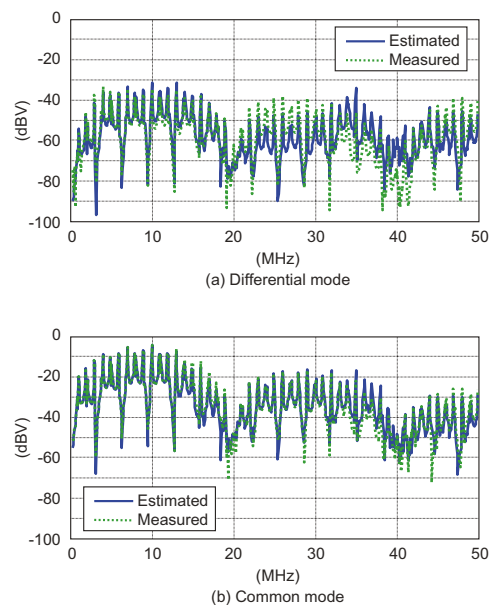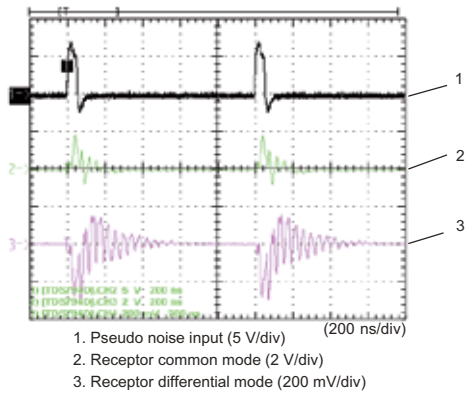
1. Pseudo noise input (5 V/div)
2. Receptor common mode (2 V/div)
3. Receptor differential mode (200 mV/div)

Fig. 8 Input (transmitter ECU)/output (receiver ECU)
signals in the time domain

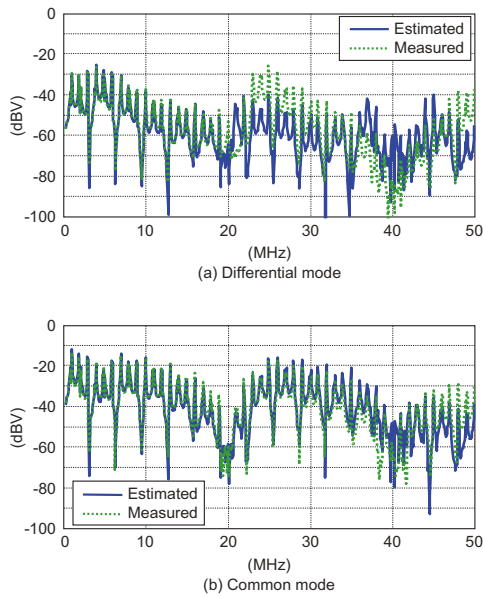(a) Differential mode

(b) Common mode

Fig. 9 Comparison of estimated and measured
propagated noise spectrums

ECUs. This method can be applied to harness wiring design in automobiles, especially hybrid vehicles whose HV ECU signal lines can be the media through which inverter noise propagates to the LAN communication lines. Since the calculation method proposed in this study only depends on the assumption that the wire harnesses can be modeled as uniform multi-conductor transmission lines, this method can be applied to any type of hybrid vehicles regardless of its size.

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