

特集 Circuit Specifications for Radio Noise Reduction in Vehicle-mounted Communication Networks*

–Specification Development Using Inverse Calculation–

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EM noise emissions in the radio bands from the communication harness of vehicle-mounted LAN are evaluated by performing an actual measurement test that complies with CISPR25. This report provides a method to define the specifications for the transmitter circuit and receiver circuit required to satisfy the AM noise limit in the test. The noise propagation is analyzed in common and differential modes and an inverse calculation is applied to obtain the specifications. Radio noise from the communication harness will be able to pass the test by designing a transmitter and receiver that meet the specifications developed using this method.

Key words: CISPR25, Radio noise, Vehicle-mounted LAN, Specification development, Inverse problem

1. INTRODUCTION

Recently, a large number of ECUs (Electronic Control Units) are being mounted in vehicles as the result of advances in micro-computer technology. ECUs are connected by LAN harnesses to facilitate mutual communication. The problem, however, is that malfunctions in vehicle-mounted electronic instruments (radio, TV, remote key and so on) could occur if electro-magnetic noise from the communication harness were sufficiently large.¹⁾²⁾ In order to avoid this, vehicle-mounted electronic instruments have to pass various tests.³⁾ Among them, CISPR25 test is widely used to evaluate automotive ‘radio noise,’ that is, emission noise in radio bands, TV bands and so on.³⁾⁻⁸⁾

Heretofore, iterating the loop of repeated measurement of actual noise in test cars and design modifications has been the only method employed in the development process. Recently, however, the use of simulation technology is being strongly urged to estimate noise generated from the communication harness without actually performing measurement in order to reduce both development time and costs. For this purpose, numbers of studies have been conducted mostly targeting frequency higher than 10MHz therefore using EM field solvers employing such as Method of Moment or FDTD.⁷⁾⁻¹⁰⁾ Applying these simulation methods instead of actual measurement, the development process is considerably shortened but still needs to iterate the loop of repeated calculation of simulated noise and design modifications.

In this report, we are targeting low speed differential voltage communications for automobiles, for example, 140Kbps bus communication for ECUs. The emission noise in AM radio band becomes significant because of this low speed. Concentrating to AM band, we can estimate the noise by simple calculation without EM field solvers. This enables us to solve the inverse calculation to directly obtain the noise source circuit specifications when the target emission noise level is given. This eliminates the iteration loop in the design process. Here, we will provide a general method constructed to define the specifications for the receiver circuit to satisfy the AM radio noise test when the transmitter circuit is given. We confirmed that the noise from the communication harness pass the emission noise test by designing the receiver circuit to meet the specifications obtained by the developed method.

2. RADIO NOISE TEST BENCH

Figure 1 shows the test bench configuration complying with CISPR25 applied to the measurement of radio noise from vehicle-mounted electronic instruments below 30MHz. The communication path comprises a master ECU (Electronic Control Unit) that outputs a differential signal, a twisted pair harness, and a slave circuit. The antenna is a monopole. The twisted pair harness is 1.5 meters long and located 5 centimeters above the ground plane. In this study, the slave circuit is substituted with a circuit consisting of resistors and a capacitor. The master ECU is covered with a

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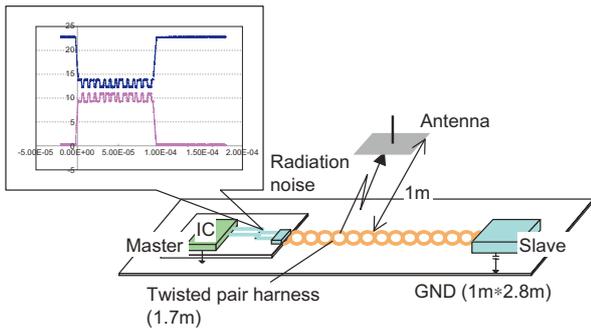


Fig. 1 Test bench configuration

shielding case. Radio noise from the twisted pair harness is evaluated as antenna voltage in 510 to 1710kHz AM radio band.

3. NOISE GENERATION AND PROPAGATION PROCESS

In this paper, we analyze noise generation and propagation in terms of their differential mode and common mode. The former originates in the differential communication signal and the latter originates in its asymmetric component.

Generally, the noise generated from the differential mode signal on the twisted pair harness is sufficiently smaller than the noise generated from the common mode signal thus can be neglected. So, the noise generation and propagation can be modeled as consisting of two independent routes: ‘Diff → Com’ and ‘Com → Com’ (Fig. 2) without sacrificing accuracy. In the first route, mode conversion in the slave circuit converts the differential mode voltage output from the master ECU into the common mode voltage, which propagates to the antenna. This is represented as ‘Diff → Com’ in this paper. Generally, master circuits are designed to have sufficient balance in the differential transmitting circuit while the slave circuits tend to have unbalance thus the mode conversion in the master circuits is neglected in this paper. In the second route, common mode voltage output from the master ECU propagates directly to the antenna. This is represented as ‘Com → Com’.

3.1 Noise generation and propagation modeling

The noise generation and propagation are mathematically modeled separately with S-parameters for Diff → Com and impedances for Com → Com (Fig. 3). The former is because recently the mode conversion is quantified with mixed mode S-parameters.¹¹⁾⁻¹³⁾¹⁶⁾ The latter is because usually the common mode characteristics are evaluated with impedances

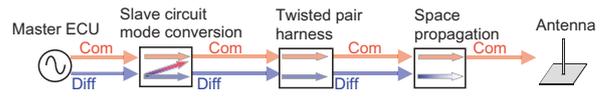
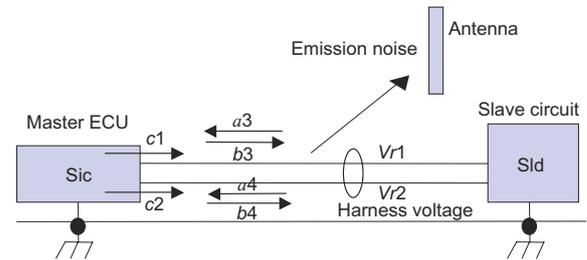
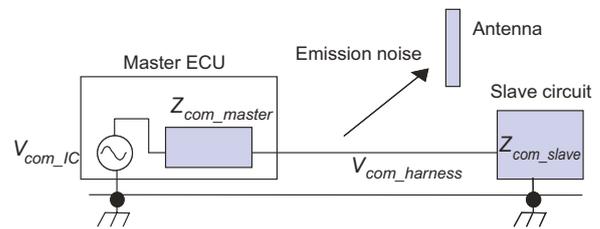


Fig. 2 Noise generation and propagation process



(a) Diff → Com route model



(b) Com → Com route model

Fig. 3 Communication path model

in the design process. The noise received by the antenna can be calculated as the sum of the noise propagating through these two routes.

The internal circuit of the master ECU is treated as an equivalent circuit consisting of internal signal sources of power waves and S-parameters for Diff → Com route or internal voltage source and impedance for Com → Com route. These modeling parameters ($c1$, $c2$, Sic , V_{com_IC} , Z_{com_master}) can be obtained from the simulation of master ECU including the transmitter IC internal circuit if it is known, or, estimated by applying a linear least square method to the measured data for output voltages from the master ECU with several different load conditions, for example.¹⁴⁾¹⁵⁾

The twisted pair harness can be considered as a bundled circuit in the AM radio band, that is, the voltage across the twisted pair harness is uniformly distributed.

The S-parameters of the slave circuit are easily obtained by measuring with a network analyzer or by calculating from the circuit parameters. The common mode impedance can be calculated from the S-parameters.

3.2 Diff → Com route

The voltages across the twisted pair harness generated from the Diff→Com route are calculated from the following equations referring to **Fig. 3(a)**.

The relation between the incident waves and reflected waves to/from the master ECU is expressed as (1).

$$\begin{bmatrix} b3 \\ b4 \end{bmatrix} = \begin{bmatrix} Sic33 & Sic34 \\ Sic43 & Sic44 \end{bmatrix} \begin{bmatrix} a3 \\ a4 \end{bmatrix} + \begin{bmatrix} c1 \\ c2 \end{bmatrix} \quad (1)$$

$c1$ and $c2$ represent the signals generated from the signal sources in the Master ECU.

The relation between the incident waves and reflected waves to/from the slave circuit is expressed as (2).

$$\begin{bmatrix} a3 \\ a4 \end{bmatrix} = Sld \begin{bmatrix} b3 \\ b4 \end{bmatrix} \quad (2)$$

Referring to these equations, the differential and common mode voltages on the twisted pair harness generated from Diff→Com route are calculated from the following equations to analyze the communication path model (**Fig. 3(a)**) in terms of differential mode and common mode. Here, let us define $adiff = (a3 - a4)$ and $acom = (a3 + a4)/2$ as the differential and common components of $a3$ and $a4$, respectively, and also make similar definitions for $b3$, $b4$ and $c1$, $c2$.

The relation of the incident wave and the reflection wave to/from the master ECU is expressed as (3).

$$\begin{bmatrix} bdiff \\ bcom \end{bmatrix} = Sicmm \begin{bmatrix} adiff \\ acom \end{bmatrix} + \begin{bmatrix} cdiff \\ ccom \end{bmatrix} \quad (3)$$

Here, $Sicmm$ is the matrix of the mixed-mode S-parameters for the master ECU converted from Sic matrix in (1). The relation of the incident wave and the reflection to/from the slave circuit is expressed as (4).

$$\begin{bmatrix} adiff \\ acom \end{bmatrix} = Sldmm \begin{bmatrix} bdiff \\ bcom \end{bmatrix} \quad (4)$$

Here, $Sldmm$ is the matrix of the mixed mode S-parameters for the slave circuit converted from Sld in (2). Using $Vr1$ and $Vr2$ in **Fig. 3(a)**, the differential mode voltage $vrdiff = (Vr1 - Vr2)$ and the common mode voltages $vrcom = (Vr1 + Vr2)/2$ on the twisted pair harness are obtained as (5) and (6).¹⁶⁾

$$vrdiff = \sqrt{Z0diff} (adiff + bdiff) \quad (5)$$

$$vrcom = \sqrt{Z0com} (acom + bcom) \quad (6)$$

where,

$$Z0diff = 2 \times Z0, \quad Z0com = \frac{1}{2} \times Z0$$

Since our target frequency is low enough in terms of the harness length, it can be analyzed as a quasi-static electromagnetic field. Consequently, both this and the antenna type mean that the horizontal electric field induced by the harness current can be ignored. The noise from the twisted pair harness is considered to consist only of the vertical electric field generated by the common mode voltage in (6).

Here, we treat the ground plane as an infinite ground in order to calculate the electric field strength at the antenna position when the harness common mode voltage is $Vrcom$.

3.3 Com → Com route

The voltage across the twisted pair harness from the Com →Com route is calculated from the following equations referring to **Fig. 3**. The common mode voltage across the twisted pair harness is the voltage obtained by dividing the common mode voltage of the signal sources in the master ECU by the ratio of the internal common mode impedance of the master ECU and slave circuit. This is expressed as (7).

$$V_{com_harness} = V_{com_IC} \times \frac{Z_{com_slave}}{Z_{com_master} + Z_{com_slave}} \quad (7)$$

The noise received by the antenna is calculated as outlined in the previous section.

According to 15), in the AM radio band, noise received by the antenna can be estimated with these models with an accuracy of 10dB when the receiver circuit is substituted with a resistor network.

4. CIRCUIT SPECIFICATIONS OBTAINED FROM THE PROPAGATION MODELS

In this study, we set our targeted noise level received by the antenna as CISPR25 class4. The specifications for the master ECU and slave circuit are calculated separately in terms of the Diff→Com and Com→Com routes. In order to achieve class4, both specifications must be satisfied simultaneously.

The circuit specifications for the master ECU and slave circuit to achieve class4 can be designed by reverse calculation of the noise generation and propagation model outlined in the previous section as a simple inverse problem.

Dividing the class4 limit by the transfer function from the harness common mode voltage to the electric field intensity at the antenna gives us the harness common mode voltage limit to achieve class4. For our sample system, the transfer function obtained by actual measurement is 84 to 87.5dB mV/m/V. Since the class4 electric field limit at the antenna is 26dB mV/m, the common mode voltage limit across the twisted pair harness to achieve class4 is -61.5 to -58.0dBV.

4.1 Specifications for Diff → Com route

The specifications for the master ECU and the slave circuit to achieve the above common mode voltage on the twisted pair harness is obtained as function of differential mode voltage output from the master ECU and mode conversion (Diff→Com) rate caused by asymmetric electric characteristic of the slave circuit. This can be obtained from the mode equations (3) to (6) in the previous section.

To obtain the relation in Diff→Com route, we should neglect the effect of *ccom*. So, let *ccom* = 0. Eliminating *adiff*, *acom*, *bdiff* and *bcom* from (3) to (6) gives us the equations for *vrdiff* and *vrcom* in terms of *cdiff* and the elements of *Sicmm* and *Sldmm*. Again, eliminating *cdiff* by calculating the ratio of *vrdiff* and *vrcom* gives us the conditional relationship that the elements of *Sicmm* and *Sldmm* should satisfy. Generally, mixed-mode *Sdc* parameter should be equal to *Scd* parameter in passive circuits. So the conditional relationship is expressed as in (8).

$$vrdiff = 2 \frac{Scd^2 \cdot Siccc + Sdd \cdot -Siccc \cdot Sec(1+Sdd) - Siccd \cdot Scd + 1}{-Siccd \cdot Scd^2 + Scd + Siccd \cdot Sdd(1+Sec) + Siccc \cdot Scd} vrcom \tag{8}$$

where, *Sicxx* denotes an element in *Sicmm* matrix and *Sxx* denotes an element in *Sldmm* matrix.

In the low speed differential voltage communication system, both the common mode and differential mode impedances in master and slave circuits are designed to be high. In this report, we assume that an ECU circuit is given and the values of *Siccc* and *Siccd* have been obtained, for example, by applying a linear least square estimation method to the master ECU.¹⁵⁾ Usually these S parameter values do not have frequency characteristics in the AM band. So, we can use the estimated values at one frequency as the representing values throughout the AM band. The estimated S parameter values for a sample master ECU are *Siccd*=0.0019 and *Siccc*=1.0. The value of *Sdd* is given by

the receiver’s differential load impedance specified in the communication circuit specification. For a sample receiver here, *Sdd*=0.89. The value of *Scd* can be obtained from the specifications for Com→Com route as described in the next subsection. For our sample target, the value is *Scd*=0.96. Since the common mode voltage *vrcom* to meet the class4 limit is -61.5 to -58.0dBV as shown before, substituting these values to *vrcom* in (8) gives us the plot for the relation of the differential mode voltage output from the master ECU *vrdiff* and the slave mode conversion (Diff→Com) *Scd* as the green band in Fig. 4.

The differential mode voltage output from the master ECU is generally defined in the communication signal specifications. For our sample system, the differential mode voltage specification for the master ECU used in this study is represented by the yellow line in Fig. 4, with a maximum value of -35dBV in the AM radio band. The intersection of this yellow line and the lower curve of class4 limit green band gives us the specification for slave mode conversion (Diff→Com) limit in order to achieve the class4 limit. In this case, the strictest specification in the AM band shall be below -62dB from Fig. 4.

4.2 Specifications for Com → Com route

The common mode voltage across the twisted pair harness expressed as (7) can be transformed to (9).

$$V_{com_IC} = V_{com_harness} \times \left(1 + \frac{Z_{com_master}}{Z_{com_slave}} \right) \tag{9}$$

The specification for the master ECU and the slave circuit required to meet the class4 common mode voltage limit across the twisted pair harness (*Vcom_harness*) is obtained



Fig. 4 Specifications for Diff → Com route

as the function of the common mode voltage of the signal source in the master ECU generated by its asymmetric electric characteristic (V_{com_IC}) and the ratio of the internal common mode impedance of the master ECU to that of the slave circuit ($Z_{com_master}/Z_{com_slave}$).

Since the common mode voltage across the twisted pair harness required to meet class4 ($V_{com_harness}$) has already been obtained as -61.5 to -58.0 dBV, by substituting these values into (9), the relationship between V_{com_IC} and $Z_{com_master}/Z_{com_slave}$ can be plotted as the green band shown in Fig. 5. The colored area below the green curve is acceptable area.

The specification indicates that increasing this ratio ($Z_{com_master}/Z_{com_slave}$) is an effective method in achieving the class4 limit at the antenna. The output of the common mode voltage from the signal source in the master ECU used in this study is plotted with the orange line shown in Fig. 5. In the case of this master ECU, the specification for the ratio of the internal common mode impedance of the master ECU to that of the slave circuit ($Z_{com_master}/Z_{com_slave}$) shall be above 3.2 as can be seen in this figure.

5. MEASUREMENT RESULTS

5.1 Diff → Com route

Figure 6 shows the measurement configuration where the impedances in the slave circuit are not symmetric ($r1 = 1.2k\Omega$, $r2 = 0.6k\Omega$, $r3 = 0.6k\Omega$, $C = 1\mu F$).

Here, a common mode filter (the value for common mode impedance is $7k\Omega$ to $14k\Omega$ in the AM radio band) is inserted in the master ECU to increase its common mode impedance. This enhances the effect of the asymmetric electric characteristics of the slave circuit on the noise received by

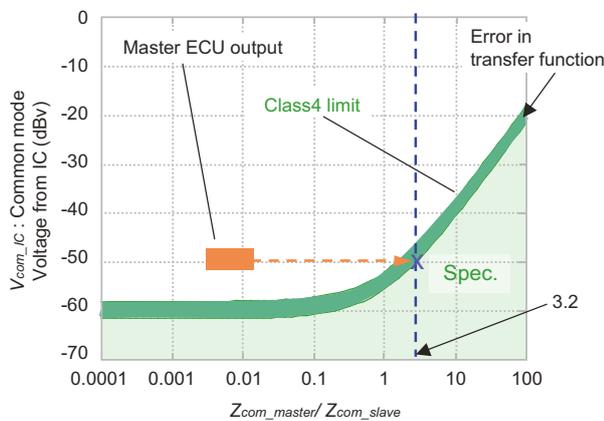


Fig. 5 Specifications for Com → Com route

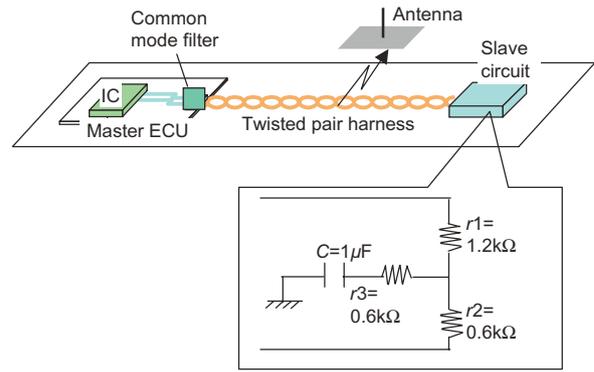


Fig. 6 Measurement configuration where impedances in slave circuit are not symmetric

the antenna.

In this case, the specification for the ratio of internal common mode impedance of the master ECU to that of the slave circuit ($Z_{com_master}/Z_{com_slave}$) is satisfied (the value based on the measurement is more than 5.5), however, the specification for mode conversion (Diff→Com) in the slave circuit is not (the value based on the measurement is 37dB). Consequently, the noise from the Diff→Com route is significant as a factor for the radio noise from the twisted pair harness. The noise from the Com→Com route is negligible in comparison with that from the Diff→Com route.

In order to achieve the specification for mode conversion (Dif→Com) in the slave circuit, we changed $r2$ from $0.6k\Omega$ to $1.2k\Omega$. Under this condition, the value for mode conversion (Diff→Com) in the slave circuit based on a measurement becomes below -65 dB which satisfies the specification.

5.2 Com → Com route

Figure 7 shows the measurement configuration where the impedances in the slave circuit are symmetric ($r1 = r2 = 1.2k\Omega$, $r3 = 13k\Omega$, $C = 1\mu F$).

In this case, the specification for mode conversion (Diff→Com) in the slave circuit is satisfied (the value based on a measurement is below 65dB), however, the ratio of the internal common mode impedance of the master ECU to that of the slave circuit ($Z_{com_master}/Z_{com_slave}$) is not (the value based on a measurement is below 1.5). Consequently, the noise from the Com→Com route is significant as a factor for the radio noise from the twisted pair harness. The

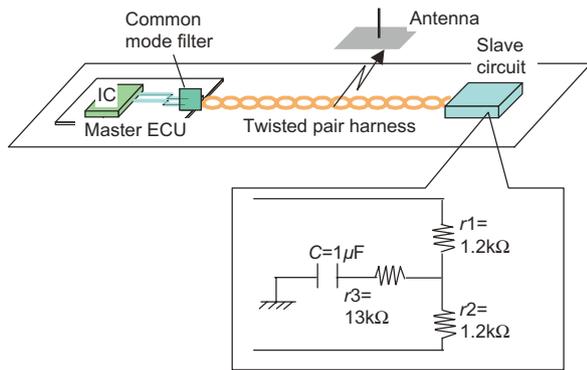


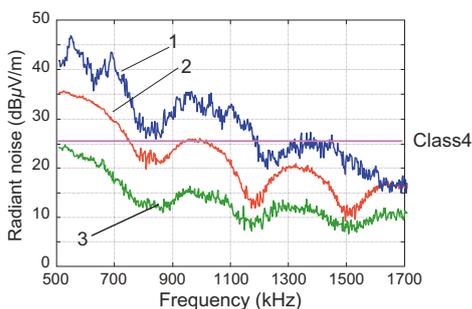
Fig. 7 Measurement configuration where impedances in slave circuit are symmetric

noise from the Diff→Com route is negligible in comparison with that from the Com→Com route.

In order to achieve the specification for mode conversion (Diff→Com) in the slave circuit, we changed r_3 from 13kΩ to 0.6kΩ. The value for the ratio of the internal common mode impedance of the master ECU to that of the slave circuit ($Z_{com_master}/Z_{com_slave}$) based on the measurement is over 5.5.

The actual measurement result for the noise received by the antenna is shown in Fig. 8.

When the configurations do not meet the specification for either the Diff→Com route or Com→Com route (lines 1 and 2 in Fig. 8), the noise received by the antenna does not meet the targeted level (class4). By changing the values of r_2 and r_3 to meet the specifications for both the Diff→Com route and Com→Com route (line 3 in Fig. 8), the noise received by the antenna also meets the targeted level (class4).



1. Slave: $r_1=1.2k\Omega$, $r_2=0.6k\Omega$, $r_3=0.6k\Omega$ Master: With common mode filter
2. Slave: $r_1=r_2=1.2k\Omega$, $r_3=13k\Omega$ Master: With common mode filter
3. Slave: $r_1=r_2=1.2k\Omega$, $r_3=0.6k\Omega$ Master: With common mode filter

Fig. 8 The actual measurement result of the noise received by the antenna

6. CONCLUSION

We developed a general method to define the specifications for the slave circuit as a low-speed differential communication receiver to meet the class4 level of noise received by the antenna in an AM radio band in a bench test complying with CISPR25. The specifications can be obtained by reverse calculation using the noise generation and propagation model, and are defined separately for the Diff→Com route and the Com→Com route. We evaluated the noise received by the antenna with the slave circuit consisting of a resistor network. We set several measurement configurations both to meet and not to meet the specifications. We confirmed also by actual measurement that the noise received by the antenna could be reduced below the target level (class4) by designing the values of the slave resistors to meet both specifications defined by this method.

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