Electromagnetic Noise Analysis of High-Voltage Wiring Harnesses

Kei SUNAGA*, Koji MIYAJIMA and Yoshiyuki MIYAZAKI

High-voltage wiring harnesses that connect an inverter to a motor in a hybrid car need to be designed to suppress electromagnetic emissions that can interfere with other electric devices nearby when alternating currents flow through the wires. To address this issue, we have studied the application of computer-aided engineering (CAE) analysis to the electromagnetic shielding design of these harnesses. This paper reports an example application of CAE analysis to the estimation of noise emissions and discusses the relationships between the electromagnetic field and the voltage or current in the system.

Keywords: wiring harness, hybrid car, electromagnetic noise, CAE analysis, shielding

1. Introduction

Hybrid electric vehicles (HEVs) and electric vehicles (EVs) are becoming popular these days. Sumitomo Wiring Systems, Ltd. has developed and commercialized low- and high-voltage wiring harnesses*1 for use in HEVs and EVs. High-voltage wiring harnesses connect the battery, inverter and motors installed in an HEV or EV, as shown in **Fig. 1**. They carry a high voltage and a large current.

Wiring harnesses are required to be highly reliable. One reliability indicator is electromagnetic compatibility (EMC)*2. Specifically, wires in the high-voltage wiring harness connecting the inverter and motor carry a high AC voltage and current. Electromagnetic filed noise generated by them has the potential to produce adverse effects including the malfunctioning of nearby electrical/electronic components. Consequently, it is necessary to draft a reliability design to reduce such electromagnetic field noise.

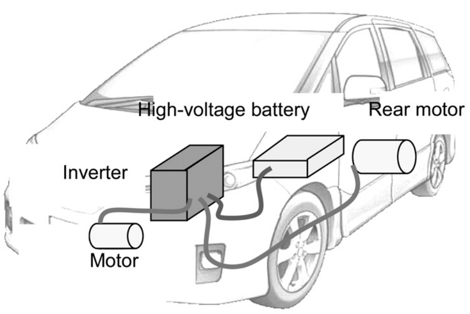


Fig. 1. High-voltage wiring harness layout

To ensure and improve reliability in the development stage, Sumitomo Wiring Systems promotes the use of CAE*3 in the early design phase. Presently, the Company uses CAE analyses to determine the flexural durability of wiring harnesses (service life prediction with respect to wire breakage resulting from repeated bending) and to estimate protective grommet insertion and removal forces. Moreover, studies are underway on the application of CAE to the estimation of electromagnetic field noise generated by the high-voltage wiring harness connecting the inverter and the motor. The present paper reports on the development of a CAE analysis technique simulating an estimation of the noise emitted by high-voltage wiring harnesses.

2. High-Voltage Wiring Harness Noise Emission Estimation

Figure 2 shows the general structure of a high-voltage wiring harness used in HEVs and EVs. Three wires are provided to carry a three-phase alternating current. One end of the three wires has terminals that connect to an inverter. The other end has terminals for connection with a motor. Accordingly, the wiring harness consists of the three wires bound at both ends and an antinoise shielding member. Generally, in an automobile, wiring harnesses are laid in a bent position. The shielding member that covers the wires is made of a braided metal wire to be bent with ease, at each end of which are flat metal connectors to be secured to the inverter and the motor, respectively.

The EMC characteristics of wiring harnesses and other electrical components in HEVs and EVs are finally estimated by individual automakers in an onboard condition. Nevertheless, auto parts suppliers, including wiring harness

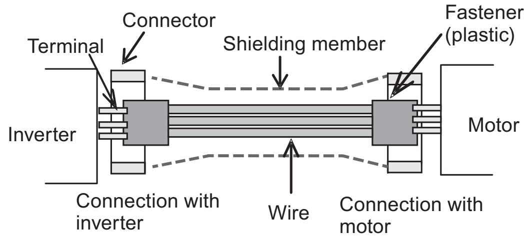


Fig. 2. Schematic drawing of high-voltage wiring harness

suppliers, need to estimate whether unmounted parts meet the specifications established by individual automakers on the basis of the applicable international standards. Each supplier has its original EMC estimation techniques.

Figure 3 shows the concept of a test system used to estimate high-voltage wiring harness noise emissions. A metal sheet known as the ground plane is placed on the workbench. A high-voltage wiring harness is connected to two metal housings secured on the ground plane. An AC power supply is connected to the terminal at one end. A terminating resistor is connected to the terminal at the other end.

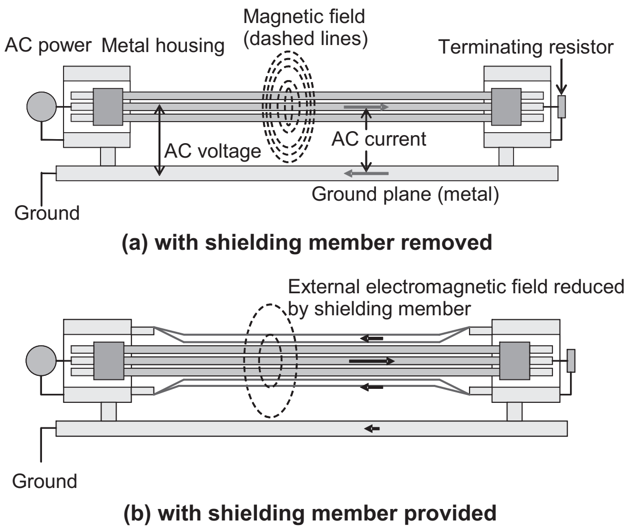


Fig. 3. High-voltage wiring harness noise emission estimation system

Figure 3 (a) shows the estimation system in which the shielding member is removed from the high-voltage wiring harness. The voltage and current supplied by the AC power supply to the estimation system generate an electromagnetic field in the surrounding space. Under this condition, a probe (antenna) is placed in a predetermined position. Electromagnetic noise is measured at different frequencies of the AC power supply.

Figure 3 (b) shows the estimation system with a shielding member fitted. The shielding member reduces the electric field and the magnetic field generated in the surrounding space. Differences in noise levels measured in dB with the two estimation systems are known as shielding effects, which are used as an indicator of wiring harness noise emission characteristics. The frequency band for estimation is generally from 10 kHz to 1 GHz.

3. Wiring Harnesses: Voltage, Current and Electromagnetic Noise

The voltage and current carried by the wiring harness estimation system generate an electric field and a magnetic field in the surrounding space. The following is the basic theory useful for understanding the relationship between the voltage and current carried by a wiring harness and the electromagnetic noise in the space surrounding the wiring harness.

Electrical charge and current distributions that cause electromagnetic noise fall into two types, as shown in **Fig. 4**.

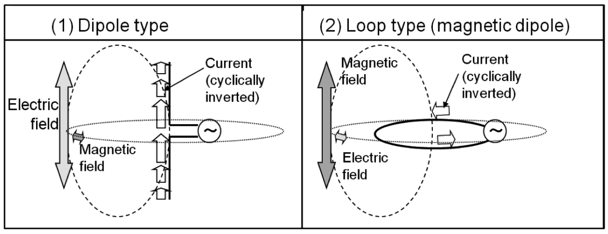
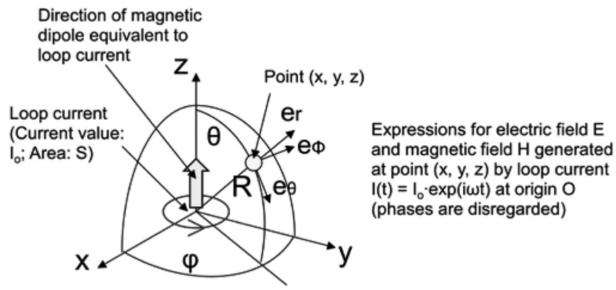


Fig. 4. Two types of electrical charge and current distributions that cause electromagnetic field noise

The dipole type is comparable to the charge and current distributions of a linear antenna. The loop type is comparable to the distribution of a closed loop current. The two sources of noise generate an electric field and a magnetic field in the space close to themselves in the directions shown in **Fig. 4**. **Figure 5** shows theoretical expressions for electric and magnetic fields generated by the loop type. The items inversely proportional to the cube of R, the square of R and R, where R is the distance between the origin and the measurement point shown in **Fig. 5**, are known as the quasi-static field, the inductive field and the radia-



$$E = -(\mu_o \cdot I_o \cdot S / 4\pi) \cdot (i\omega / R^2 - \omega^2 / cR) \cdot \sin\theta \cdot e_\varphi$$

$$H = (I_o \cdot S / 2\pi) \cdot (1/R^3 + i\omega / cR^2) \cdot \cos\theta \cdot e_r + (I_o \cdot dS / 4\pi) \cdot (1/R^3 + i\omega / cR^2 - \omega^2 / c^2 R) \cdot \sin\theta \cdot e_\theta$$

μ_o = Magnetic permeability in vacuum; ω = Angular frequency (= 2πf); c = Speed of light
Symbols e_r, e_θ and e_φ denote unit direction vectors in the r, θ and φ directions, respectively.

Fig. 5. Theoretical expressions for electric field E and magnetic field H generated by loop type current in its surrounding space

tion field, respectively.

The direction of the magnetic field generated by the loop type shown in **Fig. 4** indicates that, when $\theta = 90^\circ$, the magnetic field determined by the theoretical expression in **Fig. 5** is zero in the r direction ($\cos\theta = 0$) and increases in the θ direction ($\sin\theta = 1$).

Meanwhile, the theoretical expressions for the electric field and the magnetic field generated by the dipole type are obtained by manipulating the theoretical expressions for the loop type. More specifically, the magnitude of the magnetic dipole $I_o \cdot S$ (I_o: current; S: area enclosed by loop) is replaced by the magnitude of the dipole $q_o \cdot l$ (q_o: charge; l: distance between charges) to interchange the electric field and the magnetic field (with the coefficients and minus signs altered). The left part of **Fig. 4** shows the resultant electric field and the resultant magnetic field.

In sum, the electric and magnetic fields generated by the dipole type correspond in an interchangeable way to the magnetic and electric fields produced by the loop type. Where the relationship between the distance R and the wavelength λ is expressed by $R > \lambda/2\pi$, the radiation field becomes dominant in the theoretical expressions and the ratio of the electric field to the magnetic field takes the identical value (376.7 Ω) in both types of noise source.

When $R < \lambda/2\pi$, the quasi-static field and the inductive field become dominant in the theoretical expressions. Under this condition with the dipole type, the ratio of the electric field to the magnetic field is larger than that in the case where the radiation field is dominant, while with the loop type, the ratio is smaller than that in the case where the radiation field is dominant. Consequently, when two types of noise source are present concurrently, the dipole type is the major source of electric field noise at positions close to the noise sources ($R < \lambda/2\pi$), while the loop type is the major source of magnetic field noise at the same positions.

Using the above-mentioned relationships as basic knowledge, this section discusses electromagnetic field noise examined in high-voltage wiring harness noise emission estimation. According to the aforementioned relationship ($R < \lambda/2\pi$), at measurement points approximately 1 m apart from a high-voltage wiring harness with frequencies not higher than 30 MHz, the dipole type is presumed to be the major source of electric field noise, and the loop type is the major source of magnetic field noise. The principal loop noise source is the loop current generated by the high-voltage wiring harness and the ground plane (**Fig. 6**).

The high-voltage wiring harness noise emission estimation system, if viewed as a transmission line, has normal and common modes of transmission. In the normal mode,

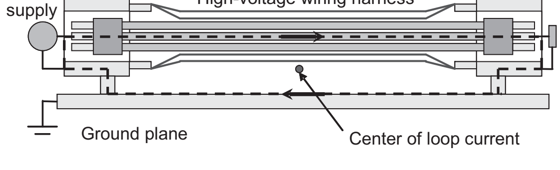


Fig. 6. Loop current path (dashed lines) in high-voltage wiring harness noise emission estimaation system

the wires and the shielding member constitute forward and return paths, respectively. In the common mode, the wires (or the shielding member) and the ground plane serve as forward and return paths, respectively. The magnetic field generated in the normal mode is small (zero in the case of an ideal coaxial cable). Therefore, one effective way of reducing magnetic field noise may be reducing the loop current (common-mode current) and/or the area enclosed by the loop current.

Meanwhile, as mentioned earlier, the dipole type is considered to be dominant over the electric field, and the major source of electric field noise is the potential difference between the high-voltage wiring harness and the ground plane. Charges produced commensurate with the potential difference form a dipole and a resultant electric field in the surrounding space. Consequently, cancelling this potential difference is expected to be effective for electric field noise reduction.

4. CAE Analyses of Electromagnetic Fields

4-1 Analysis techniques

Voltage and current distributions in circuits containing the wiring harness are decisive factors in electric field noise and magnetic field noise generated by the noise emission estimation system. The distributed-constant circuit theory that deals with multiconductor systems can potentially be applied to predicting these voltage and current distributions. However, it is not known what circuit constants should be used for complexly shaped wiring harness and metal housing. Moreover, the use of simple theoretical formulae in analysis is limited in terms of accuracy.

Therefore, we intended to analyze electromagnetic fields by CAE instead of desktop calculations using theoretical formulae. Several analysis techniques and types of commercially available electromagnetic field CAE analysis software were studied. **Table 1** shows the features of the major analysis techniques used in commercially available electromagnetic field CAE analysis software.

Table 1. Features of major electromagnetic field analysis techniques

	Finite element method	Moment method	FDTD method
Calculation domain	Mostly frequency	Frequency domain	Time domain
Division into elements	3D shapes	Linear/Planar	3D grid
Advantage	Modeling of any desired shape	Division into elements of surrounding space is not required.	Modeling of any desired medium
Good for	Analysis of complex shapes	Analysis of antennas	Large-scale analysis (parallel computation)

The finite element method models the subject of analysis, relatively accurately reproducing the subject's geometric features. Accordingly, this technique is suitable for examining the effects of minute geometric changes. However, in addition to the subject, the surrounding space through which the electromagnetic field propagates needs to be divided into elements.

Compared with this, the moment method requires only the subject of analysis to be divided into elements. Currents carried by conductors are first determined. The results and known propagation functions are used to determine electromagnetic fields at any desired points in the space. Consequently, this method enables computation over a wide band at a relatively low computational cost. However, the moment method is not very effective for analyzing three-dimensional shapes and subjects containing dielectric material.

The finite-difference time-domain (FDTD) method divides the space into a grid to find time-domain solutions. It models bulk shapes and dielectric materials with relative ease. In a single round of analysis, this method produces results concurrently for the corresponding frequency bands. However, since FDTD requires setting a longer time for computational phenomena with decreasing frequency, low frequencies incur an increased computational cost.

To predict the shielding characteristics of wiring harnesses, Sumitomo Wiring Systems has procured software incorporating the moment method that carries out computation over a wide band within a relatively short computational time, as well as software incorporating the FDTD method, which is good for dealing with high frequencies in computation. Using these software tools, the high-voltage wiring harness noise emission estimation system was simulated to perform CAE analyses.

The following sections report comparisons between experiment and analysis results, focusing on analysis cases in which analysis software incorporating the moment method was used.

4-2 Electromagnetic Field Analysis of High-Voltage Wiring Harnesses

The shapes of the high-voltage wiring harness, the metal housing and the ground plane are modeled for computation by the moment method analysis software, simulating the noise emission estimation system shown in **Fig. 3**. The models are divided into elements far smaller than the wavelength of the electromagnetic field to be evaluated. Specifically, where radical changes occur in the electromagnetic field, elements need to be finer than at other locations.

The next steps are to assign a thickness, conductivity and permeability to sections modeled into two-dimensional shapes, set power supply and resistor settings, and perform analysis.

Figures 7 and 8 compare CAE results computed by the moment method and measurement results. Two types of high-voltage wiring harness (A and B) differing in structure were used to compute and measure the magnetic field at positions 1 m apart from the high-voltage wiring harness. The CAE results agreed with the measurement results regarding global frequency dependence and the performance of the high-voltage wiring harness (high-voltage wiring harness A exhibited higher shielding effects), except for some differences: with the shielding member provided, CAE produced slightly greater absolute values than the measurements.

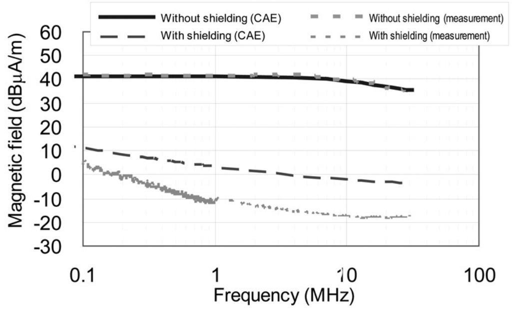


Fig. 7. Magnetic field 1 m apart from high-voltage wiring harness (high-voltage wiring harness A)

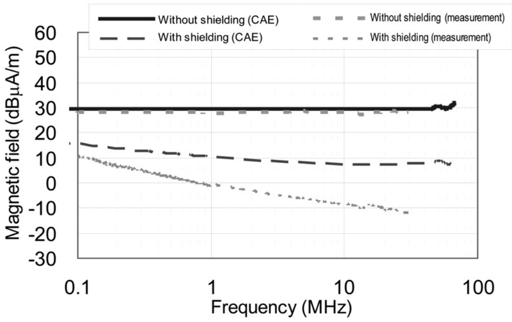


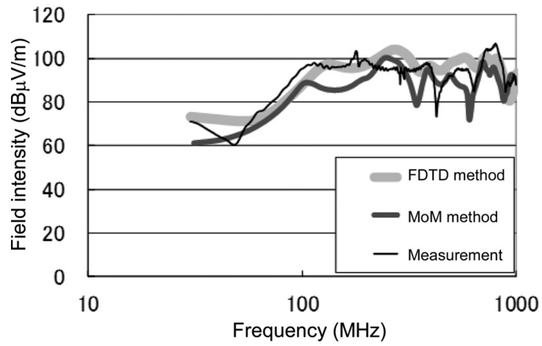
Fig. 8. Magnetic field 1 m apart from high-voltage wiring harness (high-voltage wiring harness B)

Figure 9 shows electric fields 1 m apart from the high-voltage wiring harness computed by the FDTD method and the moment method, as well as measurement results, for the high-frequency band (30 MHz to 1 GHz). Both analysis techniques revealed frequency dependence similar to that exhibited in the experiment, although some differences were present locally.

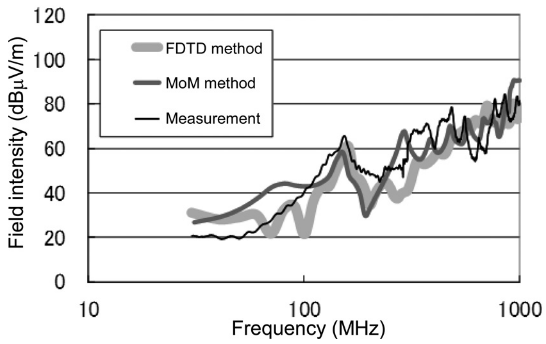
The above-mentioned comparison between the CAE analysis of electromagnetic fields using commercially available analysis software and the experiment proved that it is to some extent possible to predict electromagnetic field noise trends for the high-voltage wiring harness noise emission estimation system. One advantage of CAE analyses of electromagnetic fields is that CAE analyses produce information on electric and magnetic fields at locations other than the measurement points used in the experiment.

Major commercially available analysis software comes with contour presentation capability to render colored electromagnetic field intensity distributions. This function visualizes electric and magnetic field propagations. **Figure 10** shows an example contour of electric field intensity viewed from above the ground plane. (The contour shown in the lower part of **Fig. 10** is in the plane at the same vertical position as the wire.)

The example contour shown in **Fig. 10** reveals that the electric field is specifically strong in the proximity of the housing on the terminal end. This technique visualizes how



(a) without shielding member



(b) with shielding member

Fig. 9. Electric field 1 m apart from high-voltage wiring harness

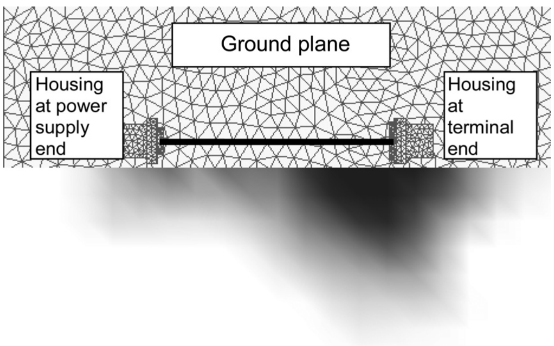


Fig. 10. Example contour of electric field intensity (Top view. Darker areas indicate higher intensity.)

electric and magnetic fields propagate from high-voltage wiring harnesses to measurement points, and facilitates the development of measures to counter the occurrence of shielding defects. Consequently, CAE analyses are useful for product development.

5. Conclusion

This paper described a noise emission estimation system designed to examine high-voltage wiring harnesses used in hybrid electric vehicles. CAE analyses of electromagnetic fields simulating the estimation system were conducted, and analysis results were compared with experiment results. The global frequency dependence revealed in these results was identical. This paper examined the relationship between the voltage or current (carried by a high-voltage wiring harness estimation system viewed as a transmission line) and electric and magnetic fields close to the high-voltage wiring harness, based on theoretical expressions for electric and magnetic fields generated by alternating current.

Our future task is to further the study on the agreement between CAE and experiment for the establishment of a wiring harness shielding design technology.

Technical Terms

*1 Wiring harness: An assembly of wires used to electrically connect electronic components and electrical parts used in automobiles, copying machines, printers and the like and transmit power and information. A wiring harness consists of wires and protective sheaths.
Typical roles of individual wires in a wiring harness are to supply power and transmit signals.

*2 EMC: EMC is an acronym for electromagnetic compatibility. In the study of phenomena in which interfering electromagnetic waves emitted from some electronic equipment (including wires) cause malfunctioning of other electronic equipment, the characteristics of the emitting side and the affected side are known as emission characteristics and immunity characteristics, respectively.

*3 CAE: CAE is an acronym for computer-aided engineering. In this paper, CAE refers to development support systems useful for establishing product design guidelines, with such systems accepting inputs such as geometric data and properties of the subject to be analyzed, approximating basic equations that describe phenomena for ease in numerical processing, using a computer to solve the basic equations, and producing outputs of various physical quantities for estimation.

References

(1) C. Paul, "Analysis of Multiconductor Transmission Lines," pp136-156, Wiley, New York (1994)
(2) B. Archambeault, C. Brench, O. Ramahi, "EMI/EMC Computational Modeling Handbook," Kluwer Academic (2001)
(3) H. Morishita, "Fundamentals of Small Antennas," Coronasha (2011)
(4) T. Keishi, "Electromagnetic Field Analysis and Its Applications to Product Development," SEI Technical Review 69-02 (2010)
(5) T. Keishi, "Electromagnetic Theory as an Aid to Understanding Electromagnetic Field Analysis," SEI Technical Review 72-02 (2011)

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