Development of Noise Visualization System for Extraneous Electromagnetic wave and Its Application to Circuit Design

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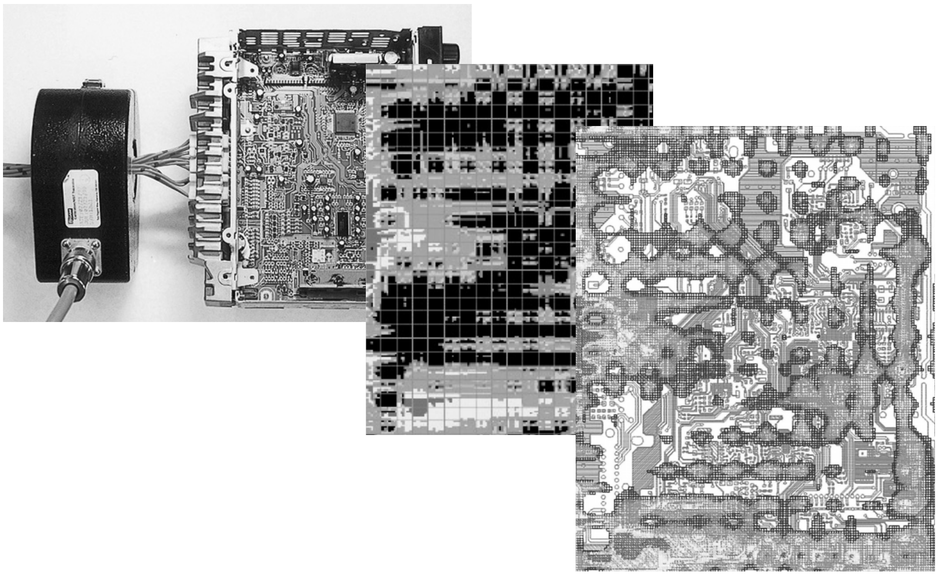


Abstract

The rapid spread of electronic products in the market has resulted in an expansion of international electromagnetic wave regulations, which now require higher EMC performance of in-vehicle electronic equipment. And they make it necessary to secure product performance under all kinds of electromagnetic environments, particularly emphasizing immunity to extraneous electromagnetic waves.

At the same time there is now demand for in-vehicle electronic equipment to be more compact, higher-performance, and lower-cost, and the shortening of vehicle development periods now necessitates more rapid development than previously. This means that engineers now have to work under extremely severe conditions when designing products.

Traditionally, if products failed to pass the "immunity test" (checking conformity of immunity to electromagnetic wave regulations), a trial-and-error method was used whereby the design of the product's printed circuit boards was replaced with different-version items as a part of anti-noise measures, and the test was repeated. But in today's lower-cost,faster-development environment,it is necessary to have tools that will support the engineers in taking anti-noise measures, so that immunity performance can be rapidly and accurately assured. Accordingly, we have developed a system that simulates the immunity test and visualizes the paths of noise by which extraneous electromagnetic wave enters printed circuit boards.

This paper mainly provides an overview of the development of the noise visualization system for extraneous electromagnetic wave, and also introduces some cases of its practical application to design.

1. Introduction

The spread of electronic products on markets worldwide has led to the widespread adoption of international regulations addressing electromagnetic compatibility (EMC)[*1].

*1 The term "electromagnetic compatibility" refers to a characteristic that electronic devices possess when they satisfy all of the following conditions:

- do not radiate electromagnetic waves
- operate normally without being affected by extraneous electromagnetic waves
- operate normally without being affected by their compliance with the above two conditions.

EMC regulations related to immunity (to extraneous electromagnetic waves) have not been given as much consideration as those covering emission[*2], because a number of countries have been delayed to take action for the regulations.

*2 The word "emission" refers to the radiation of electromagnetic waves from electronic devices.

However, these days, more importance is being attached to immunity (to extraneous electromagnetic waves) in the case of in-vehicle electronic devices. This is because from the point of view of safety enhancement, demand has become particularly strong for in-vehicle electronic devices (such as engine and brake controls) having a high degree of immunity to extraneous electromagnetic waves. These in-vehicle electronic devices are related directly to such basic vehicle functions as running, stopping, and turning.

Fujitsu TEN has been conducting an immunity test [*3] (a type of EMC test) on electronic devices, to verify their conformity to electromagnetic-wave regulations. Traditionally, if a product failed to pass an immunity test, designers had to resort to making design changes on a trial-and-error basis. Designers would repeat these design changes and EMC tests until the product passed the immunity test. (In making design changes, designers relying on experience and intuition formulated anti-noise measures and redesigned printed circuit boards by changing their circuit patterns or by adding components.)

*3 The term "immunity test" refers to a test conducted to verify the anti-noise performance of electronic devices. Typical immunity test methods include the transverse electromagnetic cell (TEM-cell) method and antenna radiation method.

Recently, however, the conventional methods for implementing anti-noise measures have reached certain limits. This has occurred because designers have to deal with a rather severe design environment. (For example, strong demand exists for high-performance devices at lower cost, and that can be developed faster). Moreover, there are not many cases of electromagnetic-immunity-related anti-noise measures that have been successfully implemented. Under these circumstances, designers require tools that will assist them in implementing anti-noise measures rapidly and accurately.

To accommodate the strong demand mentioned above, Fujitsu TEN and Toyota Motor Corp. have jointly devised a method for simulating the immunity test and visualizing the paths through which high-frequency noise equivalent to extraneous electromagnetic waves enter printed circuit boards. This method is carried out on a personal computer (PC) screen.

We also developed a system for displaying visualized data by merging it with a printed circuit board image produced by Integrated Computer Aided Design (ICAD)[*4]. By using this system together with the above-mentioned noise visualization method, designers can easily identify the paths (locations) through which noise (induced by extraneous electromagnetic waves) enters electronic devices.

*4 ICAD is a computer-assisted design tool used to design circuit patterns on printed circuit boards.

This paper mainly goes over the factors that motivated us to develop this system and an overview of the system. It also goes over certain cases where the system has actually been applied to anti-noise design.

2. Background to Development of Noise Visualization System for Extraneous Electromagnetic Wave

2.1 Diversified Electromagnetic-Wave-Related Environments for In-Vehicle Electronic Devices

Television and radio broadcasting stations are well-known sources of extraneous electromagnetic waves that affect in-vehicle electronic devices.

As shown in Fig.1, nowadays, in-vehicle electronic devices can also be affected by any of the following:

- electromagnetic waves from mobile phones and radio pager base stations near the vehicle
- mobile phones in the vehicle itself
- high-power radar sites

In addition, in-vehicle electronic devices may be exposed to electromagnetic waves from amateur radio equipment in another vehicle located near the vehicle and

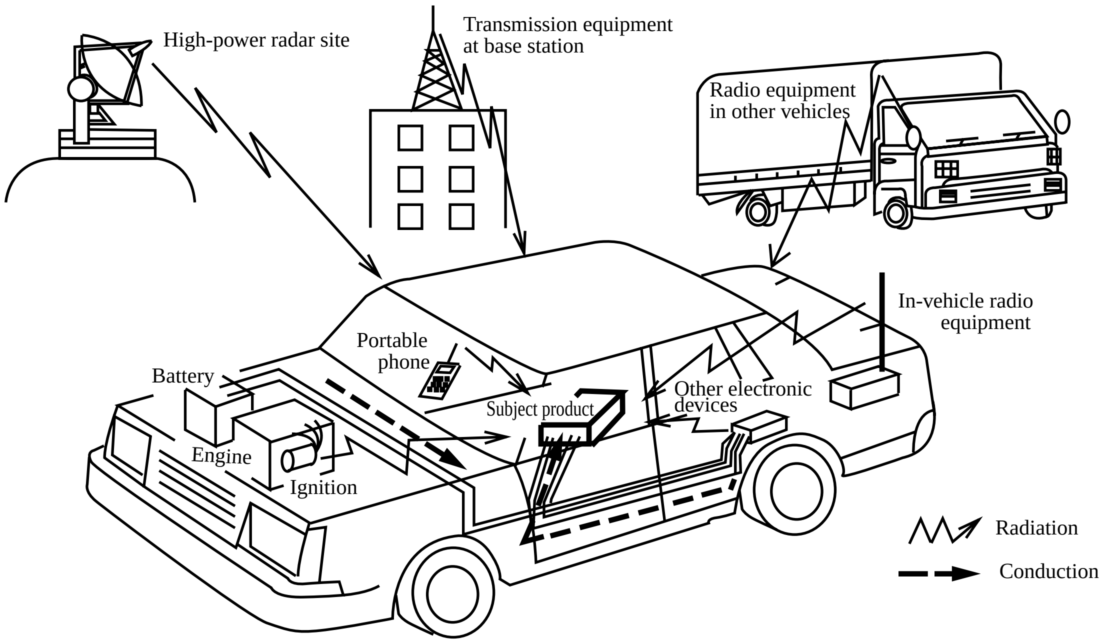


Fig.1 Extraneous electromagnetic waves around on-vehicle electronic equipment

radio equipment (if there is any) in the vehicle itself.

Conversely, sparks generated in the ignition system of a vehicle and noise from a microcomputer clock in an electronic device in the vehicle can be sources of extraneous electromagnetic waves for other electronic devices in the vehicle.

In this manner, in-vehicle electronic devices are constantly exposed to a variety of high-level extraneous electromagnetic waves in all cases.

2.2 Changes in Product Development Environment and Anti-Noise Measures

Amid intense competition in the industry these days, products have to be of higher performance, lower cost, and be developed more rapidly. This has placed designers in an increasingly severe product development environment.

Particularly in the case of hardware development, designers must give precedence to basic performance. Therefore, in many cases, they can design anti-noise measures only in the final stages, where the design of the product is basically decided on.

If a product fails to pass the EMC tests, therefore, the designer must come up with an anti-noise measure that can be applied to a parts-mounting-space that is limited owing to product miniaturization, on the printed circuit board within a limited amount of development time.

These situations have made conventional ad hoc decisions ineffective regarding the design changes to be made. In addition, significant time delays and substantial costs would be incurred as a result of making design changes to printed circuit boards.

These anti-noise measures based on so-called symptomatic treatment lead to a vicious cycle involving design changes and EMC tests, which in turn lead to increases in costs and protracted development periods.

It would not be an exaggeration to say that the key to low-cost, faster development is having a precise anti-noise measure that can be promptly implemented.

2.3 EMC Regulations Related to In-Vehicle Electronic Devices

As listed in Table 1, a number of countries are establishing EMC-related standards and regulations. In addition, international standards are also being amended in accordance with changes in electromagnetic-wave environments in markets.

Table 1 Examples of EMC regulations and standards for in-vehicle electronic devices

Currently, more countries are enforcing new electromagnetic-immunity-related regulations in particular.

Manufacturers that supply electronic devices to markets must conform to these EMC regulations, because it is their responsibility to do so.

As stated above, it is important for manufacturers of in-vehicle electronic devices to take precise anti-noise measures related to electromagnetic immunity quickly in

Table 1 Examples of EMC regulations and standards for in-vehicle electronic devices

Country	Standard and regulation	Type
International standard	CISPR12,25 etc.	Emission
	ISO11452-1 etc.	Immunity
Europe	95/54/EC	Emission
		Immunity
USA	FCC part15 etc.	Emission
	SAEJ1448 etc.	Immunity
Japan	Manufacturers' voluntary self-regulation and others	Emission
	Manufacturers' voluntary self-regulation and others	Immunity
Australia	AS/NZS standard and others (equivalent to 95/54/EC)	Emission
		Immunity
China	Chinese Product Verification Law and others	Emission

accordance with changes in electromagnetic-wave environments and related standards and regulations. Accordingly, the anti-noise design tool can be effective.

3. Development of Noise Visualization System for Extraneous Electromagnetic Waves

3.1 Aim of Development

In developing the noise visualization method for extraneous electromagnetic waves, we set up the four goals given below so that this method can help designers take precise measures against noise rapidly in severe development environments where higher performance, lower cost, and faster development are strictly demanded.

(1) To realize a noise visualization method for extraneous electromagnetic waves
(2) To quickly localize portions that are contaminated by noise
(3) To establish an organization for supplying noise visualization data to the designer.
(4) To enable low-cost system construction

These goals are intended to enable engineers to do away with having to rely on conventional anti-noise measures, which are based on a trial-and-error method.

3.2 Noise Visualization Method for Extraneous Electromagnetic Waves and Its Features

There was no conventional method for visualizing extraneous electromagnetic waves. So, we tried to newly realize an extraneous electromagnetic-wave visualization method jointly with Electronics Laboratory, Electronics Engineering Div.1, Toyota Motor Corporation, by combining an immunity test method that puts extraneous electromagnetic waves in electronic devices and a technique that visualizes the electromagnetic waves in the electronic devices.

We combined existing technologies to enable fast development at low cost. Typical immunity tests include the TEM-cell method test and antenna radiation method test. In both tests, electromagnetic waves are radiated over wire harnesses and products under test, and a check is made to see whether the products can operate normally, without being affected by electromagnetic waves.

As shown in Fig.1, extraneous electromagnetic waves enter the printed circuit board in in-vehicle electronic devices mainly through wire harnesses, because the electronic devices are generally enclosed in

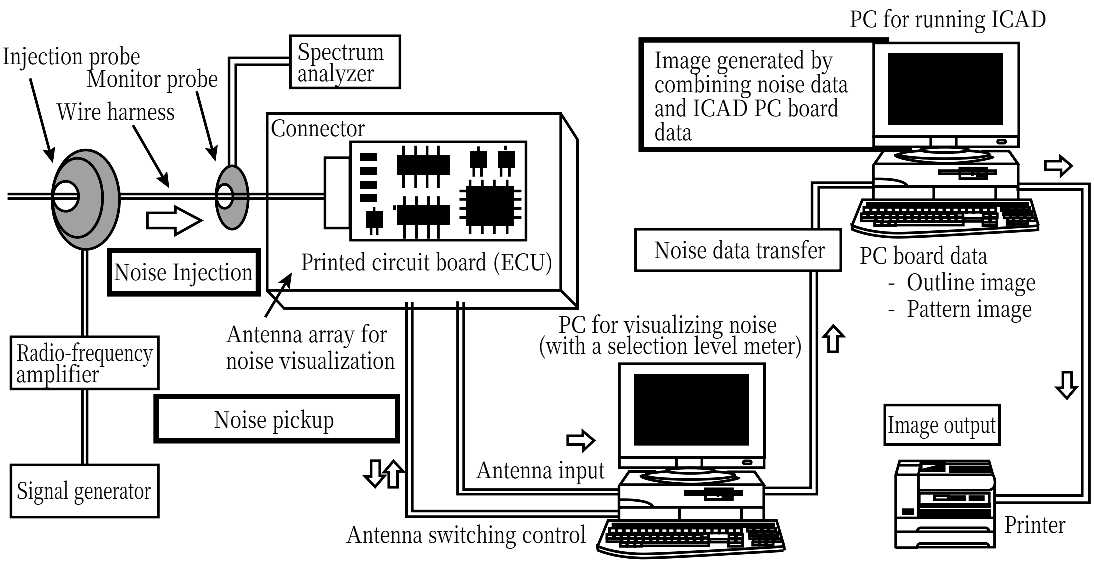


Fig.2 Configuration of noise visualization system for extraneous electromagnetic wave

metal cases. (There might be exceptions, if the printed circuit board is grounded to the case.)

We, therefore, decided to use the bulk current injection (BCI) method[*5] whereby extraneous electromagnetic waves are input directly into the wire harness. The particulars of this method are briefly described below.

*5 BCI is a method for injecting radio-frequency noise equivalent to extraneous electromagnetic waves into a wire harness. The BCI method immunity test is one of immunity tests that use the BCI method to check the operation of a unit under test.

A signal generator, radio-frequency amplifier, and injection probe are used to inject high-frequency noise in the wire harness so that it will enter the in-vehicle electronic device. (The term "radio-frequency noise" refers to all forms of artificially generated noise that are the equivalent of extraneous electromagnetic waves; this is to distinguish this type of noise from the extraneous electromagnetic waves described in Section 1 of Chapter 2.)

An antenna array (commercial antenna array for emission) for noise visualization is used to visualize high-frequency noise in printed circuits. The path through which radio-frequency noise is picked up by the antenna array and then enters the printed circuit board is displayed as a noise visualization image on the PC screen (the term "noise visualization image" refers to any display of digitized radio-frequency noise on the PC screen).

In summary, the system we developed is characterized by the extraneous electromagnetic waves that are forcibly input into an electronic device under test and the radio-frequency noise on the printed circuit board patterns is visualized in the form of noise paths, unlike other EMC-related design support tools.

Fig.2 shows the configuration of the noise visualization system we developed. The following sections detail individual technologies used in developing the system.

3.2.1 Injecting extraneous electromagnetic waves by using the BCI method

This section explains how to input extraneous electromagnetic waves by using the BCI method.

(1) Generate radio-frequency noise equivalent to extraneous electromagnetic waves, using a signal generator.
(2) Amplify the generated radio-frequency noise, using a radio-frequency amplifier, and feed it to an injection probe.
(3) Cause the injection probe (that was previously connected to a wire harness) to inject the radio-frequency noise in the wire harness in accordance with the amplitude of radio-frequency signal applied through electromagnetic induction.
(4) Monitor the radio-frequency noise injection in the wire harness, using a monitor probe. The injection current that represents the amplitude of the radio-frequency noise is generally obtained from Equation (1) given below. The injection current is increased to a prescribed value.

Injection current $I=(10^{((E-Z)/20)})/1000$ [mA] (1)

E：Spectrum analyzer reading [dBμV] (including cable loss)

Z：Monitor probe transfer impedance [dBΩ]

3.2.2 Noise visualization method

An antenna array for noise visualization is used to detect the radio-frequency noise that was injection into a wire harness, using the method described in the previous section, and to display it on a PC screen. How this is done is described below.

(1) When radio-frequency noise is injection into the wire harness, it goes from the wire harness to the foil patterns and components of the circuit via the printed circuit board connector.
(2) The antenna array for noise visualization detects the radio-frequency noise in the printed circuit.
(3) The detected radio-frequency noise is sent to the PC, in which a built-in selection level meter converts the radio-frequency noise to signal strength. The PC performs the prescribed image processing on the signals it received.
(4) The entry path of the radio-frequency noise and its amplitude are displayed on the PC screen as a noise visualization image for the printed circuit board.

3.3 Combining Noise Visualization Image with ICAD Printed Circuit Board Image

Conventionally, when only a noise visualization image was used to display noise paths in the printed circuit, designers used to compare it with a separately prepared PC board drawing by putting them side by side or laying one on the other and looking through them. However, this method was time-consuming, and it was difficult to spot the exact location of the noise.

We took two steps to eliminate these difficulties. We converted individual noise data items comprising the noise visualization image to a form in which they could be processed using ICAD. We also integrated the resulting data into the ICAD user layer so that it could be displayed on the PC screen together with the circuit patterns, outline, and components of the printed circuit.

The color of the noise visualization image is represented using hatching (line information), and the hatching spacing can be altered at the user's discretion. This configuration allows the user to further increase the visibility of the display, for example, by decreasing the hatching spacing to enhance the noise visualization image and increasing the hatching spacing to emphasize the circuit patterns of the printed circuit board.

In this manner, designers can accurately spot the noise paths on the printed circuit board. Fig.3 is an example of image synthesis. How this is done is explained below.

(1) The PC for noise visualization converts noise data on the individual ultrasmall antenna elements of the antenna array for noise visualization and the coordinate data of the ultrasmall antenna elements to a form in which data can be handled by ICAD.

(2) The data generated at step (1) above is integrated into the ICAD user layer in the PC for ICAD, then the previously stored data about the printed circuit board is called up.

(3) The origins of both the noise data and printed circuit board data are aligned so that they can be placed on the same position, then both types of data are combined, and the image based on the resulting data is displayed on the screen of the PC for ICAD.

Use of the ICAD data has made it possible to

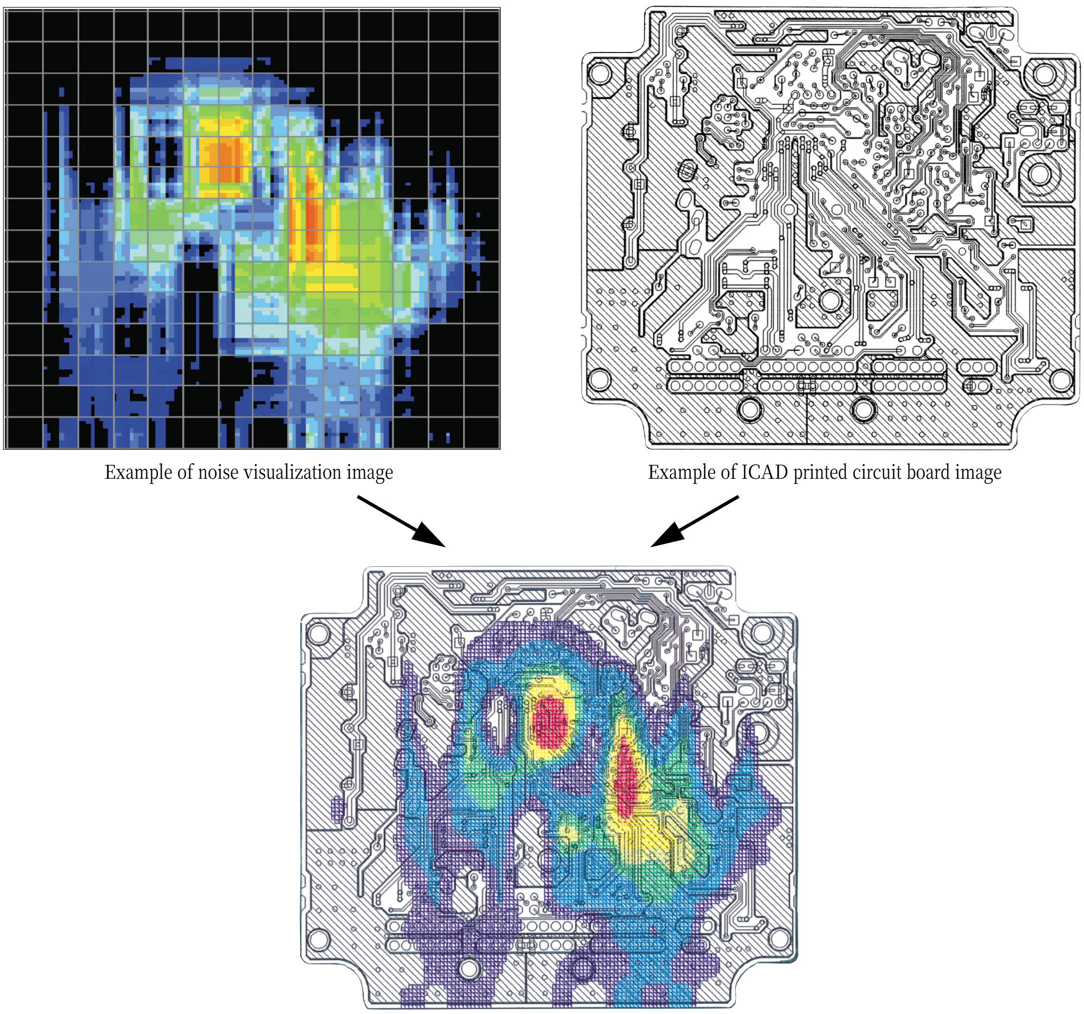


Fig.3 Synthesis of noise-visualization image and ICAD printed circuit board image

generate any noise visualization image not only for the solder-side circuit patterns of a printed circuit board but also for the component-side circuit patterns, components, and even invisible internal-layer circuit patterns.

3.4 Identifying Noise Paths

By using the method stated above, the path through which extraneous electromagnetic waves enter a printed circuit board can be visualized and localized rapidly and accurately, using a PC.

In addition, inputting radio-frequency noise into a selected wire harness makes it possible to identify the path through which noise enters a specific location. Moreover, combining noise data with circuit patterns in an arbitrary layer using ICAD can increase the accuracy at which the noise path is identified.

3.5 Supplying Measured Noise Visualization Results to Designers

The system we developed has enabled extraneous electromagnetic waves are identified more accurately. Another important step to take is to set up an environment in which measured noise visualization results can be promptly supplied to designers.

To meet this demand, we contrived a method for presenting the information about noise paths over the company Intranet and employed a method for saving this information directly to an ICAD database. These methods allow designers even at remote locations between Nakatsugawa and Kobe to effectively use the anti-noise measure information.

3.6 Verifying Validity of Noise Visualization System

3.6.1 Aim of verification experiments

This system visualizes noise by inputting extraneous electromagnetic waves using the BCI method in the immunity test that is simulated for frequencies at which a product failed in using the TEM-cell test method or radiated immunity test method.

To verify the validity of the noise visualization system, therefore, we decided to cooperate with a design department in conducting the following two verification experiments.

Verification 1: Verify whether the BCI method immunity test can reproduce the degree of effect (in this verification, audio output fluctuation) of the TEM-cell test method or radiated immunity test method on a product.

Verification 2: Verify whether the BCI method can accurately visualize the path in a printed circuit through which extraneous electromagnetic waves pass.

3.6.2 Conditions for verification experiments

To accommodate the purpose of the verification experiments, we removed an anti-noise component from a mass production product so that the unit under test was simplified as much as possible. Accordingly, the quality of the resulting unit under test is very low in terms of electromagnetic immunity. To be more specific, a bypass capacitor was removed from the speaker line in order to facilitate the entry of extraneous electromagnetic waves into the printed circuit board.

Table 2 lists the other conditions of verification experiments.

Table 2 Conditions of verification experiments

	BCI method	TEM-cell method	Radiated immunity method
Frequency range (MHz)	20～1000	20～400	200～1000
Measurement step	2%	2%	2%
Radiated electric field strength (V/m)	—	150	60
Injection current (mA)	30	—	—
Radiation and input time	2s	2s	2s
Antenna polarization	—	—	Horizontal
Orientation of Device under test	—	X direction	—
Device under test	Audio amplifiers (two types) (1) Mass-production product (2) Product with a lowered noise immunity (Mass-production product from which a speaker line bypass capacitor has been removed)		

3.6.3 Results of verification experiment

1) Verification experiment 1

As shown in Fig.4, in the BCI method immunity test developed, at the same frequency, the same symptom as

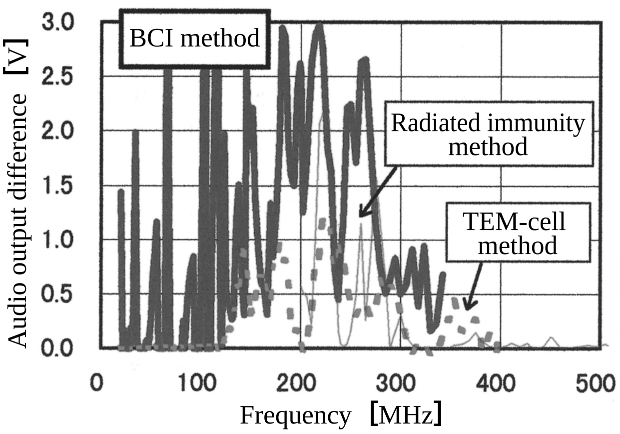


Fig.4 Difference in audio output among the various immunity test methods

the audio output fluctuation observed in the TEM-cell test method and radiated immunity test method was observed. (This audio fluctuation is represented as an output difference generated by subtracting a value measured on a typical mass-production product, from the value measured on a product with a lowered noise immunity.)

2) Verification experiment 2

When a frequency of 157 MHz, at which the audio output fluctuated, was forced into the wire harness of the unit under verification experiment 1, the noise did not enter the printed circuit board to a significant degree.

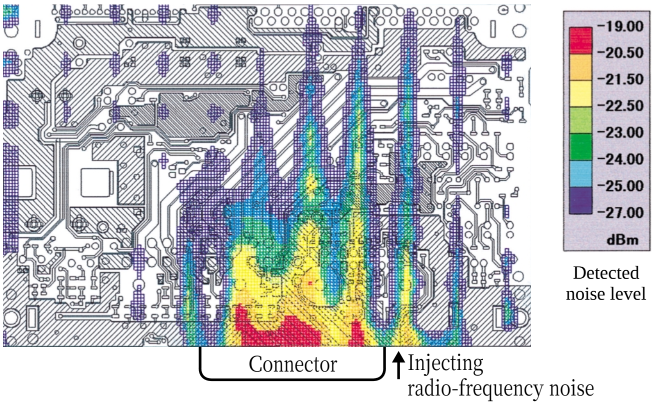


Fig.5 Noise visualization image (157 MHz) of mass-production product

(See Fig.5.)

In the product with lowered noise immunity, noise entered the printed circuit board (Figure 6), and the level of noise on the speaker line was 8 dB (maximum) higher

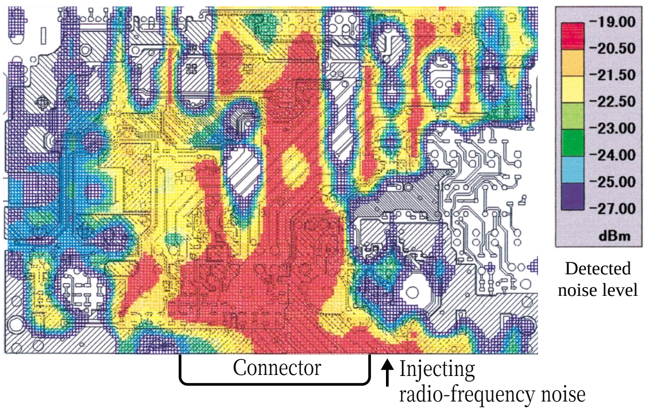


Fig.6 Noise visualization image (157 MHz) of item with deteriorated mass-production product

compared with the typical mass-production product.

3.6.4 Examining verification experiments for system validity

The result of verification experiment 1 proved that the BCI method is an appropriate method for inputting extraneous electromagnetic waves, because the BCI method immunity test successfully reproduced the audio output fluctuation observed using the TEM-cell test method and radiated immunity test method. Therefore, we can say that the system successfully simulated the TEM-cell test method and radiated immunity test method. (If an output used to monitor the operation of a unit under test is in digital format, in which pass/reject decisions are made based on a threshold value instead of analog format, however, there may be exceptions where the system is ineffective. This is owing to the limited capacity of the equipment regarding the high-frequency noise generated.)

The result of verification experiment 2 proved that when high-frequency noise was input to a unit whose noise immunity had been deliberately made lower, the noise entered the inside of the printed circuit board as previously conjectured. Therefore, we can conclude that the system accurately visualized the path through which noise entered the printed circuit board. In addition, it was recognized from Fig.4 that there was a significant fluctuation of the audio output.

In this way, it was known that the noise visualization method for extraneous electromagnetic waves based on the BCI method immunity test could accurately simulate the TEM-cell test method and radiated immunity test method. This means that the noise visualization system was proved to be effective.

The audio output shown in Fig.4 was obtained by subtracting the level measured on the usual mass-production product from that on the product with a lowered noise immunity. So, it was verified again that, in each test, the usual mass-production product outperformed the product with lowered noise immunity with respect to noise immunity. Moreover, this verification is supported by the fact that it is more difficult for noise to enter a typical mass-production product as compared with a product with lowered noise immunity.

Therefore, it was also known that the noise visualization system was successfully used to prove the validity of past anti-noise measures.

4. Applying Noise Visualization System to Design of Anti-noise Measures for Immunity

The verifications described in the previous sections proved the validity of the noise visualization system for

extraneous electromagnetic waves.
The following sections explain the cases in which we analyzed noise by applying this system to actual design situations.

4.1 Cases of Applying Noise Visualization System to Power Train Control Unit

4.1.1 Effect of extraneous electromagnetic waves on power train control unit

The TEM-cell method immunity test conducted on a power train control unit revealed that the ON time of an output signal fluctuated from a prescribed value. Normally, the ON time stays within a tolerance of ±5% of 4.1 ms. When electromagnetic waves were radiated, however, the ON time changed 8% or 9% from the reference value.

The examination previously made by the designer revealed that the supply voltage dropped from 5 V to 3.8 V. But the cause could not be determined.

4.1.2 Analysis by means of noise visualization system

We measured this fluctuation of the output ON time by performing the verification procedures described in Chapter 3, with the noise visualization system. The frequency used in this measurement is 196 MHz, at which the output fluctuation in the unit occurred.

1) Analyzing visualized noise

Analysis using this system revealed that radio-frequency noise equivalent to extraneous electromagnetic waves enters the ground section of digital circuits near the power supply IC through the wire harness and +B and power supply system ground terminals, and then passes through the bypass capacitor for grounding the case. (This noise is presumed to cause a voltage drop in the power supply IC by passing through the bypass capacitor.) (See Fig.7 and 8.)

From this analysis, we found that the voltage drop occurred because the high-frequency noise that entered the unit fluctuated from the reference ground level of the comparator for generating 5 V in the power supply IC.

Fig.9 and 10 show this symptom in diagram form, using circuit blocks.

2) Anti-noise measure

The power supply section containing the power supply IC was reinforced by removing the bypass capacitor (see Fig.10) for the power supply section ground from which noise was likely to enter the power supply IC digital section ground.

Additional analysis by means of the noise visualization system has enabled a specially designed anti-noise measure to be taken around the power supply IC, thus enabling the printed circuit board to pass the TEM-cell test after only one design change, as shown in Fig.11 and 12.

4.1.3 Reduction in number of labor-hours required to implement anti-noise measures

Using the noise visualization system enabled us to identify the path through which extraneous electromagnetic waves entered the printed circuit board, and screen out the locations for which an anti-noise

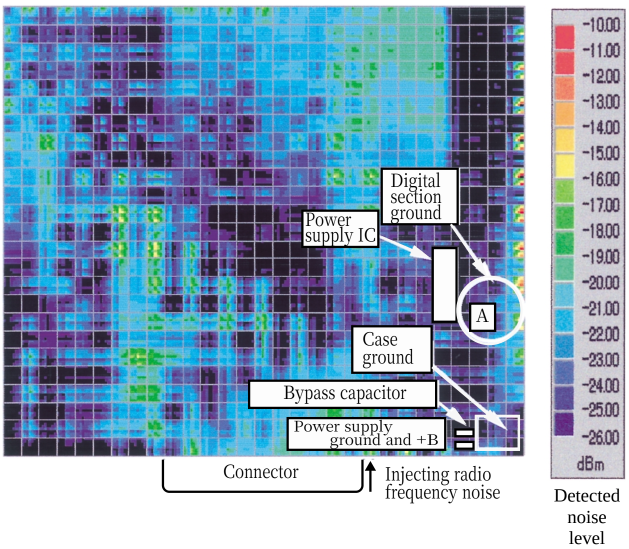


Fig.7 Noise visualization image (196 MHz) prior to anti-noise measures

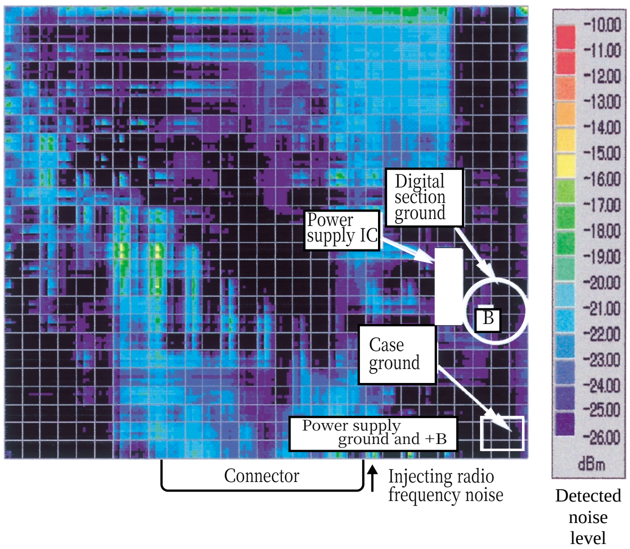


Fig.8 Noise visualization image (196 MHz) following anti-noise measures

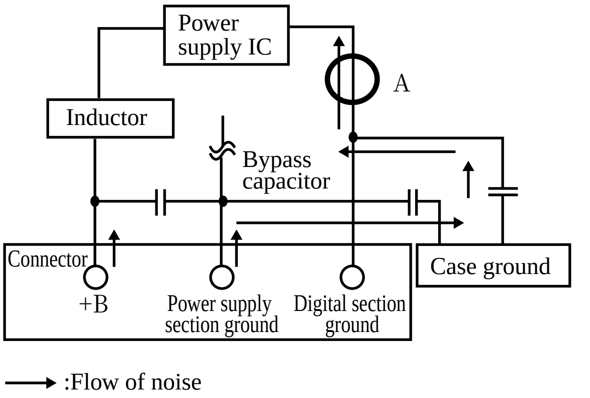


Fig.9 Circuit block diagram prior to anti-noise measures

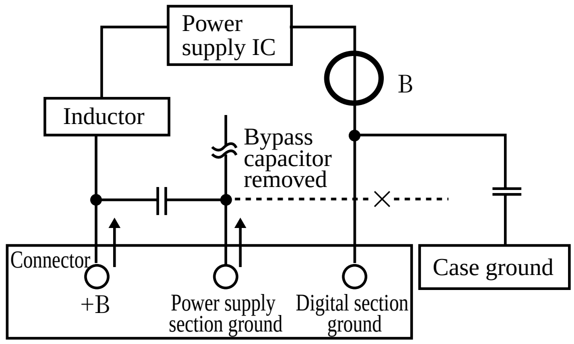
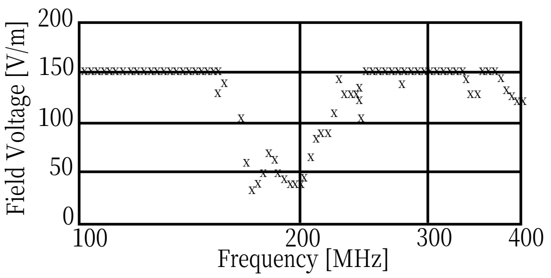


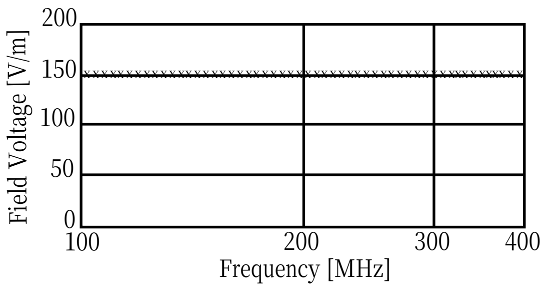
Fig.10 Circuit block diagram following anti-noise measures



<Typical output-fluctuating frequencies extracted from all 41 frequencies>

Frequency (MHz)	Level at which the output starts fluctuating (V/m)	Output fluctuation
172	35	+5% over input time
175	40	Same as stated above
196	40	Same as stated above
199	40	Same as stated above

Fig.11 Results of TEM-cell method immunity test prior to anti-noise measures



〈No output fluctuation（150V/m）〉

Fig.12 Results of TEM-cell method immunity test following anti-noise measures

measure is to be taken.

Screening locations in which an anti-noise measure is to be taken consumes more labor-hours than any of the other steps required to implement the anti-noise measure. Applying the noise visualization system to this job enabled a near 40% reduction in the number of design labor-hours.

5. Conclusion

This paper stated that it is important to secure a high-immunity performance to extranceaus electromagnetic waves with respect to diverse extraneous electromagnetic waves in in-vehicle electronic devices, because safety is especially required of these devices.

It also explained that we developed a system for forcibly injecting extraneous electromagnetic waves into electronic devices using the BCI method and visualizing the path through which the noise enters the printed circuit board. It also proved that the system is effective and can be used in design situations.

We will continue to perform noise analysis using this system, thereby gathering cases of analyzing mechanisms in which noise enters circuits and integrating the cases as design know-how in order to secure EMC quality.

Finally, we would like to express our gratitude to Mr. Junzo Ooe from Toyota Motor Corp. for his cooperation in jointly devising the noise visualization method for extraneous electromagnetic waves used in the system.

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