Transfer Function Measurement for Automotive Intentional Electromagnetic Interference

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***Abstract*—The transfer function between the intentional electromagnetic interference (IEMI) attacker and the engine control unit (ECU) circuit in an automobile is extracted to analyze how the IEMI affects the vehicle. A log-periodic antenna is used as the IEMI aggressor based on the frequency domain measurement and the transfer function of the log-periodic antenna is compared with the transfer function of the standard mesoband source generator measured in the time domain. The electric field of the standard source is regenerated with the transfer function of the log-periodic antenna. It is then compared with the original field of the standard source to validate the transfer function of the log-periodic antenna. Since the D-dot sensor is used to measure radiated field in the time domain, a noise in low frequency region is amplified and it is investigated.**

Keywords—Transfer Function, Intentional Electromagnetic Interference, IEMI, Electromagnetic Threat

I. Introduction

With an increasing demand for electric vehicles and autonomous driving, many components of a vehicle are being replaced as electric components. This implicates the possibility of an increase in the malfunction of electric components due to unknown electromagnetic interferences. As an example, when antilock braking system (ABS) was first introduced, braking problems arose on the German autobahn when vehicles passed a nearby radio transmitter [1]. Malicious IEMI is being considered as a growing threat for the current and next generation of automotive technology. It works by intentionally inducing noise, thereby disrupting the normal operation of a system. This issue emphasizes the importance of understanding potential risks that this intentional threat will cause.

Several experiments were conducted to understand automotive IEMI [2-4]. They were based on the time domain measurement and a D-dot sensor was used to measure the radiated electric field [5]. Due to the characteristic of a D-dot sensor, the low frequency noise is amplified with the time domain measurement and it occurs the uncertainty of the measurement. Also, standard IEMI source generators are usually required to analyze automotive IEMI [6]. However, experiments using these source generators were costly and dangerous, since they are huge and generate high power electromagnetic (HPEM) fields of tens or hundreds of kV/m at peak field strengths. This facilitates the need to test the IEMI using an alternative aggressor other than standard IEMI attackers.

In this paper, the transfer function between the IEMI source and the ECU circuit in the automobile is extracted to analyze how IEMI affects the vehicle and the low frequency noise with the time domain measurement is investigated. Instead of standard IEMI sources, the log-periodic antenna is used as an aggressor and the measurement is conducted in the frequency domain. A transfer function of a system is a ratio of the output to the input of the system and it is used to describe and analyze the system in the frequency domain. To offset the effect using different IEMI sources, a transfer function is considered to show how a radiated electric field affects the vehicle; therefore, vulnerable frequencies can be specified. It is calculated with reconstructed dipole moments of the log-periodic antenna and compared with the transfer function of the standard mesoband source measured in the time domain. To validate if the transfer function of the log-periodic antenna is comparable to the standard source generator, the electric field of the standard source is regenerated with the transfer function of the log-periodic antenna and is compared with the original standard source field waveform.

II. IEMI Source Characterization

To calculate the transfer function, the system's input and output need to be well defined. In [2], the mesoband standard source generator was used as Fig. 1 to reconstruct the IEMI source for the numerical simulation. Since the generator is based on the dipole antenna structure, the dominant current flows in the vertical direction through dipole arms; therefore, the Hertzian dipole is considered for the source reconstruction. Also, the transverse electromagnetic (TEM) sensor is placed at a height similar to that of the center of the standard source to measure the radiated field from the generator. In this case, the dominant field's component is in the vertical direction. The dipole moment of the aggressor P_z and its radiated electric field E_z to the victim are considered as the input and output to extract the transfer function for IEMI analysis.

In this section, IEMI dipole moments P_z was reconstructed by the source reconstruction using the log-periodic antenna. Also, radiated electric fields E_z from the log-periodic antenna

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(a) The setup for the source reconstruction

(b) IEMI measurement setup

Fig. 1. The mesoband standard source measurement setup

were measured using a D-dot sensor. With these values, the transfer function of the log-periodic antenna is calculated and compared with the standard source. To validate if the transfer function of the log-periodic antenna is comparable to the standard source, the electric field is regenerated as the transfer function of the log-periodic antenna multiplied by dipole moments of the standard source and compared with the original electric field radiated from the standard source.

A. Measurement for IEMI Source Modeling

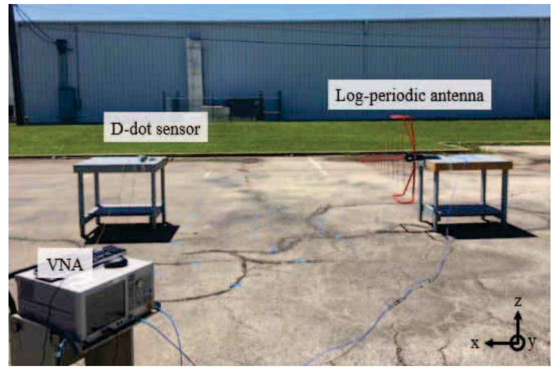
The measurement setup with the log-periodic antenna is illustrated in Fig. 2. The log-periodic antenna was used as an IEMI source. The free-field D-dot sensor and the log-periodic antenna are placed at z = 1 m. The preamplifier is a low noise amplifier (LNA) to improve the signal-to-noise ratio (SNR).

In the far-field region, it is reasonable to replace the source with an ideal infinitesimal electric dipole. Based on the log-periodic antenna structure with a height of 0.74 m, the far-field boundary can be estimated as 1.825 m at 500 MHz by the following equation [7]:

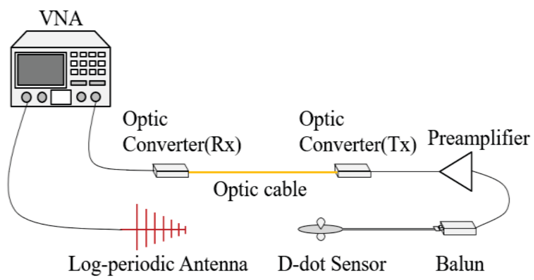
$$R = \frac{2D^2}{\lambda} = \frac{2\times(0.74m)^2}{\frac{3}{5}m} \approx 1.825m \tag{1}$$

where D is the largest dimension of the antenna, and λ is the wavelength of the signal in the air at 500 MHz.

The D-dot sensor was used to measure the radiated electric field. Since it is mounted on a small ground plane, it can be placed in the vehicle where it will measure a surface electric field quantity. The z-components of electric fields were measured at different observation points from 2 m to 6 m which are the distances between the log-periodic antenna's calibration reference point and the D-dot sensor. The output of the D-dot sensor is proportional to a time derivative of the electric field; it is proportional to the frequency by Fourier transform. The electric field $E_z(f)$ can be calculated as:



(a) Measurement setup for the source reconstruction



(b) Measurement setup illustration

Fig. 2. The measurement setup for IEMI source modeling

$$E_z(f) = \frac{V(f)}{A_{eq}R_0 \times j2\pi f \varepsilon_0} \tag{2}$$

where $V(f)$ is the output voltage of the D-dot sensor in the frequency domain, A_{eq} indicates the equivalent area of the D-dot sensor, R_0 is the characteristic impedance of the D-dot sensor and ε_0 is the permittivity of free space. Fig. 3 shows measured electric fields E_z converted by (2).

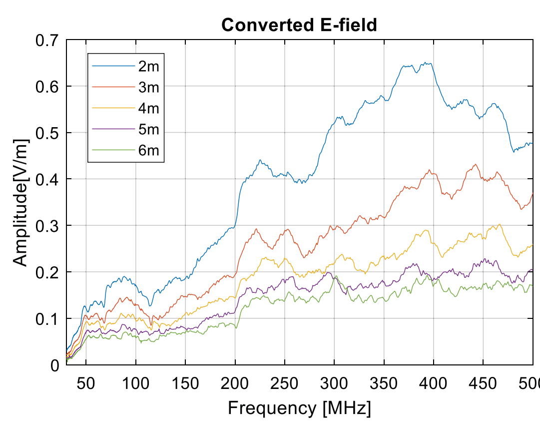


Fig. 3. Electric field E_z measurement data

B. IEMI Source Reconstruction

With measured field data, the equivalent dipole moment P_z of the log-periodic antenna was reconstructed by the source reconstruction and the least square method [8, 9]. Since the log-periodic antenna supports above 30 MHz based on the datasheet and the far-field boundary estimation calculated as (1) can be considered below 500 MHz, the dipole moment is reconstructed from 30 MHz to 500 MHz with the step of 10 MHz. Fig. 4 shows reconstructed dipoles $P_z(f)$ of the log-periodic antenna. It correlates the antenna factor of the log-periodic antenna on the datasheet especially at a peak near 50 MHz region.

To validate reconstructed dipole moments, the dipole moments are imported on the simulation. The equivalent dipole is placed at z = 1 m which is the same height as the log-periodic antenna placement. Fig. 5 compares measurement and simulation results at the point located 2 m away from the source. The simulation result matches well with the measurement. The reconstructed source generates the same field as the log-periodic antenna does. Also, the data from 3 m to 6 m away from the log-periodic antenna matched well.

C. Validation of the Transfer Function

The transfer function of the log-periodic antenna can be calculated as shown below:

$$TF(f) = \frac{E_z(f)}{P_z(f)}. \quad (3)$$

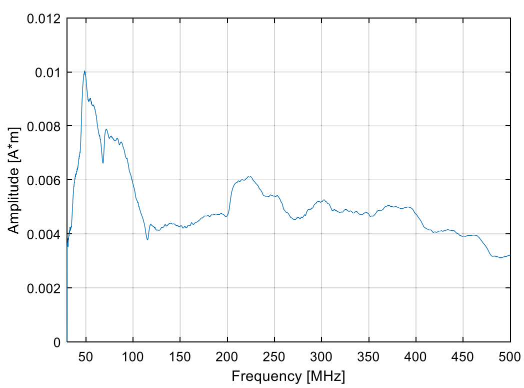


Fig. 4. The equivalent dipole moment $P_z(f)$ of the log-periodic antenna

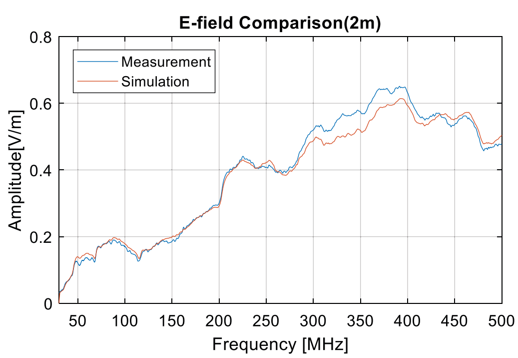


Fig. 5. Electric field comparison at 2 m away from the source

The transfer function of the mesoband standard source measured using the TEM sensor was also calculated with the data in [2]. On the simulation, the unit dipole was set as a source in Fig. 6 to extract the transfer function directly from the measured field. In Fig. 7, the transfer function of the log-periodic antenna is similar to the other sources below 250 MHz. Due to the structure of the standard source generator mentioned above, the standard source generator is a dipole antenna, which has a length of 1.15 m. Since it operates as an open circuit when the wavelength is the same as the length of the dipole, it shows a null at 260 MHz.

To verify the transfer function of the log-periodic antenna, the electric field was regenerated with dipole moments of the standard source multiplied by the transfer function referring to (3) and it is compared with the measured electric field of the standard source as shown in Fig. 8. The regenerated waveform matched well with the real standard source measurement. It

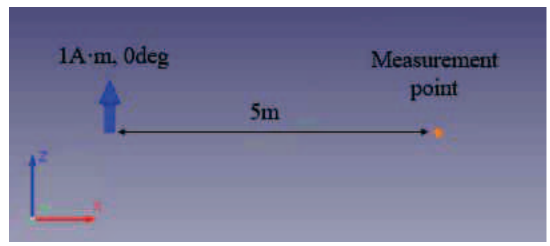


Fig. 6. Simulation setup for the transfer function of the unit dipole

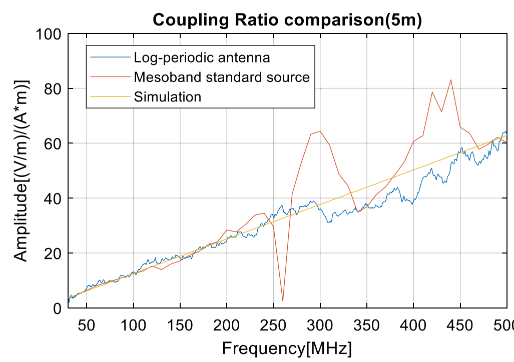
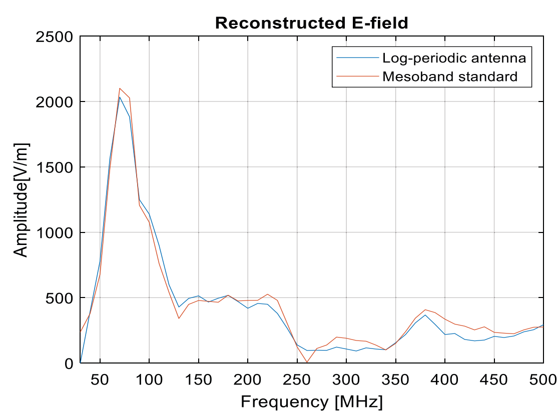
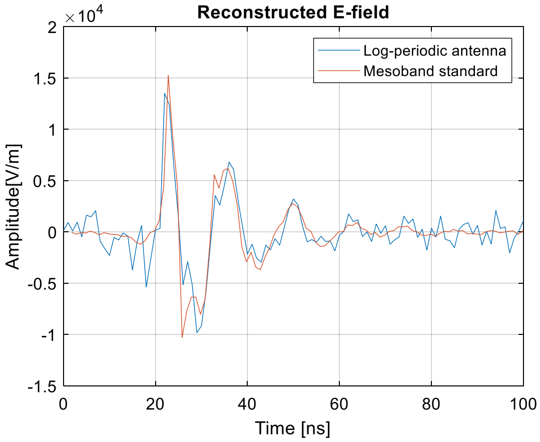


Fig. 7. Transfer function comparison



(a) Single side spectrums in the frequency domain



(b) Waveforms in the time domain

Fig. 8. Comparison of the reconstructed and the measured electric fields E_z

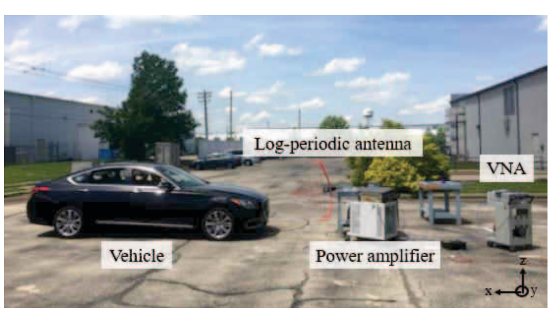
shows that the transfer function of the log-periodic antenna is comparable to the transfer function of the standard source.

III. Transfer Function Measurement to Characterize Automotive IEMI

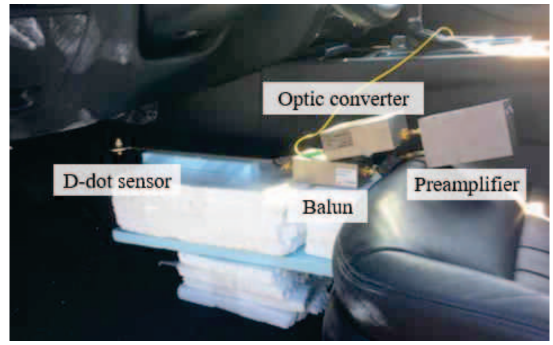
Most vehicles have ECUs, which are placed near the front center console. To check the IEMI effect to the ECU, the IEMI source is placed 5 m away from the front, rear, and side of the vehicle and the D-dot sensor is placed near the accelerator pedal to extract the transfer function between the attacker and the victim.

A. IEMI Measurement with the Log-periodic Antenna

Fig. 9 describes the IEMI measurement setup. The log-periodic antenna was placed as the IEMI source and the vehicle as the victim. Similar to in Section II, two external amplifiers were added. The power amplifier was attached to the log-periodic antenna, and the preamplifier was attached to the output of the balun. Compared with the preamplifier, the power amplifier is used to amplify the power of a 0 - 10 dBm range. The D-dot sensor was placed near the accelerator pedal to measure the radiated electric field from the IEMI source, since the pedal is near the front center console. Fig. 10 shows the measured electric field E_z. To extract the transfer function, the electric field E_z was divided by the dipole moment P_z of the log-periodic antenna.



(a) Measurement setup with the vehicle



(b) D-dot sensor placement near the pedal

Fig. 9. The IEMI measurement setup with the vehicle

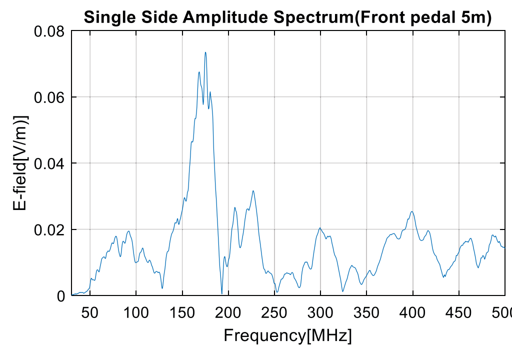


Fig. 10. The electric field E_z at 5 m away from the source to the vehicle

B. Validation of the Transfer Functions with Different IEMI Sources

The transfer functions of different IEMI sources with the vehicle 5 m away from the source to the front of the vehicle are extracted and compared as shown in Fig. 11. Transfer functions of the log-periodic antenna and the standard source can be calculated by (3) with a measured electric field inside the vehicle.

To validate the transfer function of the log-periodic antenna with the vehicle, the electric field was regenerated with dipole moments of the standard source and compared with the real measurement of the standard source as Fig. 12. The magnitude

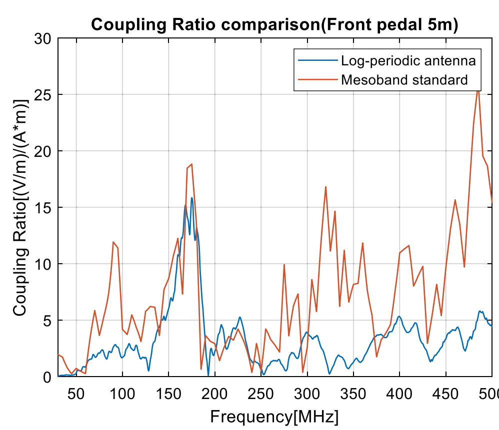
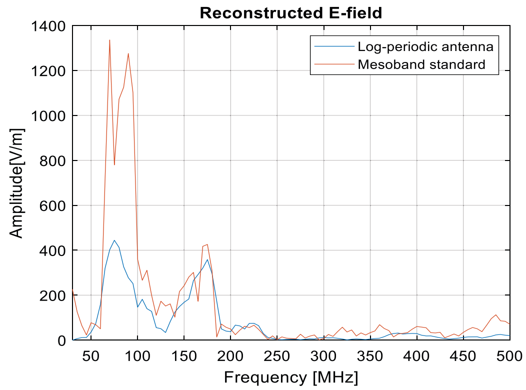
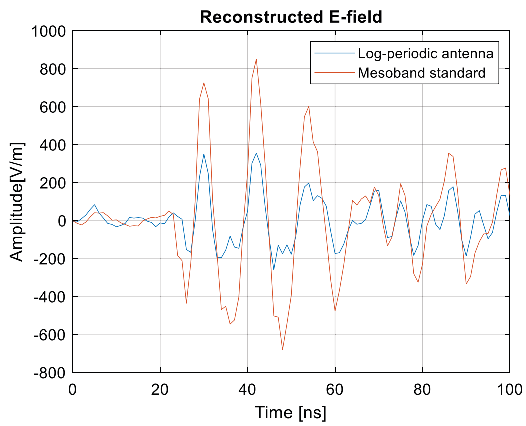


Fig. 11. Transfer function comparison with the vehicle



(a) Single side spectrums in the frequency domain



(b) Waveforms in the time domain

Fig. 12. E-field comparison generated with different transfer functions

of the log-periodic antenna at 50 – 100 MHz range is lower than the standard source due to the transfer function. Consequently, the main signal of the time domain waveform is 80 MHz and the magnitude of the log-periodic antenna is affected by the transfer function. Overall, the regenerated waveform in the time domain follows the same trend as the standard source, and it shows that the transfer function of the log-periodic antenna is comparable to the measurement of the standard source. Additionally, the victim was illuminated from the rear, and side. The measurement results show similar tendencies as the front and are not included in the manuscript.

To measure the field radiated from the standard IEMI source, an oscilloscope and the D-dot sensor was used. An oscilloscope has internal noise, and the noise floor level is related with the bandwidth as shown below:

$$\text{Noise Floor } [dBm] = -174 + \text{Noise Figure} + 10\log_{10}(\text{Bandwidth}) \quad (4)$$

where the bandwidth indicates the range of frequencies that the oscilloscope can acquire and display accurately with less than 3 dB attenuation. As mentioned in Section II, a D-dot sensor captures the time-derivative of the electric field; it has the $j\omega$ term in the frequency domain. The output voltage of the D-dot sensor is divided by $j\omega$ to get the electric field as (2), which is affected by the oscilloscope's noise in the low frequency region. However, there was not a similar trend of the mesoband standard source in Fig. 8 (a) below 50 MHz, since the TEM sensor was

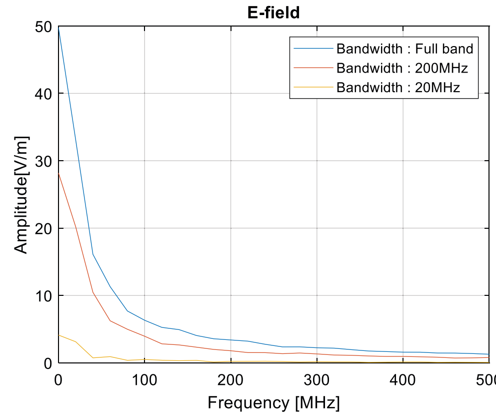


Fig. 13. Idle noise measurement with different bandwidth settings of the oscilloscope

used to measure the field to characterize the standard source generator in Section II. As the output of the TEM sensor is proportional to the electric field, it does not need to be divided by $j\omega$.

To verify the low frequency noise in the standard source measurement, the idle noise was measured using the D-dot sensor and the oscilloscope with the following bandwidth settings: full band, 200 MHz, and 20 MHz. Measured signals were converted to the electric field in the frequency domain as Fig. 13. In the low frequency region, it is similar to the measurement data of the standard source in Fig. 12 (a). It shows that the low frequency noise is related with the internal noise of an oscilloscope and the characteristic of a D-dot sensor. This issue can be resolved by attaching an integrator after the D-dot sensor, using a vector network analyzer (VNA) or a spectrum analyzer.

IV. Conclusion

Using a log-periodic antenna as an IEMI attacker, the transfer function between the aggressor and the ECU is extracted and compared with the mesoband standard source measurement. To validate the transfer function, the electric fields are reconstructed as the extracted transfer function multiplied by dipole moments of the standard source. It is found that the extracted transfer function of the log-periodic antenna is comparable to the transfer function of the standard source. It is expected that the transfer function measurement can be considered to analyze how the automotive IMEI affects the vehicle.

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