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Air gap measurement in cable of automotive electronics based on electromagnetic wave

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Abstract: Time-frequency domain reflectometry (TFDR) based on electromagnetic theory is first introduced to measure air gap in cables. By using the relationship between propagation velocity and permittivity in electromagnetic theory, the new relationship between the air gap and the propagation velocity in cables can be obtained. The proposed method adopts a chirp signal as an incident signal and uses a normalized cross-correlation function for deriving propagation velocity. To reduce signal distortion caused by cable attenuation characteristics, a modified overcomplete wavelet transform is applied. The air gap volume, which can be measured by the proposed method, can be used as an indicator of poor contact between the cable and connector. The performance of the proposed method is verified through experiments.

Keywords: electromagnetic wave, signal restoration, permittivity measurement, air gap detection, reflectometry

Classification: Electromagnetic theory

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1 Introduction

As automobiles become increasingly automated, the safety of automotive systems has become the most important issue. The main reasons for failure of automotive electronics are cable faults and poor contact between cables and connectors. The reflectometry method, which is nondestructive, is mainly used for diagnosing problem with cables installed in automobiles because they are vulnerable to shock without insulation. Reflectometry methods can be divided into time domain reflectometry (TDR), frequency domain reflectometry (FDR), and TFDR [1, 2, 3, 4] depending on the reference signal type. TDR and FDR have been widely used for cable diagnostics, because they are easy to implement. However, the signals of TDR and FDR have characteristics in one domain. In contrast to TDR and FDR, TFDR has robustness property against noise because TFDR signals have characteristics in both time and frequency domains. The TFDR method, which is based on radar theory, estimates an impedance discontinuity position using the time delay of the reflected signal generated from the impedance discontinuity point. The time-frequency cross correlation function, which is based on Wigner-Ville distribution, is used to calculate the time delay of the reflected signal. Therefore, we introduce the TFDR method to obtain the time delay, which can be converted to propagation velocity.

There are many studies on the diagnosis of cable defects. However, there is little research on poor contact between cables and connectors [5]. The study about detection of contact failure [5, 10] uses the phenomenon that the contact resistance is changed when there is a contact failure between the cable and the connector. However, in the case of poor contact other than contact failure, since the contact resistance changes every time the car moves, real-time resistance monitoring is required and accurate resistance measurement is difficult due to noise. Poor contact is more difficult to find because it occurs intermittently, owing to vibration that occurs when automobiles move. Poor contact indicates that there is an air gap between cable and connector. Therefore, the air gap volume can be used as an indicator of poor contact. To measure air gap in cables, we use the relationship between propagation velocity and permittivity in electromagnetic waves. The TDR method based on this relationship is used to determine the soil-to-water ratio of soil

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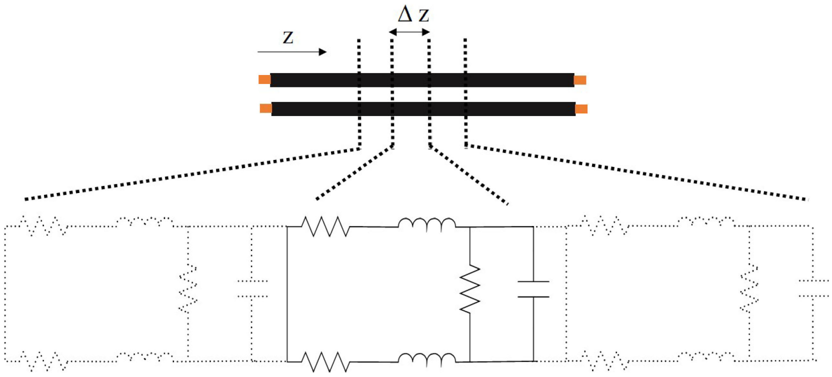

Fig. 1. Equivalent circuit of the cable.

[6, 7, 8]. However, the TDR method, which is not robust to noise, has a lot of errors when it is applied to automotive electronics in noisy environments. Since the TFDR signal has characteristics in the frequency domain, it is possible to find the frequency range in which the relationship between the propagation velocity and the air gap appears well, and then we can design the incident signal which fits for the frequency region. In addition, the cable used in automobiles has severe attenuation characteristics, because the cable has no insulation layer. To reduce the signal distortion due to this characteristic of cable, a modified regularization method based an overcomplete transform [9] is proposed in this paper. Therefore, we used the overcomplete transform for restoring the reflected signal. The air gap in cable can be measured by analyzing the propagation velocity, which varies according to the permittivity derived from the proposed method.

2 Cable air gap measurement based on electromagnetic wave theory

The proposed air gap measurement method consists of two main parts. The first part is an air gap detection method using TFDR based on combining radar and electromagnetic theory. After the first step, the signal restoration process is needed to recover from the signal distortion caused by cable attenuation characteristics. In electromagnetic theory, the phase velocity of an electromagnetic plane wave can be derived as follows:

$$v_p = \frac{\omega}{\beta} = \frac{\omega}{Im\sqrt{(R + j\omega L)(G + j\omega C)}} \tag{1}$$

where β is a phase constant, L is the line inductance in series with a resistance R, C is the capacitance of the transmission line per unit length, and G is the transmission line conductance in Fig. 1. In a transmission line with losses caused by a dielectric, the conductance term in (1) cannot be neglected and thus the phase velocity of the signal is derived as follows [5]:

$$v_p = \frac{1}{\sqrt{\mu_r \epsilon_r'/2\left(1 + \sqrt{1 + ([\epsilon_{relax}'' + (\sigma_{dc}/\omega\epsilon_0)]/\epsilon_r')^2}\right)}} \tag{2}$$

where ϵ_r' is the real part of the relative permittivity, ϵ_{relax}'' is the imaginary permittivity due to molecular relaxation, ϵ_0 is the permittivity of free space, μ_r is

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the relative magnetic permeability, and σ_{dc} is the direct current equivalent electrical conductivity. The propagation velocity of waves in dispersive media is affected by permittivity. The apparent permittivity K_a is a function that is affected by electrical conductivity $[\sigma_{dc}/(w\epsilon_0]$; it is represented as follows:

$$K_a = \frac{\mu_r \epsilon_r'}{2}\left(1 + \sqrt{1 + ([\epsilon_{relax}'' + (\sigma_{dc}/\omega\epsilon_0)]/\epsilon_r')^2}\right) \tag{3}$$

The incident signal, Gaussian linear chirp signal, is represented as follows:

$$s(t) = \begin{cases} Ae^{-\alpha t^2/2 + j(0.5\xi t^2 + \omega t)}, & \mathrm{t = 0 \le t \le T} \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

where T is the duration of the incident signal, A is the amplitude, ξ is the normalized angular frequency sweep rate, and ω is the normalized angular frequency. The incident signal used in this paper is a chirp signal composed of many frequencies. For this reason, it is difficult to apply the incident chirp signal to (3). However, for materials with low ionic conductivity, the chirp signal is also applicable to (3) as a single frequency signal [5]. By using the relationship between the propagation velocity and the permittivity, the change in permittivity due to the air gap can be detected. The reflected signal generated from the cable termination is expressed as follows:

$$r(t) = \eta \cdot Ae^{-\alpha t^2/2 + j(0.5\xi(t-d)^2 + \omega(t-d) + \phi)} \tag{5}$$

where η is the magnitude of the reflection coefficient at the cable termination, and d is the time delay of the reflected signal. The normalized cross-correlation between the incident signal and the reflected signal is used to detect the reflected signal from the cable termination. This may be expressed as follows [1]:

$$C_{sr}(t) = \sum_{k=0}^{N-1} \frac{s_k \bigotimes r_{k-t}}{\sqrt{E_s E_r}} \tag{6}$$

where E_s is the energy of the incident signal in Wigner-Ville distribution, E_r is the energy of the reflected signal, and $\bigotimes$ is the correlation operator. Through the normalized cross-correlation process, the time of arrival in the target cable and the propagation velocity can be derived. The propagation velocity of signals in cables under various environments can be obtained in order to observe the air gap in the cable.

3 Signal restoration using the overcomplete wavelet transform

A target cable installed in car has no insulation layer. According to this property, the attenuation of the signal is very severe and the part of signal is induced by the adjacent cable, so called coupling effect. Therefore, a signal restoration algorithm is essential for analyzing the relationship between the air gap and the propagation velocity. The measured reflected signal is distorted as follows:

$$\tilde{r}(t) = H_{cable} \otimes r(t) + n \tag{7}$$

where H_{cable} represents the transfer function of the cable attenuation characteristic, $\otimes$ is the convolution operator, and n is the white Gaussian noise. $\tilde{r}(t)$ is the signal to be measured. H_{cable} is a known transfer function, which can be derived by a

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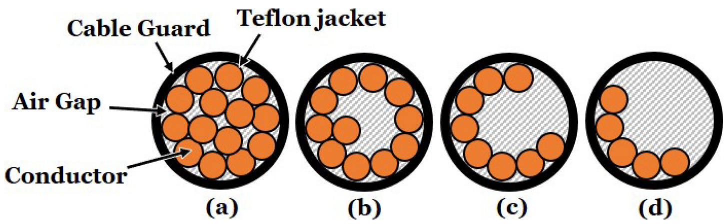

Fig. 2. Air gap experimental setup.

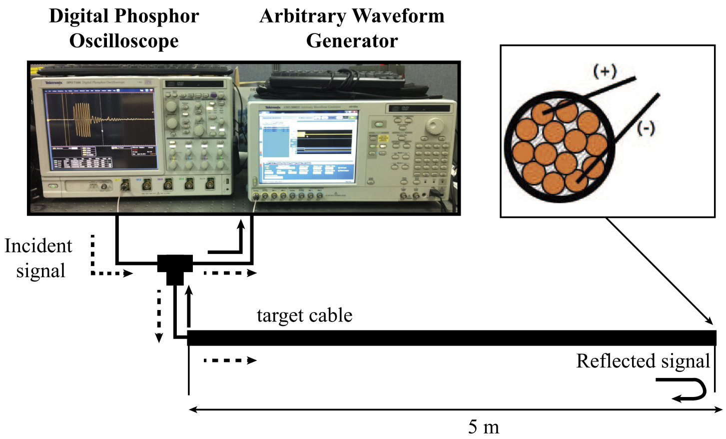

Fig. 3. Air gap measurement system diagram.

network analyzer. The variational approach to signal restoration uses an objective function, which consists of a data fidelity term and a regularization term. The restoring signal r_k is based on minimizing the objective function as follows:

$$J(\hat{r}(t)) = \|\tilde{r}(t) - \hat{r}(t)\|_2^2 + \lambda\|A\hat{r}(t)\|_1 \tag{8}$$

where $\hat{r}(t)$ is the estimated signal of $r(t)$, and the first term, $\|\tilde{r}(t) - \hat{r}(t)\|_2^2$, represents the measurement error between the measured signal and the estimated signal. The second term, $\|A\hat{r}(t)\|_1$, is called the regularization term or the penalty term, and is ℓ_1-norm. The parameter λ is the regularization constant, and we control the speed of regularization using this parameter. An algorithm for minimizing the analysis-prior objective function, (9), is given by the Chambolle algorithm [7].

$$\begin{aligned} b^{(i)} &= \hat{r}^{(i)} + \frac{1}{\alpha}(\tilde{r} - \hat{r}^{(i)}) \\ z^{(i+1)} &= (cz^{(i)} + A(b^{(i)} - A^t z^{(i)})) \Big/ \left(\frac{2\alpha}{\lambda}|A\hat{r}^{(i)}| + c\right) \\ \hat{r}^{(i+1)} &= b^{(i)} - A^t z^{(i+1)} \end{aligned} \tag{9}$$

where the superscript i is the iteration index. In this paper, the restoration signals are based on the bandpass coefficients from the target cable transfer function. For this reason, the regularization term and the optimal signal for minimizing the analysis-prior objective function can be solved through overcomplete wavelet transforms.

4 Experimental results

The experiments for verifying the performance of the proposed method is conducted. The poor contact situation means that the connection section between cable

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Table I. Estimation results of propagation velocity.

	5 cores	8 cores	11 cores	14 cores
propagation velocity	$2.4 \cdot 10^8$ m/s	$2.2 \cdot 10^8$ m/s	$1.9 \cdot 10^8$ m/s	$1.8 \cdot 10^8$ m/s

and connector can be intermittently separated by vibration. The fact that it can be separated by vibration indicates that the connection section is loose and that part contains a lot of air gap in cable. The experiments were designed to show the relationship between air gap and propagation velocity. The cable guide called corrugated tube and teflon wires which has teflon jacket were used to quantitatively control the amount of air gap. The cable guide was filled with the bunch of teflon wires, and the propagation velocity was measured every three strands removed in Fig. 2. The Fig. 3 shows the air gap measurement system diagram which consists of digital phosphor oscilloscope, arbitrary waveform generator, and signal processing unit. The propagation velocity was measured by the conventional TDR and TFDR, respectively, and the results of comparative analysis are shown in Fig. 4. The conventional TDR results according to number of teflon wire are illustrated in Fig. 4(a). As shown in Fig. 4(a), there is little change in the propagation velocity depending on the number of cores. The conventional TDR waveforms except 5 cores have no difference in propagation velocity when viewed from the part where the waveform is raised, around 50 ns, due to the reflected signal returned from the cable end. In TFDR case, we selected parameter of incident signal which is designed to fit for target cable length and the operational frequency range as follows: (center frequency: 54 MHz, bandwidth: 100 MHz, time duration: 30 ns). The distorted signal due to cable attenuation property and restored signal by modified overcomplete wavelet transforms based on the target cable transfer function are compared and analyzed in Fig. 4(b). The restored TFDR waveforms according to number of cores are shown in Fig. 4(c). Like the TDR waveforms, the waveforms in Fig. 4(c) cannot indicate the propagation velocity.

To derive the propagation velocity, we performed the cross correlation process with acquired the TFDR signals and the results of cross correlation are shown in Fig. 4(d). As shown in Fig. 4(d), the first peak indicates the starting point of cable, the second peak means the cable end, and the signal reflected two times appears as the third peak. There are multiple connectors in automotive electrons. The proposed method should be applied even in the presence of multiple connectors. The proposed method based on radar theory can detect multiple target and multiple reflection from same object. As shown in Fig. 4(d), the distance between first peak and second peak is same as the distance between second peak and third peak, in each correlation graph respectively. This means that the multiple reflection from same object can be detected and the multiple reflection can be distinguished from other reflection. The cross correlation graph was drawn assuming the propagation velocity is $1.8 * 10^8$ m based on the propagation velocity of 14 cores. The propagation velocities of target cable are derived from Fig. 4(d) as following Table I. The number of cores in cable guard indicates the volume of air gap in cable guard. Therefore, the propagation velocity according to the number of cores means the relationship between the air gap in cable and the propagation velocity. In

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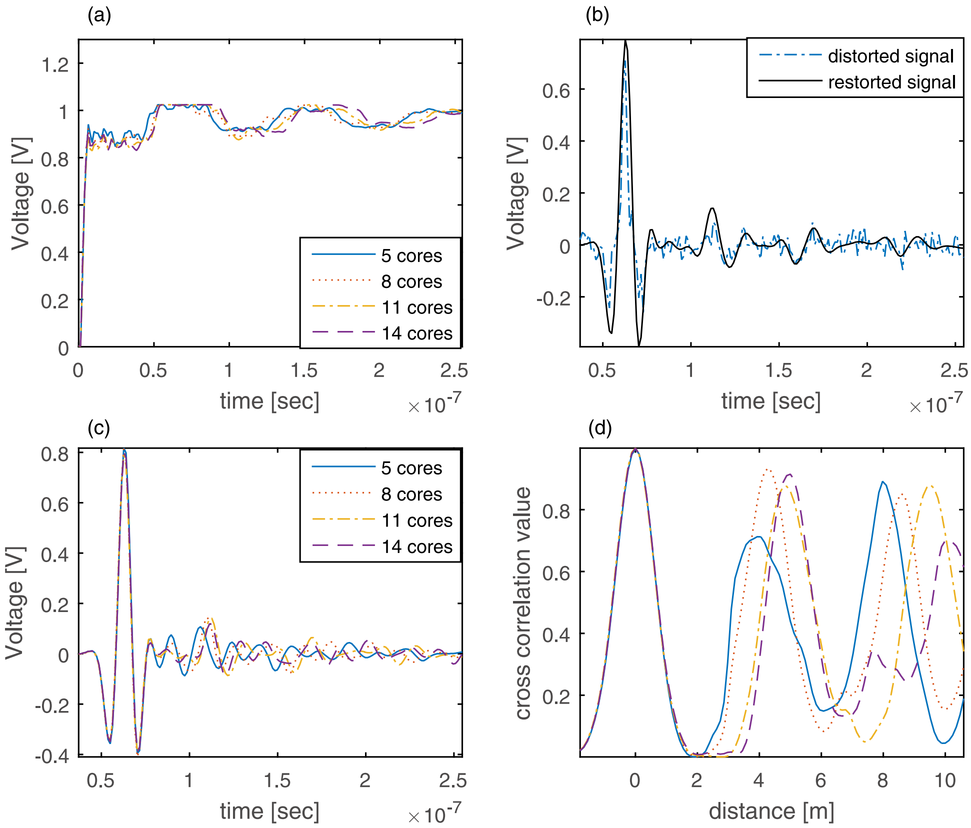

Fig. 4. (a) TDR results depending on the number of cores, (b) The distorted signal and the restored signal, (c) The restored TFDR waveforms depending of number of cores, (d) cross correlation results depending on number of cores.

future work, vibration is applied to derive a state in which contact failure occurs intermittently. And then, based on the derived relationship between the propagation velocity and air gap volume, the threshold of propagation velocity of poor contact between the cable and connector can be obtained. Using the derived threshold value, the proposed method can be applied to actual automotive electrons which has multiple connectors.

5 Conclusion

In this paper, we first proposed the TFDR method based on electromagnetic theory and modified overcomplete wavelet transform to measure air gap in cable. Using the relationship between the permittivity and propagation velocity, the new relationship between the air gap volume between the propagation velocity can be derived. To obtain the exact propagation velocity, we introduced the normalization cross-correlation method based on the Wigner-Ville energy distribution. The modified overcomplete wavelet transform was applied to restore the distorted signal due to cable attenuation property. Through the experiments, the performance of the proposed method is verified.

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