Effect of a Backplate Using in Electromagnetic Induction Method for Permittivity Measurement

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Abstract

This paper presents permittivity measurement method for non-electrical-conductive materials by using electromagnetic induction method. The electromagnetic non-destructive technique has been widely used to detect surface cracks of conductive materials. In recent years, it was found that the technique also can be used for permittivity measurements of non-conductive materials. However, the sensitivity of this new measurement method is low. In this study, in order to increase the sensitivity, the use of a conductive backplate which is set behind the specimen is proposed. Permittivity of non-conductive specimens are measured by electromagnetic induction method with and without using the backplate. The thickness and the conductivity of the backplates are also changed during the experiment. As a results, it was found that the backplate increase the sensitivity of permittivity measurement. It was also found that the thickness and conductivity of the backplate in our test range are not influence to the sensitivity of the measurement.

Keywords: Backplate, Conductivity, Non-conductive material, Permittivity and Thickness

1 Introduction

Glass fiber reinforced plastics (GFRPs) have been used in some structural materials such as tanks, bridges and turbine blades for windmills due to its high potential for weight saving, high strength, cheapness and corrosion resistance. Some damages occur in GFRP for these structures in the service and manufacturing process. In the service, strength degradation caused by the moisture absorption in the atmosphere occurs. Moisture absorption in GFRP causes characteristic degradation such as deterioration of the tensile and compressive strengths, affecting matrix and the interface between fiber and matrix [1]. Furthermore, in the manufacturing process, the quality of GFRP strongly depends on the molding methods. Especially for resin transfer molding (RTM), strength degradation caused by the voids called dry spots is easy to occur when this molding method is applied to large structures.

Some non-destructive testing (NDT) methods have been proposed as the alternative testing method of visual inspection (VI), which is applied as the periodic inspection, because VI strongly depends on the skills of inspectors than other NDT methods. Especially for ultrasonic testing (UT), this method has been proposed to detect strength degradation caused by the moisture absorption and dry spots. It is
reported that this method can detect the progress of the defects such as a delamination caused by the moisture absorption in GFRP [2, 3]. Furthermore, it is reported that this method also detects some dry spots by constructing the c-scan images in GFRP [4]. However, this method is the time consuming method because it needs to apply couplant to the surface of the specimen.

We propose a NDT method based on electromagnetic induction as the method to detect the permittivity. This method can detect defects and the change of the electrical properties by detecting the change of the electromagnetic field. Although this method has been used for conductive materials, Heuer and Gäbler reported that it was able to be applied to non-conductive materials [5, 6]. Mizukami proposed a new probe that was able to measure the permittivity change [7]. This method can detect defects and electrical property changes quickly at some points in a specimen due to its high degree of freedom for probe composition. Therefore, this method has a potential to overcome the disadvantages of VI and UT.

However, this method has disadvantages in that it is easy to be affected by some noise and an output is very small. We have reported that the obtained signals were unstable when this method was applied to the measurements of the moisture absorption rate in GFRP [8]. Therefore, the sensitivity of this method needs to be increased in order to stabilize the measurements. Gäbler reported that the sensitivity of this method was able to be increased with using the conductive materials (we refer this conductive material as a backplate) [9]. However, there are less cases reported in detail about the reason why the sensitivity increases by using a backplate including that previous research.

The purpose of this study is to improve the sensitivity of the proposal method by using the backplate and investigate the effect of the thickness and conductivity of it on this method. In this paper, we conducted the permittivity measurements with the backplate of the different thickness and conductivity.

### 2 Principle of the proposal method without a backplate

We adopted a non-destructive testing method based on electromagnetic induction as the method to detect the permittivity. Configuration of this method is shown in Fig.1.

![Fig.1 Configuration of the proposal method.](attachment:image.png)
The driver coil induces the displacement current into the material by applying ac voltage at high frequency and the pickup coil detects the change of the electromagnetic field of the displacement current.

Maxwell’s equation in the proposal method can be written as the following (1).

\[
\frac{\partial^2 A_\theta}{\partial r^2} + \frac{1}{r} \frac{\partial A_\theta}{\partial r} + \frac{\partial^2 A_\theta}{\partial z^2} = -\mu_0 i_0 + (j \omega \mu_0 \sigma_{xy} - \omega^2 \varepsilon_0 \varepsilon_{xy}) A_\theta
\]

Here, \( A_\theta \) is vector potential in \( \theta \) component, \( \mu_0 \) and \( \varepsilon_0 \) are magnetic permeability and the permittivity of a vacuum respectively, \( i \) is the imaginary unit, \( \sigma_{xy} \) and \( \varepsilon_{xy} \) are conductivity and relative permittivity in-plane direction, and \( \omega \) is frequency. In (1), the first term in the bracket is due to eddy current and second term in it is due to displacement current. We regard the first term as \( J_E \) and the second term as \( J_D \). In the proposal method, the effect of \( J_D \) is much larger than \( J_E \) by calculating them about non-conductive materials. Therefore, this method does not need to take the effect of \( J_E \) into consideration. Furthermore, the effect of \( J_D \) is larger by using high frequency because the frequency of \( J_D \) is contributing twice as much as that of \( J_E \). Therefore, we used high frequency in order to increase the effect of \( J_D \).

3 Fabrication of the probe for the proposal method

The configured probe was based on the tall transmitter and differential probe (TTDR probe). [7].

The configured probe is shown in Fig.2. This probe was composed of one driver coil and the two pickup coils. A copper wire of 1.0 mm in diameter was wound onto the driver coil and the number of turns of the coil is 21. Furthermore, a copper wire of 0.30 mm in diameter was wound onto the pickup coils and the number of turns of the coils was 20 respectively. The two pickup coils were hard-wired reversely. In comparison with diameter of copper wires, that of the driver coil is larger than that of the two pickup coils. This is because a coil becomes a capacitance in case of applying ac voltage at high frequency. If a coil becomes a capacitance, it does not work as an inductor. Hence, the driver coil was wound by the thick wire such that the number of turns per height was as small as possible.

![Fig.2 Configuration of the fabricated testing probe. (a) top view, (b) front view.](image-url)
Regarding the arrangement of the driver coil and the pickup coils, the driver coil and the pickup coils were set left and right and two pickup coils were set up and down. Mutual induction occurred because they were placed next to each other. However, the effect of mutual induction can be reduced because the pickup coils separately placed at upper and lower part of the cylinder, and wound reversely. Furthermore, the difference in the magnetic field from the displacement current was generated between the two pickup coils due to the difference in the lift-off. The difference was amplified by using differential and inverting amplifier circuits and we measured the signals from them.

4 Experiment

4.1 Permittivity measurement without the backplate

Firstly, we conducted the permittivity measurements without the backplate by using the fabricated probe. The specimens used in this experiment are shown in the Fig.3. The permittivity in these specimens was measured by the LCR meter (IM3536, HIOKI) and these values are shown in Table 1. The thickness of these specimens was 2 mm.

![Fig.3 Plastic specimens with the different permittivity.](image)

<table>
<thead>
<tr>
<th>Plastic</th>
<th>6 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTFE</td>
<td>1.66</td>
</tr>
<tr>
<td>HDPE</td>
<td>1.89</td>
</tr>
<tr>
<td>PC</td>
<td>2.34</td>
</tr>
<tr>
<td>PA66</td>
<td>2.74</td>
</tr>
<tr>
<td>PAI</td>
<td>2.80</td>
</tr>
<tr>
<td>GFRP</td>
<td>3.87</td>
</tr>
</tbody>
</table>

The experimental setup for detecting the permittivity is shown in Fig.4. Sinusoidal voltage was supplied from a function generator (NI PXI-5421, National Instruments) to the driver coil, and amplified differential pickup coil output was measured by an oscilloscope (PicoScope 5244A, Pico Technology). The amplitude of the drive voltage was 1 V, the frequency was 7 MHz and lift-off was 0 mm. Then, the obtained signals were organized by using the software (Labview 2014, National Instruments).

Experimental results are shown in Fig.5. In this figure, the vertical axis shows the output calculated by dividing output voltage $V_{out}$ by input voltage $V_{in}$ and the horizontal axis shows the relative permittivity in the plastic specimens. According to Fig.5, there is a linear relation between the output and permittivity. Therefore, the permittivity can be estimated by using this proposal method.
4.2 Permittivity measurement with the backplate on the opposite side as the probe

Secondly, we conducted the permittivity measurements with the backplate. The backplates with different conductivity used in this experiment are shown in Fig. 6. The conductivity in these backplates is shown in Table 2. We also prepared different thickness specimens with 1, 2 and 3 mm in order to investigate the effect of the thickness on the proposal method. The experimental setup is shown Fig. 7.

<table>
<thead>
<tr>
<th>Backplate</th>
<th>Conductivity [S/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS304</td>
<td>$1.39 \times 10^6$</td>
</tr>
<tr>
<td>C1100P</td>
<td>$6.97 \times 10^7$</td>
</tr>
<tr>
<td>C5191P</td>
<td>$4.47 \times 10^8$</td>
</tr>
</tbody>
</table>
Experimental results are shown in Figs. 8-10. In these figures, the vertical axis and horizontal axis are the same parameters as Fig. 5. Furthermore, we did not conduct the measurement for air in this case because it was expected that the effect of the backplates was much larger than that of air. According to Figs. 8-10, these figures also indicate that there are linear relations between the output and permittivity. Then, the output of PA66 is different from the others. This is because the only specimen of PA66 has the curvature slightly. When a specimen have the curvature, the gap between the specimen and backplate occurs and the output decreases caused by it.

Although the output is almost similar value in case of using the different thickness of the backplates in Figs. 8, 9, the output using the 1mm backplate is much smaller than that of 2 and 3 mm in Fig. 10. This tendency in Fig. 10 was seen even in the experiment after 1 week. We expect that the molding method of this specimen influenced on the measurements. Therefore, we conclude that the thickness of the backplates does not influence on the proposal method excluding C5191P with the thickness of 1 mm.

According to Figs. 8-10, the output is almost similar value although the conductivity of C5191P is approximately 100 times larger than that of SUS304. Therefore, the conductivity of the backplates in the range of using this experiment does not influence on the proposal method. However, the effect of the backplates need to be investigated by using numerical analysis because there is a possibility that the slight output difference between different backplates is generated from the conductivity difference.

According to Fig. 5 and Figs. 8-10, the output change is approximately 0.8 between PTFE and GFRP in Figs. 8-10 while it is approximately 0.4 in Fig. 5. Although the reason why the output increases need to be investigated in detail, we expect that the concentration of the magnetic flux into the plastic specimens is much larger by using the backplate. Therefore, the sensitivity of the permittivity measurements can be improved by using the backplate in case of defining it as the permittivity change.

![Fig.8 Experimental results using SUS304 as the backplate.](image1)
![Fig.9 Experimental results using C1100P as the backplate.](image2)
![Fig.10 Experimental results using C5191P as the backplate.](image3)
4.3 Permittivity measurement with the backplate on the same side as the probe

Finally, we conducted the permittivity measurements with the backplate placed opposite side in comparison with Fig.7. The experimental setup is shown in Fig.11. In this experiment, SUS304 with the thickness of 5 mm was used.

Experimental results are shown in Fig.12. In this figure, the vertical axis and horizontal axis show the same parameters as Fig.5. According to Fig.12, the output is almost constant although the permittivity increases. This is because the effect of eddy current is much larger than that of the displacement current. Furthermore, the depth of penetration $\delta$ is written in the following (2) and that of SUS304 is much smaller than the thickness of SUS304.

$$\delta = \frac{1}{\sqrt{\mu_0 \sigma}} \approx 0.161 \, [\text{mm}]$$

Hence, the conductivity of SUS304 was measured in this experiment. Therefore, it is difficult to detect the permittivity when the backplate is closer to the probe than the specimen because the effect of the eddy current of the backplate is much larger.

Fig.11 Experimental setup for measuring the permittivity with the backplate on the same side as the probe.

Fig.12 Experimental results in Fig.11.

5 Conclusion

In this paper, we proposed to use the backplate in order to improve the sensitivity of the NDT method based on electromagnetic induction.

Firstly, we conducted this method without the backplate. The results of this measurement indicated that permittivity was able to be estimated by using this method.
Secondly, we conducted this method with the backplate on the opposite side as the probe. The results indicated that the thickness of the backplates did not influence on this method. The results also indicated that the conductivity of the backplates in the range of using this experiment did not influence on this method. Furthermore, the results indicated that the output change with backplates was two times larger than that without backplates. Therefore, the sensitivity of this method was able to increase by using the backplate.

Finally, we conducted this method with the backplate on the same side as the probe. The results indicated that the output was constant caused by the large effect of the backplate. Therefore, it was difficult to detect the permittivity when the backplate was closer to the probe than the specimen because the effect of the eddy current of the backplate was much larger.

In future work, it is necessary to investigate the effect of the backplates by using numerical analysis. Although, we only investigated the effect of the thickness and conductivity on the proposal method, we also need to do that of the permeability. Furthermore, it is necessary to investigate that the effect of the much higher and lower conductivity on the proposal method because we did in the limited range in this experiment. It is expected that these investigations are suitable for using numerical analysis.

References


