Thickness Detection of Corroded Steel Plate by Low-Frequency Eddy Current Testing

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Abstract. To maintain the safety of infrastructure, it is important to detect not only cracks but also corrosion due to aging. Ultrasonic testing is thus widely used to detect reduced material thicknesses from corrosion; eddy current testing, however, is not presently utilized for such investigations. A rapid testing method is nonetheless needed because of pretreatment protocols (such as the peeling of coatings) associated with ultrasonic inspection. In this study, we attempted to measure magnetic signals of the back sides of thick steel plates by applying low-frequency magnetic field measurements via large skin depths and a magnetoresistive (MR) sensor with a wide-range uniform frequency response, as opposed to simply utilizing a pickup coil.

The developed measurement system consisted of an excitation coil, a compensation coil, an MR sensor, a lock-in amplifier, a function generator, an amplifier, and an A/D converter. The compensation coil was mounted in a sensor position to cancel any direct excitation magnetic field and thereby improve the signal to noise ratio. The lock-in amplifier detects a frequency component signal to the same extent as an applied magnetic field. The magnetic field vector was obtained by the in-phase and quadrature components of the detected signal. The sensor was arranged in the normal (z-) axis direction to obtain magnetic field from samples. The magnetic response characteristics using the magnetic field vector (with a range of low frequencies from 1 Hz to 1 kHz of different thickness samples) were measured. Consequently, the magnetic response characteristics showed a general dependency with thickness. Next, 12-mm-thick steel plate test samples that exhibited partial corrosion of different depths on their back sides were measured and subsequently imaged by two-dimensional scanning. As a result, the back side corrosion levels were visually characterized, with associated thickness-dependence images ultimately obtained.

The results showed that the developed system is useful and convenient as a nondestructive testing technique for detecting the corrosion of ferromagnetic material objects.

Introduction

Recently, considerable corrosion has accumulated in key infrastructural articles such as plants, cranes, and bridges. Such corrosion is caused by the permeation of rainwater due to material deterioration over time. It is altogether difficult to visually distinguish back side corrosion; for such cases, the detection of associated thickness reduction is required since the majority of a corroded area is generally widespread (and the thicknesses of steel plates used in large structures generally have a thickness of >10 mm). Therefore, there is an ongoing possibility that a decreased loading capacity (via such corrosion) may ultimately result in a serious failure accident such as the collapse of a building or other major structures. The use
of conventional eddy current testing (ECT) is challenging for adequately detecting internal corrosion of structures; hence, thickness inspections by ultrasonic methods have alternatively been performed conventionally for the evaluation of such internal corrosions [1], [2]. To improve the limitation of depth information for conventional ECT, this study provides an ECT method that employs a magnetoresistive (MR) sensor that can be widely utilized in the range from DC to high frequency. In addition, the study discusses an analytical method that evaluates magnetic spectra via the use of a magnetic vector [3]-[5]. Through low-frequency operation and deeper skin depths, an efficient level of corrosion mapping was hence obtained. The study furthermore evaluated an additional measurement method employing low-frequency magnetic flux leakage for detecting deep defects [6], [7]. In summary, imaging of back side corrosion was comprehensively investigated using such proposed measuring systems and magnetic spectrum analytical techniques.

**Experiment setup**

Figure 1 shows the developed ECT system. The system consists of an induction coil, a compensation coil, an anisotropic magnetoresistive (AMR) sensor, a lock-in amplifier, a function generator, an amplifier, and an A/D converter. The compensation coil was mounted on the sensor position to improve the S/N ratio so that the AMR sensor did not directly detect the applied magnetic field. The induction coil of 50 turns and the compensation coil of 10 turns were connected in series. A sine wave voltage was generated by the function generator and converted to induction current by the current source. The induced current was then applied to the induction coil. Consequently, the induction coil was driven by a sine wave of 0.5 A. The variation of the secondary magnetic field, which was determined by the thickness of a ferromagnetic plate, was converted to a voltage signal by the MR sensor. The MR sensor was maintained at a distance of 1 mm from the sample’s surface. As implied above, the lock-in amplifier detected a signal of comparable frequency to that of the applied magnetic field. In such a case, a change of magnetic field vector was measured by the in-phase and quadrature components of the detected signal. The sensor was arranged so that the sensitive axis was parallel to the z-axis direction to obtain the resulting magnetic fields of the samples. The subject magnetic fields generated from the samples (with differing corrosion thicknesses) were measured in the frequency range of 1 Hz to 1 kHz.

![Figure 1. Schematic of the developed ECT system.](image-url)
The measurement objects are SS400 steel plates of 12 mm thickness having different depths of backside corrosion created by acid etching and electric field erosion. The plates displayed galvanic corrosion at their backside center locations. Figure 2 displays the state of corrosion, and Table 1 provides the details of the corrosion sizes for each sample. The associated magnetic fields were measured in the range of 100 mm × 100 mm around the center of the corrosion.

![Fig. 2. Measurement object with corrosion.](image)

**Table 1.** Conditions of the measurement objects with corrosion.

<table>
<thead>
<tr>
<th>Corrosion rates</th>
<th>10 %</th>
<th>20 %</th>
<th>40 %</th>
<th>50 %</th>
<th>60 %</th>
<th>80 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A : Corrosion depth (mm)</td>
<td>1.2</td>
<td>2.4</td>
<td>4.8</td>
<td>6.0</td>
<td>7.2</td>
<td>9.6</td>
</tr>
<tr>
<td>B : Depth from surface (mm)</td>
<td>10.8</td>
<td>9.6</td>
<td>7.2</td>
<td>6.0</td>
<td>4.8</td>
<td>2.4</td>
</tr>
<tr>
<td>C : corrosion width (mm)</td>
<td>59.0</td>
<td>62.0</td>
<td>60.1</td>
<td>62.1</td>
<td>63.9</td>
<td>74.0</td>
</tr>
</tbody>
</table>

**Experimental Results**

1.1 Relationship between the magnetic field vector spectrum and the thickness of corroded steel plate

Figure 3 shows the magnetic spectrum that traces the change in the magnetic field vector at several measured frequencies (between 1 Hz and 1 kHz) at the center of the backside corrosion area. Each magnetic field vector in Fig. 3 is the differential vector between the signals with and without samples, at each frequency. By increasing the frequency of the magnetic field from 1 Hz to 1 kHz, the magnetic field vector shifts in a clockwise direction on the elliptical curve due to impedance change, as shown in Fig. 3 (a) [5]. Figure 3 (b) is the enlarged figure of the low-frequency range from 1 to 20 Hz shown in Fig. 3 (a). The correlation between the magnetic field vector and corrosion rate was found to be low in the high-frequency segment since the “skin-effect” causes the eddy current to flow only on the surface of the steel plate. However, in contrast, a high correlation between the magnetic field vector and the corrosion thickness was observed in this low frequency range. Therefore, a difference of corroded thickness from 10% to 80% could be evaluated by the low-frequency magnetic field vector. It was moreover possible to determine the difference in thickness of the corresponding 1.2 mm as 10% of the variation given that the noncorroded part of the plate thickness was 12 mm.
1.2 Magnetic image of corrosion

A good correlation between the corrosion thickness and magnetic field vector spectrum in the low frequency range was confirmed. As such, magnetic images were ultimately measured using steel plates that exhibited different corrosion rates. To optimize measurement conditions, a 20%-corroded steel plate was evaluated, with a suitable frequency for corrosion detection ultimately employed. The excitation coils were operated by a 0.5 A sine wave using current sources with frequencies of 1 and 20 Hz. The resulting magnetic images were obtained within the range of 100 mm × 100 mm around the corrosion. Figure 4 shows the intensity map of the subject steel plate with 20% corrosion measured at excitation frequencies of both 1 and 20 Hz. Both images, resultantly, did not exhibit correlations of defect size. This indicated that the magnetic field intensity was likely affected by the variations in permeability on the plate’s surface. Figure 5 shows the phase map of the subject plate, measured at frequencies of 1 and 20 Hz. The 1 Hz map shows the presence of the backside corrosion more clearly than that measured at 20 Hz. This implies that the magnetic field more deeply penetrated inside the samples as a function of decreasing frequency, which ultimately led to the reduction of skin-effect. Nevertheless, the corrosion shape remained relatively nebulous in the 1 Hz phase image.

![Fig. 3. Relationship of the magnetic field vector spectrum and the corrosion rates. Frequency ranges are from (a) 1 Hz to 1 kHz and (b) 1 to 20 Hz.](image)

**Fig. 4.** Intensity map of the steel plate with 20% corrosion. (a) 1 Hz and (b) 20 Hz
Fig. 5. Phase map of the steel plate with 20% corrosion. (a) 1 Hz and (b) 20 Hz

1.3 Evaluation of thickness in corroded steel plate

The unclear magnetic images obtained at a single frequency are thought to be due to the influence of magnetization at the plate surface. As such, a magnetic image was strategically created by calculating the difference of the magnetic vector between 1 and 20 Hz. Accordingly, the magnetic signals for the corrosion rates of 10%, 20%, 40%, 50%, 60%, and 80% were measured, with the magnetic vector of 1 Hz ultimately subtracted from that of 20 Hz. Figure 6 shows the intensity maps of the differential magnetic vectors. The maps essentially depicted the existence of corrosion when the corrosion rate was greater than 50%. Meanwhile, the phase map of the differential vector showed depth improvement, with clear corrosion shapes being discernible at even a 20% corrosion level. A corrosion rate of 20% corresponds to a depth that is 9.6 mm from the front surface of the steel plate.

Fig. 6. Intensity maps using the differential vector of different corrosion rates: (a) 80%, (b) 60%, (c) 50%, (d) 40%, (e) 20%, and (f) 10%.
Next, we endeavored to quantitatively evaluate the change-relationship of the differential magnetic field vectors versus corrosion rates. Figure 8 portrays the changes in magnetic field intensity at the centerline of the Y-axis. The Y-axis centerline is the 50 mm location of the axis, which corresponds to the middle of the corrosion segment that exists from 30 to 70 mm. The changes of signal intensity and phase for the corrosion rates of 10%, 20%, 40%, 50%, 60%, and 80% are shown in Fig. 8. Figure 8 (a) shows the signal change of the different corrosion levels, with large changes being observed for cases greater than 50%. No correlation was found to exist between signal intensity and corrosion depth due to baseline fluctuations. Figure 8 (b), however, shows a strong correlation between corrosion rate and phase, with phase-change ultimately increasing as a function of corrosion depth. As such, corrosion rates of greater than 20% can be satisfactorily detected using the developed subject system.

![Fig. 7. Phase maps using the differential vector of different corrosion rates: (a) 80%, (b) 60%, (c) 50%, (d) 40%, (e) 20%, and (f) 10%.](image)

![Fig. 8. Variation of differential vectors between 1 and 20 Hz at the centerline of steel plate: (a) signal intensity and (b) phase.](image)
Figure 9 shows the correlational relationship between corrosion rates and phase. Phase was obtained by the differential vector at the center of corrosion. Corrosion rates from 10% to 80% demonstrated well-defined changes in phase, with phase notably increasing as a function of incremental change (i.e., increase) in corrosion depth. This result indicates that the size and depth of a back side defect can be estimated using the magnetic image of phase.

Conclusion

Back side corrosion of a steel plate was successfully imaged by a two-dimensional scanning technique using a newly developed ECT system that employs a magnetic sensor. By calculating the difference of magnetic vectors at two low frequencies, it was possible to measure corroded ferromagnetic steel plates without the unwanted influence of magnetic permeability fluctuations. The study’s developed system was ultimately able to consistently and effectively visualize the back side corroded areas of evaluated steel plates and, moreover, displayed a general corrosion detection limit of greater than 20%.

References

