Magnetic measurement of corrosion in a steel structure using extremely low-frequency eddy current testing without surface treatment

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ABSTRACT: We previously reported an extremely low-frequency eddy current testing (ELECT) method to detect the thickness of steel. In this study, our developed ELECT device was applied to an actually corroded steel structure and the influence of rust was investigated. In particular, we evaluated the influence of lift-off variations caused by the severe corrosion of a thick and laminated structure. Using a magnetic spectrum analysis and multiple frequencies in the range of 1 Hz–1 kHz, the thickness of steel was measured through rust and paint without surface treatment. Signal fluctuation caused by lift-off variations was also corrected using the magnetic spectrum analysis. Therefore, we obtained the same estimated thickness from the front as well as back sides.

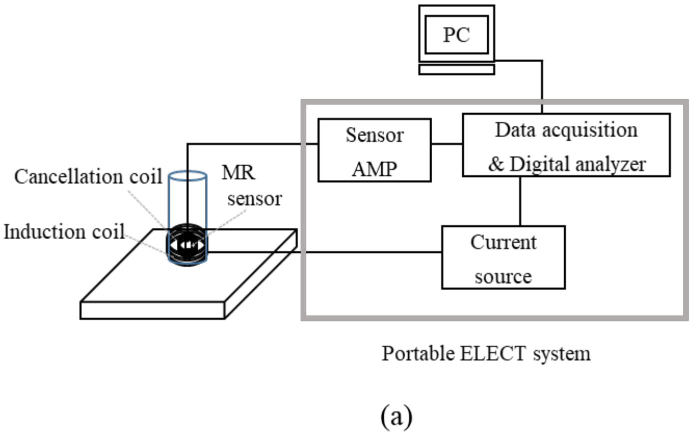
1 INTRODUCTION

There are several concerns regarding the long-term safety and maintenance of civil engineering structures that have aged and deteriorated. Many of these structures are made of steel and are prone to corrosion, which causes the thinning of these structures, which in turn reduces their durability. A special problem is that corrosion occurs not only on the surface but also inside the structure. Consequently, ultrasonic testing is commonly used to detect the thickness of the corroded steel. Therefore, surface treatment removing rust or paint is necessary to obtain good acoustic impedance for ultrasonic testing. However, surface treatment requires a long time, which makes inspecting a wide area of the structure difficult. As corrosion becomes severe, an extra amount of scraping is needed, excessively reducing the thickness of the non-corroded interior part of the steel. Recently, pulsed eddy current testing (ECT) has started to be used as a method to measure thickness. It is based on the time domain measurement that measures time attenuation of the detected magnetic signal after applying the pulsed excitation magnetic field to a sample. We previously reported an ECT method, that can detect low-frequency signals, using a magnetic sensor instead of a detection coil, and it can characterize magnetization and eddy current distribution of the metal by using magnetic spectrum to measure a wide range of frequencies (Tsukada et al, 2006). Based on the ECT method using the magnetic sensor, another type of pulsed ECT using a magnetic sensor based on frequency domain analysis using Fourier analysis was reported (Kiwa et al. 2009). The rectangle pulsed excitation magnetic field contains rich frequency information compared with a single sinusoidal excitation magnetic field. To detect thick steel plates in the infrastructures, only a low-frequency range is needed to get a deep enough penetration depth of the excitation magnetic field. Therefore, we recently reported an extremely low-frequency ECT (ELECT) method using multiple frequencies lower than 1 kHz to detect the thickness of thick steel (Tsukada, et al. 2016). Furthermore, magnetic intensity fluctuation due to the localized magnetization differences that occur when measuring ferromagnetic materials, i.e., magnetic noise, was solved by the developed spectroscopy analysis of the magnetic field (SAM). In this study, we developed a portable ELECT device using SAM designed for field testing. Using the ELECT device, we evaluated the influence of rust and paint on steel thickness measurements. In particular, we evaluated the influence of magnetic characteristics of the rust and lift-off variations caused by the severe corrosion of a thick and laminated structure.

2 EXTREMELY LOW-FREQUENCY ECT METHOD

2.1 ELECT device

The ELECT system for detecting steel thickness consists of a magnetic probe, sensor amplifier, a current source operable with multi-frequency for excitation of the coil of the sensor probe, data acquisition and digital analyzer for obtaining the magnetic vector with intensity and phase of the detected magnetic signal, as well as a personal computer (Fig. 1(a)). The sensor probe consists of an anisotropic magnetic resistance (AMR) sensor to detect the normal magnetic component, a small cancellation coil to reduce the excitation magnetic field directly coupled to the AMR sensor. The induction coil is circular-shaped, with an inner diameter of 26 mm with 50 turns. The excitation coil was driven with an AC constant current of 0.15 A. The portable ELECT device was packed in a shoulder case. The sensor probe has a water-protective structure enabling its use in water (Fig. 1(b)).



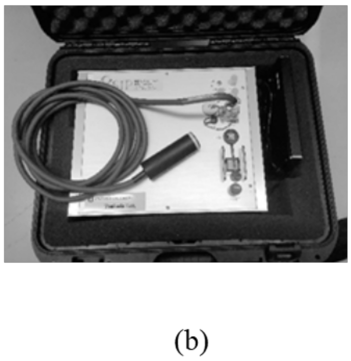


Figure 1. ELECT system; (a) schematic diagram, (b) photograph of the portable ELECT system.

2.2 Spectroscopy analysis of the magnetic field

To estimate the steel thickness, the previously reported SAM technique was used. The magnetic spectrum that traces the change in the magnetic field vector has intensity and phase at multiple frequencies. The raw data of the magnetic spectrum contained the eddy current component, magnetization component, and residual magnetic field of the excitation magnetic field. The magnetic vector obtained at the lowest frequency, e.g., at 1 Hz, has almost no eddy current component but only residual and magnetization components. Therefore, the magnetic spectrum consisting of only the eddy current component is obtained by shifting the raw magnetic spectrum to the origin of the spectrum graph, thus, erasing the residual and magnetization components (Fig. 2). The SM steel plates with different thicknesses were measured, and then the magnetic spectrum shows apparent thickness dependence. Furthermore, the phase parameter of the differential magnetic vector at two different optimally selected frequencies was used to estimate the thickness from the magnetic spectrum. Here, thickness dependence of the phase parameter using the differential magnetic vector subtracted a 3-Hz magnetic vector from the 20-Hz magnetic vector, as shown in Fig. 3. By using the differential vector, the thickness estimation process became very simple, and the measuring time was reduced.

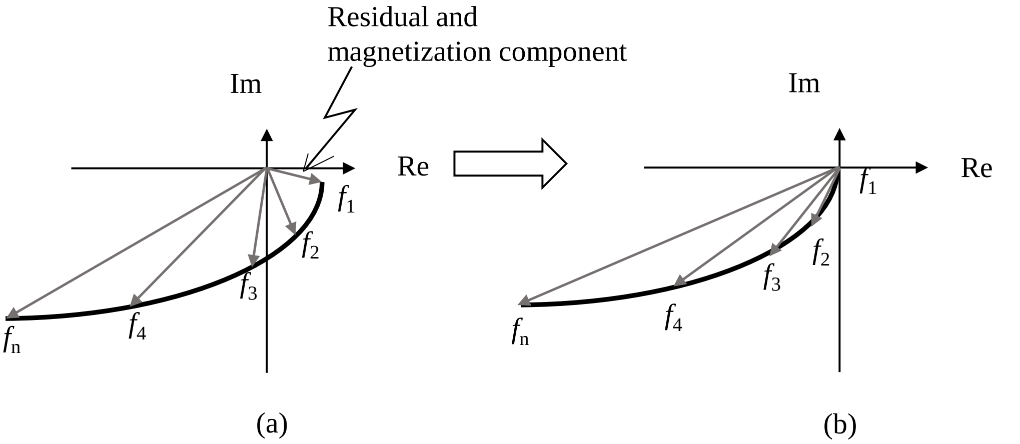


Figure 2. Magnetic spectrum; (a) raw magnetic spectrum, (b) origin corrected magnetic spectrum.

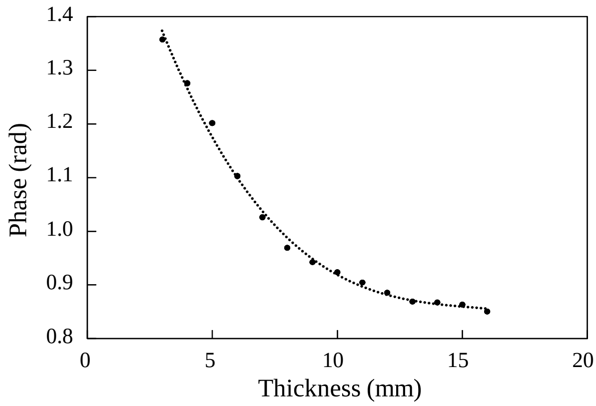


Figure 3. The thickness dependence of the phase change of the differential magnetic vectors.

3 EXPERIMENTAL PROGRAM

3.1 Influence of lift-off

In the case of severely corroded steel, rust thickness is not ignored because the magnetic field strength depends on the distance between the magnetic sensor and sample. Therefore, influence of the lift-off has to be investigated for application to practical field testing. Figure 4 shows the lift-off dependence of the magnetic vectors of the 6 mm thick steel plate when lift-off was changed from 0 to 5 mm. The magnetic field intensity gradually decreased according to the increment of lift-off. However, the phase θ of the differential subtracting the 20-Hz magnetic vector from the 3-Hz magnetic vector did not change at all. Therefore, the phase parameter of the differential magnetic vector was not affected by the lift-off in the thickness detection.

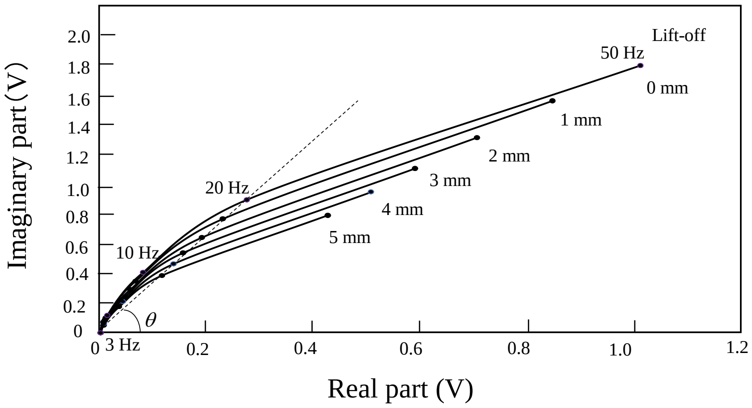


Figure 4. Lift-off dependence of the magnetic spectrum

3.2 Influence of electromagnetic characteristic difference

A steel structure gradually corrodes in the presence of water or air moisture, and the surface is oxidized to form iron oxides such as Fe_2O_3. The surface oxidized layer of the steel is thought to have low conductivity because the material structure is expanded, porous, or laminated. However, magnetization of the oxidized layer is thought to affect electromagnetic measurements. Therefore, influence of the magnetization characteristic of the oxidized steel was investigated. Figure 5 shows the magnetization (M-H) curve of rust measured by vibrating the sample magnetometer. The sample sizes were obtained by cutting to 4 mm × 4.5 mm × 1 mm. It shows ferromagnetic characteristics having hysteretic behavior. Therefore, the magnetic spectrum will be changed by the oxidation layer. To check the influence of the oxidized layer on the magnetic spectrum of the bulk steel plate and the rust put on the bulk steel plate were compared (Fig 6). When the bulk steel plate was measured, the lift-off was set at 1 mm. When the rust put on the bulk was measured, the lift-off was set to keep the same lift-off as that of the bulk steel. Before reduction of the magnetization component from the magnetic spectrum, the spectrum of the steel with the rust showed a differently shifted origin due to the rust magnetization component (Fig. 6(a)). However, both magnetic spectrums became identical after the origin of the magnetic spectrums was set to zero. This means that conductivity of the rust could be ignored in the SAM because of the low conductivity.

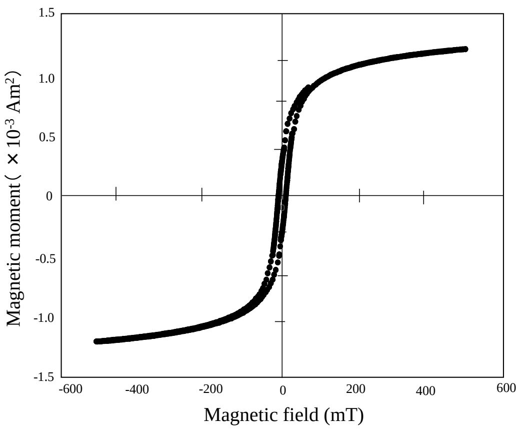


Figure 5. Magnetization (M-H) curve of the rust.

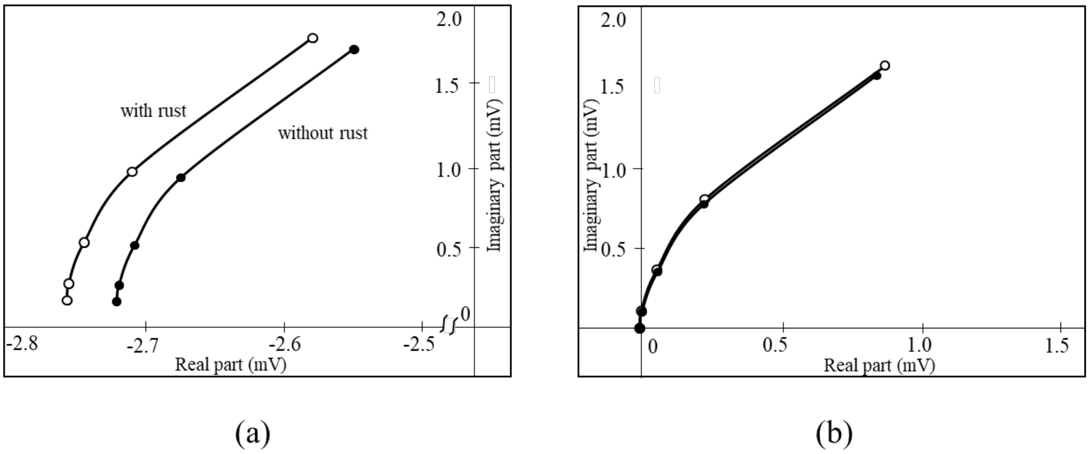


Figure 6. Comparison of the magnetic spectrum of the steel with rust and without rust; (a) raw magnetic spectrums, (b) after origin correction

3.3 Influence of surface roughness

Surfaces of severely corroded steel structures are often not flat but uneven. Therefore, it is necessary to know what the measured value indicates when ELECT is applied. The thickness calibration curve was measured using a steel plate having a stepwise thickness change. Thickness estimation was done by scanning across the step from the front and back sides of the steel plate. Both results from front and back continuously showed same estimated thickness changes. The middle value of the thickness at the step of changing thickness was obtained. These curves were also same to the averaged thickness by the magnetic sensor probe area. This means that the ELECT probe measures averaged thickness of the sensor probe area of 28 mmϕ, i.e., the footprint of the sensor probe.

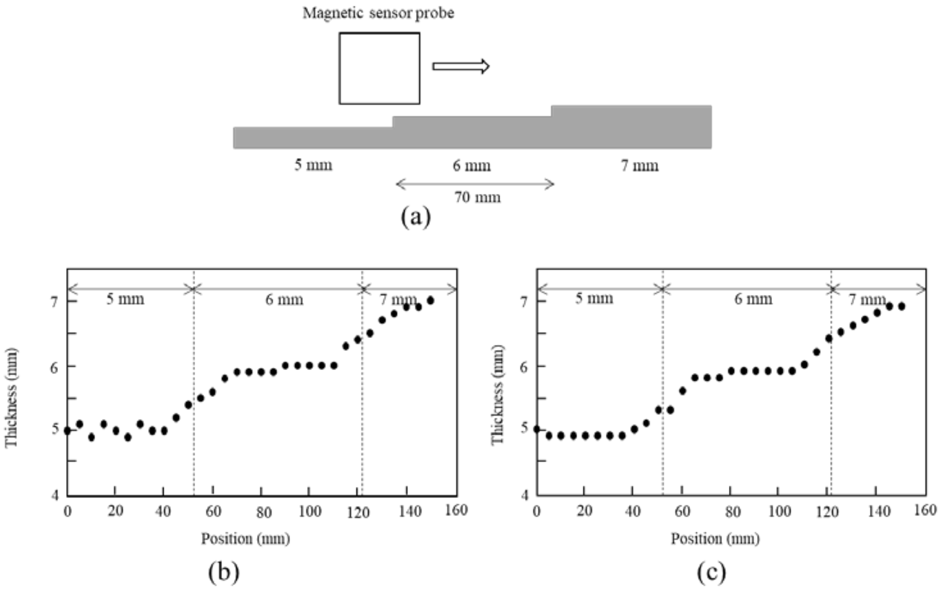


Figure 7. Scanning thickness measurement using the step-like steel plate; (a) schematic diagram of the test sample, (b) estimated thickness from the front side, (c) estimated thickness from the back side.

4 THICKNESS MEASUREMENTS OF A CORRODED STEEL STRUCTURE

4.1 Front and back side measurement of a corroded steel plate

The thickness of practically used and corroded steel was measured and compared with other thickness measurements using an ultrasonic thickness gauge and micro gauge. The front and the back surfaces were corroded, and the front side was severely corroded (Fig. 8(a), (b)). The thicknesses at two points were measured from the front and back surface. As shown in Fig. 8(c), the front surface at point No. 1 was covered with thick rust. Before cleaning the surface, thicknesses of point No. 1 and No. 2 measured by the micro gauge were 6.2 and 5.8 mm, respectively (Table 1). ELECT was also applied directly on the corroded surface. The measured thicknesses were 5.6 and 5.7 mm. After the rust was removed by Keren using an electric brush, both thicknesses measured by the micro gauge were 5.6 mm. These values were coincident to the ELECT data. After cleaning the surface, the ultrasonic testing could be applied except for the font surface of point No. 1. The measured thicknesses of points No. 1 and No. 2 obtained by ultrasonic testing were 5.7 and 5.8 mm. As a result, the measured values by ELECT without surface treatment were coincident to the values measured by ultrasonic testing and micro gauge after Keren.

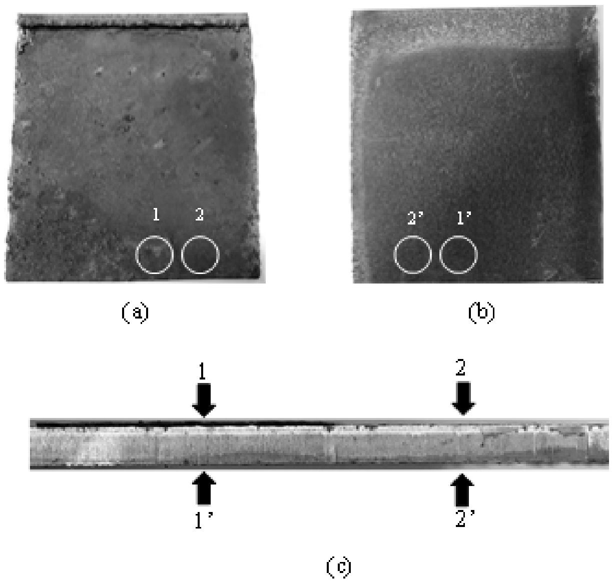


Figure 8. The corroded steel plate; (a) front surface, (b) back surface, (c) cross section.

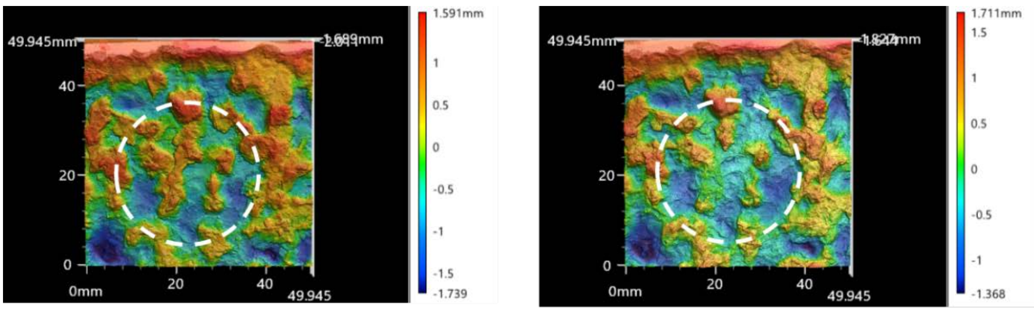
Table 1. Comparison of the estimated thickness

		Estimated thickness (mm)			
Measurement point		1	1’	2	2’
ELECT		5.6	5.6	5.7	5.7
Ultrasonic testing after Keren		Not applicable	5.7	5.8	5.8
Micrometer gauge	(before Keren)	6.2		5.8	
	(after Keren)	5.6		5.6	

4.2 Severely corroded steel plate

The first example of the corroded steel plate was not so sever corrosion, so that the rust has a layer-like structure. The next sample has severe corrosion so that the surface is uneven and corrosion is advanced. This plate was a part of the dam that was made to prevent landslide disasters (Fig. 9). The back side of the sampled plate was not so corroded and kept a flat surface. To obtain accurate surface undulations, 3D shape of the steel was measured (Fig. 10). First, the thickness of the corroded steel was measured from the rust, and the averaged thickness was 5.04 mm and roughness was ± 1.67 mm by 3D measurements. The thickness measured by the ELECT was 4.8 mm. After Keren was applied using an electric brush, 3D measurement was applied again. The average thickness was 4.98 mm, and the roughness was ± 1.54 mm by 3D measurement, and 4.8 mm using ELECT. Even though the rust was removed by Keren, ultrasonic testing measurements could not be applied. The average value obtained by the 3D shape measurement after Keren was close to the result of ELECT. ELECT showed an average value of the footprint and could be applied to very uneven surfaces to which ultrasonic testing could not applied.

Figure 9. Photograph of the corroded steel dam.



(a) (b)

Figure 10. 3D surface images of the corroded steel; (a) before Keren, (b) after Keren

(dotted circles show footprint of ELECT)

5 CONCLUSIONS

ELECT is applicable for thickness measurement of corroded steel structures without surface treatment. The measured values by ELECT were consistent with the value obtained by ultrasonic testing and a micro gauge. The measured values were equal to the average thickness of the footprint of the magnetic sensor probe. The ELECT method can be used as a rapid inspection method for detection of residual thickness even for severely corroded steel structures.

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