1. Mohd Mawardi SAARI[1,2], 2. Mohd Aufa Hadi Putera ZAINI[1], 3. Ummi Sabihah MOHD YUSDI[1], 4. Nurul Ain NADZRI[1], 5. Mohd Herwan SULAIMAN[1], 6. Toshihiko KIWA[3]

Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang (1), Centre for Advanced Industrial Technology, Universiti Malaysia Pahang (2), Graduate School of Interdisciplinary Science and Engineering in Health Systems, Okayama University (3)
ORCID: 1. 0000-0002-3049-5548; 2. 0000-0001-6497-2739; 4. 0000-0003-3317-0236; 5. 0000-0003-2590-3807; 6. 0000-0002-6594-2096

doi:10.15199/48.2023.12.37

# Assessment Of Surface Corrosion On Carbon Steel Plates Using A Differential Fluxgate Probe

***Abstract**. In this work, magnetic responses from artificial corrosion defects were investigated using a differential fluxgate probe. Different rates of corrosion defects were prepared based on the electrolytic corrosion process on the surface of a carbon steel plate by manipulating the corrosion period. Then, the differential fluxgate probe, consisting of two miniature fluxgates arranged in a planar configuration and a circular excitation coil, was used to measure the real and imaginary components of magnetic responses from the corrosion defects in the range of 5 to 510 Hz. The real differential magnetic response from the probe showed that the magnetic signal change was proportionally increased with the corrosion period, revealing the increased depth of the corroded region with the electrolytic corrosion period. The magnetic response induced by an excitation field from 10 to 110 Hz could be utilized to enable a sensitive depth estimation of a corrosion defect on high-permeability steel at a sub-millimeter resolution.*

***Streszczenie.** W tej pracy zbadano reakcje magnetyczne wywołane sztucznymi defektami korozyjnymi za pomocą różnicowej sondy fluxgate. W oparciu o proces korozji elektrolitycznej na powierzchni płyty ze stali węglowej przygotowano różne stopnie defektów korozyjnych poprzez manipulację okresem korozji. Następnie za pomocą różnicowej sondy fluxgate, składającej się z dwóch miniaturowych bramek strumieniowych ułożonych w układzie planarnym oraz kołowej cewki wzbudzającej, dokonano pomiaru składowych rzeczywistych i urojonych odpowiedzi magnetycznych od defektów korozyjnych w zakresie od 5 do 510 Hz. Rzeczywista różnicowa odpowiedź magnetyczna z sondy wykazała, że zmiana sygnału magnetycznego była proporcjonalnie zwiększona wraz z okresem korozji, ujawniając zwiększoną głębokość skorodowanego obszaru wraz z okresem korozji elektrolitycznej. Odpowiedź magnetyczną indukowaną przez pole wzbudzenia o częstotliwości od 10 do 110 Hz można wykorzystać do dokładnego oszacowania głębokości korozji stali o wysokiej przenikalności z rozdzielczością poniżej milimetra. (**Ocena korozji powierzchniowej płyt ze stali węglowej przy użyciu sondy różnicowej Fluxgate**)*

**Keywords:** corrosion, magnetic response, surface defect, steel, magnetic probe.
**Słowa kluczowe:** korozja, odpowiedź magnetyczna, defekt powierzchni, stal, sonda magnetyczna.

## Introduction

Defects from corrosion in steel components is among the major issues in aging structures, where even minor corrosion can lead to a catastrophic accident. Corrosion can start at the steel surfaces and progresses to penetrate penetrates deep inside the steel components. This phenomenon will cause the steel components to deform/crack due to the volume expansion and strain of the corroded region [1], [2]. When the corrosion enters the propagation stage, the structure deterioration will be accelerated [1]; hence, it is imperative to detect the corrosion at its early stage and be able to continuously monitor its progress while maintaining the operation of the steel structures. It has been reported that worldwide USD$ 2.5 trillion is used for maintenance and repairs of corrosion-affected structures [3].

Visual inspection, half-cell potential, and electrochemical impedance spectroscopy methods are conventionally used to assess corrosion. Despite the effectiveness of half-cell potential and electrochemical impedance spectroscopy methods for in-depth corrosion investigation [1], these methods require an invasive and contact measurement procedure, i.e., destructive testing. Moreover, the assessment using the visual inspection method can be difficult and misdiagnosed for internally occurring or hidden corrosion, i.e., not visible by eye inspection, and sufficient experience and training are sought for an inspector [1], [4].

The emerging electromagnetic methods such as eddy current (EC)/ pulsed-eddy current (PEC) and magnetic flux leakage (MFL) methods offer a non-invasive non-destructive method for corrosion rate assessment [2], [3]. However, the detection sensitivity in these conventional PEC and low-frequency EC methods is governed by the properties of steel, particularly the magnetic permeability, where the high permeability value will limit the penetration of the induced eddy current, thus, the detection of subsurface/backside corrosion [5]:

$$\text{penetration depth } \delta = \sqrt{1/\pi f \mu\sigma}, \quad (1)$$

where $f$, $\sigma$, $\mu$ are frequency, electrical conductivity and magnetic permeability of the material, respectively. Moreover, the simultaneously induced strong magnetization signal will bury the weaker eddy current signal since the eddy current signal is smaller than the magnetization signal. On the other hand, the magnetic permeability value of steel, such as carbon steel, ranges from 100 to 1000, while the iron oxide FeO, i.e., rust, is around 1. The large permeability difference between the non-corroded and corroded regions greatly benefits the electromagnetic methods, where corrosion can be regarded as similar to the thinning phenomena of steel.

Conventional EC and MFL probes employ conventional magnetic sensors such as Hall sensors and copper coils to detect the magnetic responses from a sample [6], [7]. To further enhance the detection sensitivity of corrosion in a high permeability sample, it is indispensable to use a sensitive magnetic sensor in the low-frequency region [8]. In this work, we test a differential fluxgate probe based on miniature fluxgate sensors (DRV425, Texas Instruments) to assess different corrosion rates of surface corrosion defects on a carbon steel plate.

## Experimental

A differential magnetic probe consisting of two miniature fluxgate sensors (DRV425, Texas Instruments) has been developed. The fluxgate exhibited a magnetic field noise of 1.5 nT/√Hz at 10 Hz in the shielded environment when biased at 5 V. The evaluated sensitivity was 30 mV/μT when shunted by 200 Ω with a linear region of [-0.5 mT, 0.5 mT] [7]. The two fluxgates were placed at the center of a 100-turn excitation coil fabricated from a 0.1 mm diameter Cu wire. The size of the coil and the fluxgates were given by 14 mm (internal diameter) and 4 mm × 4 mm, respectively. A 2-mm baseline separated the fluxgates with their sensitive axis in the z-direction to form a planar differential configuration of $dB_z/dx$. The outputs of the fluxgates were sampled individually by a data acquisition card (NI-USB 6212, National Instruments), and the differential signal of the fluxgates was obtained digitally after a phase-sensitive signal separation in a computer. The probe was attached to an *XY*-stage to allow positioning over a sample, and the *XY*-stage was controlled by the computer through LabVIEW. The diagram of the measurement setup can be found in Figure 1. The differential magnetic response was expressed as $\Delta B_z$ based on this approximation:

(2) $$\frac{\partial B_z}{\partial x} \approx \frac{\Delta B_z}{\Delta x} = \frac{B_{z,\,fluxgate1} - B_{z,\,fluxgate2}}{baseline} \propto \Delta B_z\,,$$

where the baseline of the differential fluxgates was a fixed value.

A 6-mm carbon steel (mild steel) plate was used to prepare a surface corrosion sample at different corrosion periods. The plate has a dimension of 25 × 25 $cm^2$. Since corrosion could take quite a long time to form, the electrolytic corrosion process was used, also known as accelerated corrosion. For this electrolytic corrosion process, the electrolyte was made up using a combination of vinegar, 6% hydrogen peroxide solution, and iodized salt. Then, a DC voltage supply was applied to an array of copper sheets, and the carbon steel plate was connected to the negative terminal of the power supply. Then, between the plate and the copper sheets, cotton buds soaked with the electrolyte solution were introduced to complete the electrical circuit. The electrolytic corrosion process was performed continuously for a specific corrosion period, and the electrolyte solution was continuously maintained during the period. Four areas were prepared for the different corrosion periods: 5, 10, 15, and 20 days. The complete setup of the electrolytic process is illustrated in Figure 2 (a), and the sample photograph is shown in Figure 2 (b). After measuring magnetic responses using the differential fluxgate probe, the corrosion depth was assessed by carefully removing the corrosion layer and measuring the resulting depth using a micrometer.

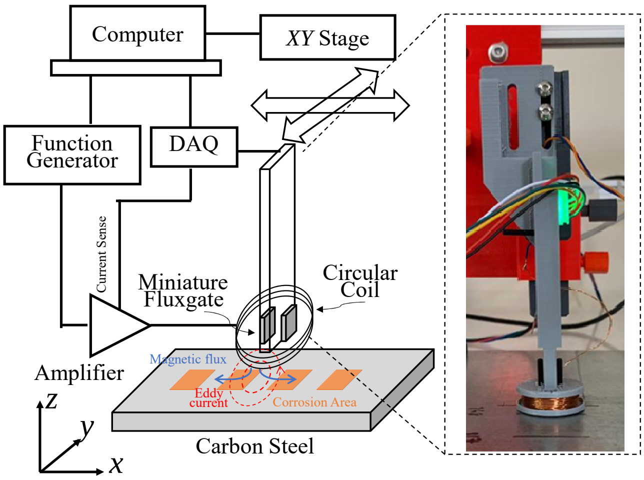


Fig. 1. Simplified diagram of the differential fluxgate probe.

Table 1. The parameters of the corrosion defects

| Defect | Defect 1 | Defect 2 | Defect 3 | Defect 4 |
|---|---|---|---|---|
| Corrosion Period (day) | 5 | 10 | 20 | 30 |
| Measured depth (mm) | 0.12 ± 0.04 | 0.17± 0.04 | 0.26 ± 0.03 | 0.35 ± 0.04 |

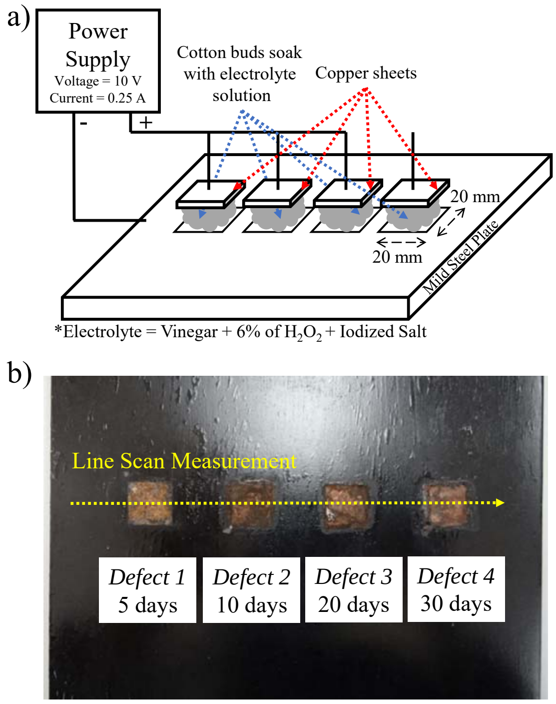


Fig. 2. (a) Diagram of the corrosion defect preparation and (b) photograph of the prepared corrosion defects on the carbon steel plate.

## Results and Discussion

### Effect of Frequency and Excitation Current on Magnetic Responses of Corroded Area

Figure 3 shows the real and imaginary magnetic responses $\Delta B_z$ of the corrosion defects measured from 5 to 510 Hz. The real component Re[$\Delta B_z$] showed that the signal responded by a minimum and maximum value at each edge of the corrosion defect. Defect 4, with the highest corrosion period, showed the largest signal peak of Re[$\Delta B_z$] compared to other defects. On the other hand, the defects could not be identified from the waveforms of Imag[$\Delta B_z$] compared to the waveforms of Re[$\Delta B_z$]. When the excitation frequency was increased, Re[$\Delta B_z$] showed a change in the peak values of each defect, while for the Imag[$\Delta B_z$] waveforms, their signal offset was reduced. The increased intensity of the signal offset in Imag[$\Delta B_z$] could be inferred as the increased intensity of eddy current generation near the surface due to decreasing penetration depth as the frequency was increased. The change in signal intensity of Re[$\Delta B_z$] due to different excitation frequencies was then analyzed by calculating the peak-to-trough signal $B_{pp}$ for each defect, as shown in Figure 3 (a). The calculated $B_{pp}$ at different frequencies for each defect is plotted in Figure 5 (a). A linear correlation could be assumed between the $B_{pp}$ signal and the defect depth, indicating the probe could resolve the corrosion depth at a sub-millimeter sensitivity. Although the slope of the correlation was slightly different, the highest slope was obtained at 10 Hz (slope $m$=0.079 mV/mm), while the lowest slope was at 510 Hz (slope $m$=0.069 mV/mm).

Figure 4 shows the effect of the excitation current intensity on the real and imaginary components of $\Delta B_z$ from 10 to 70 mA. Similar to the case of different excitation frequencies, the signal change of Re[$\Delta B_z$] at the defect edges was increased as the defect depth was increased. Furthermore, the increased excitation current intensity improved the $B_{pp}$ signal for each defect, as shown in Figure 5 (b). The increased excitation current intensity linearly increased the $B_{pp}$ signal for each defect, showing a potential to increase the probe sensitivity by using a higher excitation current intensity. This could be related since the increased current intensity would increase the magnetization signal, thus improving the signal change at the defect edges. For Imag[$\Delta B_z$] shown in Figure 4 (b), the increased offset signal intensity was resulted from the increased eddy current induction in the steel plate.

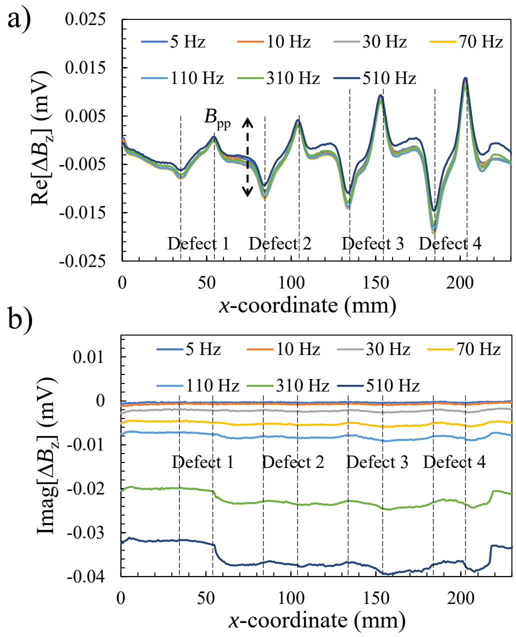


Fig. 3. (a) The real and (b) imaginary differential magnetic responses from different corrosion defects measured from 5 to 510 Hz using a fixed 70 mA excitation current.

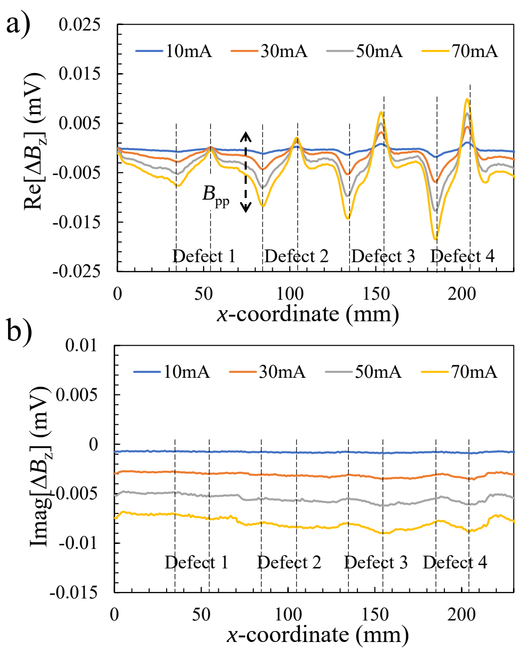


Fig. 4. (a) The real and (b) imaginary differential magnetic responses from different corrosion defects measured from 10 to 70 mA of excitation currents and a fixed 110 Hz frequency.

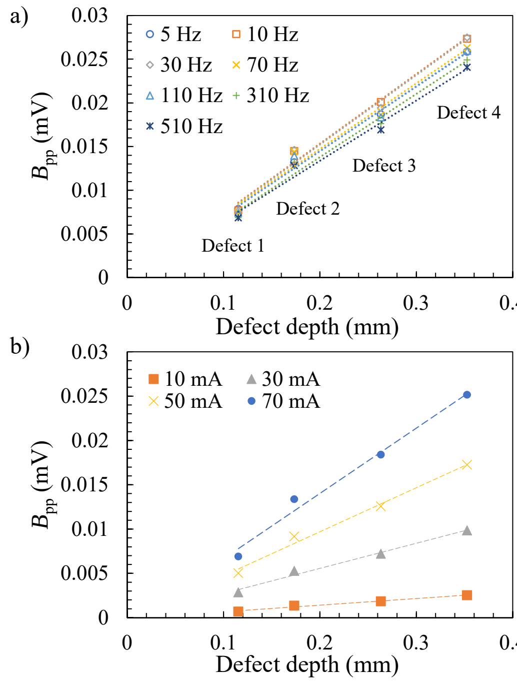


Fig. 5. The dependency of the real differential magnetic responses on the (a) frequency and (b) excitation current intensity.

**Magnetic Response Distribution of Corroded Area**

Figure 6 shows the 2-D map of $\Delta B_z$ over an area of 230 mm × 80 mm of the steel plate measured at the 70 mA and 110 Hz excitation current. The defect location could be clearly identified from the signal contour changes indicated by negative and positive contours. As evident from the line scan measurements, the intensity of the contour peaks/ trough intensified with the increase of the corrosion period, revealing the different depths of the corrosion regions. The location and area size of the changing contours agreed with the visual image of the corrosion regions in Figure 2 (b). It could be concluded that the Re[$\Delta B_z$] signal from the differential probe could be utilized to evaluate surface corrosion on carbon steel plates using the low-frequency excitation current.

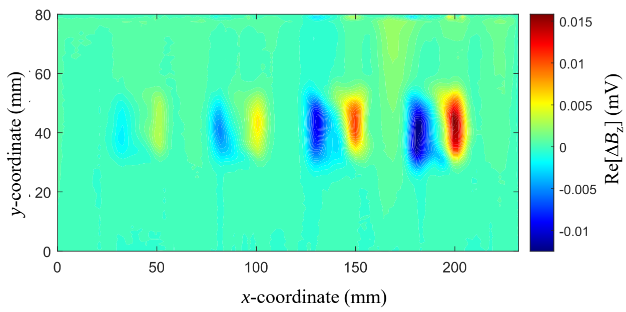


Fig. 6. The signal distribution of Re[$\Delta B_z$] over the steel plate area mapped using the 70-mA and 110-Hz excitation current.

**Conclusions**

In this work, the different rates of corrosion defects on the carbon steel sample were evaluated using the magnetic responses measured by the differential fluxgate probe. The results showed that the real component of the differential magnetic response induced by a low-frequency excitation field could be used to assess the corrosion depth. The signal intensity change of the differential magnetic responses was found to be linearly correlated with the corrosion periods/depths. A range of excitation frequency from 10 to 110 Hz was found to be suitable for obtaining a sub-millimeter depth detection sensitivity of corrosion defects on the carbon steel plate. The usage of higher intensity excitation current further enhanced the signal change caused by the corrosion defects. Scanning magnetic response over the corrosion defect areas revealed the geometrical size of the corrosion. The proposed differential fluxgate probe could be useful for assessing corrosion defects at sub-millimeter sensitivity on a high-permeability steel plate.

***Acknowledgments**: This work was supported by the Ministry of Higher Education of Malaysia under grant number FRGS/1/2022/TK07/UMP/02/9 (University Reference: RDU220109) and the Research Management Center of Universiti Malaysia Pahang under International Publication Grant number RDU223315.*

***Author:** assoc. prof. dr. Mohd Mawardi Saari (corresponding author), E-mail: mmawardi@ump.edu.my; Mohd Aufa Hadi Putera Zaini, E-mail: pek21001@student.ump.edu.my; Ummi Sabihah Mohd Yusdi, E-mail: sabihahyusdi1997@gmail.com; Nurul A'in Nadzri, E-mail: pek19004@student.ump.edu.my; assoc. prof. dr. Mohd Herwan Sulaiman, E-mail: herwan@ump.edu.my, Universiti Malaysia Pahang, Faculty of Electrical and Electronics Engineering Technology, 26600 Pekan, Pahang Malaysia; prof dr. Toshihiko Kiwa, Graduate School of Interdisciplinary Science and Engineering in Health Systems, Okayama University, Okayama 700-8530, Japan , E-mail: kiwa@ec.okayama-u.ac.jp.*

Corresponding author. E-mail address: mmawardi@ump.edu.my

## REFERENCES

[1] R. Rodrigues, S. Gaboreau, J. Gance, I. Ignatiadis, and S. Betelu, "Reinforced concrete structures: A review of corrosion mechanisms and advances in electrical methods for corrosion monitoring," *Constr. Build. Mater.*, vol. 269, p. 121240, 2021, doi: 10.1016/j.conbuildmat.2020.121240.

[2] Z. Li, Z. Jin, Y. Gao, T. Zhao, P. Wang, and Z. Li, "Coupled application of innovative electromagnetic sensors and digital image correlation technique to monitor corrosion process of reinforced bars in concrete," *Cem. Concr. Compos.*, vol. 113, no. July, p. 103730, 2020, doi: 10.1016/j.cemconcomp.2020.103730.

[3] D. Tamhane, J. Patil, S. Banerjee, and S. Tallur, "Feature Engineering of Time-Domain Signals Based on Principal Component Analysis for Rebar Corrosion Assessment Using Pulse Eddy Current," *IEEE Sens. J.*, vol. 21, no. 19, pp. 22086–22093, 2021, doi: 10.1109/JSEN.2021.3103545.

[4] S. Wakabayashi, M. Hayashi, T. Saitoh, K. Sakai, T. Kiwa, and K. Tsukada, "Optimization of inclined angle magnetic sensor probe to improve detection performance of corrosion near the ground using extremely low-frequency eddy current testing," *10th Int. Work. NDT Prog.*, 2019.

[5] N. A. Nadzri, M. M. Saari, M. A. H. P. Zaini, A. M. Halil, M. Ishak, and K. Tsukada, "Anisotropy magnetoresistance differential probe for characterization of sub-millimeter surface defects on galvanized steel plate," *Meas. Control (United Kingdom)*, 2021, doi: 10.1177/00202940211028618.

[6] S. Tumanski, "Modern magnetic field sensors - a review," *Prz. Elektrotechniczny*, vol. 89, no. 10, pp. 1–12, 2013, Accessed: May 06, 2015. [Online]. Available: http://www.red.pe.org.pl/articles/2013/10/1.pdf.

[7] S. Tumański, "Modern methods of electrical steel testing – a review," *Prz. Elektrotechniczny*, vol. 97, no. 3, pp. 162–167, 2021, doi: 10.15199/48.2021.03.31.

[8] M. M. Saari, N. A. Nadzri, M. A. H. P. Zaini, N. H. Ramlan, and K. Tsukada, "A Low-frequency Eddy Current Probe Based on Miniature Fluxgate Array for Defect Evaluation in Steel Components," *IEEE Trans. Magn.*, pp. 1–5, 2021, doi: 10.1109/TMAG.2021.3076441.

[9] N. Sathappan *et al.*, "Development of an MFL coil sensor for testing pipes in extreme temperature conditions," *Sensors*, vol. 21, no. 9, 2021, doi: 10.3390/s21093033.

[10] M. A. H. P. Zaini, M. M. Saari, N. A. I. Nadzri, Z. Aziz, N. H. Ramlan, and K. Tsukada, "Extraction of Flux Leakage and Eddy Current Signals Induced by Submillimeter Backside Slits on Carbon Steel Plate Using a Low-Field AMR Differential Magnetic Probe," *IEEE Access*, vol. 9, pp. 146755–146770, 2021, doi: 10.1109/ACCESS.2021.3123421.