Corrosion monitoring of metals through magnetic sensing

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Abstract

Corrosion in infrastructure causes significant financial losses. Effective monitoring of corrosion could allow for great savings and enable proper maintenance. A magnetic sensing approach is described to overcome some of the difficulties faced by traditional NDE techniques. This new approach explores the use of Giant Magneto-Resistive (GMR) technology to determine both rate and extent of corrosion. Active and passive configurations are used for remote monitoring. Results on corroding metal samples are presented and future developments for this technology are described.

Résumé

La corrosion dans les infrastructures entraîne des pertes financières significatives. Un suivi efficace de la corrosion pourrait permettre de réaliser de grandes économies et d'effectuer des réparations appropriées. Une approche utilisant des capteurs magnétiques est décrite pour surmonter certaines des difficultés auxquelles les techniques de NDE traditionnelles sont confrontées. Cette nouvelle approche explore l'utilisation de la Magnéto-Resistivité Géante (GMR) pour déterminer à la fois la cinétique et l'étendue de la corrosion. Des configurations actives et passives sont utilisées pour réaliser un suivi à distance. Les résultats obtenus sur des échantillons métalliques corrodés sont présentés et les développements futurs pour cette technologie sont décrits.

Keywords

Corrosion, Magnetic Sensing, GMR Sensors, Concrete Reinforcement

1 Introduction

Corrosion is the irreversible consumption of materials due to the interaction with the environment. Corrosion is a severe problem, not only due to material loss and costs, but also because it is a principal cause in some cases of injury and loss of life [1]. In the US, some estimates of the cost of corrosion damage to highway bridges alone are \$6 to \$10 billion per year [2]. Given its importance, there is a clear need to monitor and characterize corrosion. Many techniques already exist to monitor corrosion, ranging from direct mass loss to characterization of kinetics and thermodynamics involved. There is however always a need to increase the sensitivity and practicality of the sensing techniques.

The objective of this ongoing research program is to characterize corrosion with the use of magnetic sensing. Corrosion is an electrochemical process involving the movement of ions and electrons, which should generate small magnetic fields as predicted by Maxwell's equations and Biot-Savarat law. Studies done with Superconducting Quantum Interference Devices (SQUIDs) have shown the feasibility of this approach [3, 4].

1.1 Corrosion basics

Corrosion an electrochemical process in which the material is lost in the form of ions and electrons. Each corrosion half-cell reaction takes place at a different location. At the anode, electrons and ions are lost. Electrons move through the metal and ions through the environment to a different location where they combine. The equilibrium state is governed by the principles of thermodynamics while rates, effects of electrical potential, temperature, pressure, and concentration are governed by the principles of kinetics [5].

1.2 Traditional non-destructive methods

Traditional NDE techniques make use of the electrochemical nature of corrosion. The half-cell method requires a precision voltmeter and a reference electrode and is generally used to indicate likelihood of corrosion [6]. The major limitation of half-cell potential measurements is that the rate of corrosion of time testing cannot be determined directly. For this, the linear-polarization resistance (LPR) method is used. An external potential is applied to a freely corroding element and the resulting "linear" current response is measured. The ratio of these changes is known as polarization resistance and it is used to determine corrosion rates [6]. Other techniques are available such as electrochemical noise measurements, pH measurements, and ultrasonic guided wave measurements [7, 8, 9]. These techniques and sensors have limitations, particularly since electrical connection to the metal is needed. Corrosion sensors measure the environment but they do not monitor the corrosion of the metal itself.

2 Proposed approach

Given the limitations of traditional NDE techniques, magnetic sensing is proposed as a way to monitor corrosion. Some ground breaking research in the area has already being performed with the use of Super Quantum Interference Devices (SQUIDs). These are highly sensitive magnetometers but present some limitations for field use [10, 11, 12]. Among their drawbacks is the need for cooling which is commonly done with helium as a working gas. Although there have been advances in cooling techniques from Stirling coolers to pulse-tube coolers, there is still a need to improve lifetime and noise due to moving parts. An additional limitation to implement them in the field is cost and high power draw requirement. In 2002, the cost of a cooling unit could reach US$40.000 [13].

Giant Magneto-Resistive (GMR) Sensors are proposed here as an alternative to measure magnetic fields. They have a broad sensing range, with favorable environmental performance, low power consumption, and low cost. Their drawback is that sensitivities are at least an order of magnitude less than those of SQUIDs [14].

The principle behind GMR is now summarized. Layers of ferromagnetic and non-magnetic materials are stacked, originally facing opposite directions due to anti-ferromagnetic coupling. These layers are usually a few nanometers in width. As a magnetic field is applied, the anti-ferromagnetic coupling is overcome causing a drop in the electrical resistance [14].

3 Experimental testing

3.1 Passive sensing

Passive sensing is the measurement of random fluctuating magnetic fields generated by corrosion. Tests were carried out on ferromagnetic (steel) and non-ferromagnetic (aluminum) plates. The square plates 25 mm in length were coated and a narrow 2 mm wide and 10 mm long stripe was exposed in the center. The samples were then placed in different environments and magnetic field measurements taken at four different locations. Air and plain water were used as reference non-corrosive environments. A basic aqueous solution (pH 13.5) was used to actively corrode aluminum samples. An acidic aqueous solution (pH 2) was used to corrode the steel plates. Two aligned GMR sensors were placed perpendicular to the plate, as shown in figure 1a. The separation distance from the first sensor to the plate was about 1 cm. Measurements were taken away from the plate, at both sides of the exposed area, and over the exposed area or notch.

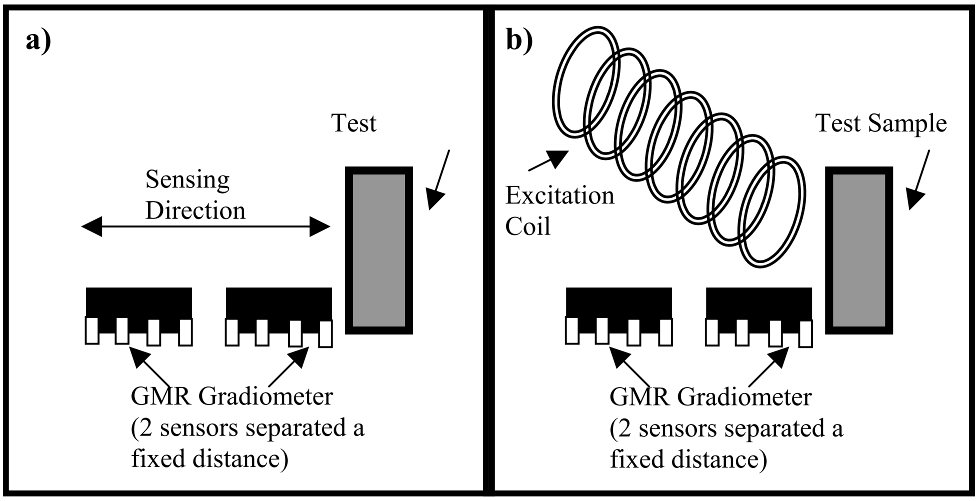

Figure 1. *Sketch for active (a) and passive (b) experimental setups.*

The difference of the measurements from the two GMR sensors is a gradiometric response and is used to correct for environmental noise. Ten repetitions were taken at each location, with 2^{14} points acquired each time at a rate of 1MSPS.

A power spectral density analysis (PSD) was used to clearly identify changes in the signal. From the PSD analysis, regions of interest were discovered which seem to be directly related to corrosion. The frequency region from 50 to 80 kHz seems particularly sensitive, as shown in figure 2.

Several features of the PSD plots were calculated and their averages over the ten repetitions were taken. Figure 3 summarizes the response of the aluminum plate in the different environments, as considered by taking the area under the PSD plot in the 70 to 80 kHz range. The plot shows that the measurements over the exposed area in the corrosive environment stand out from all other measurements. The experimental data naturally contain variability, which explains differences in the measurements over the two coated plate locations.

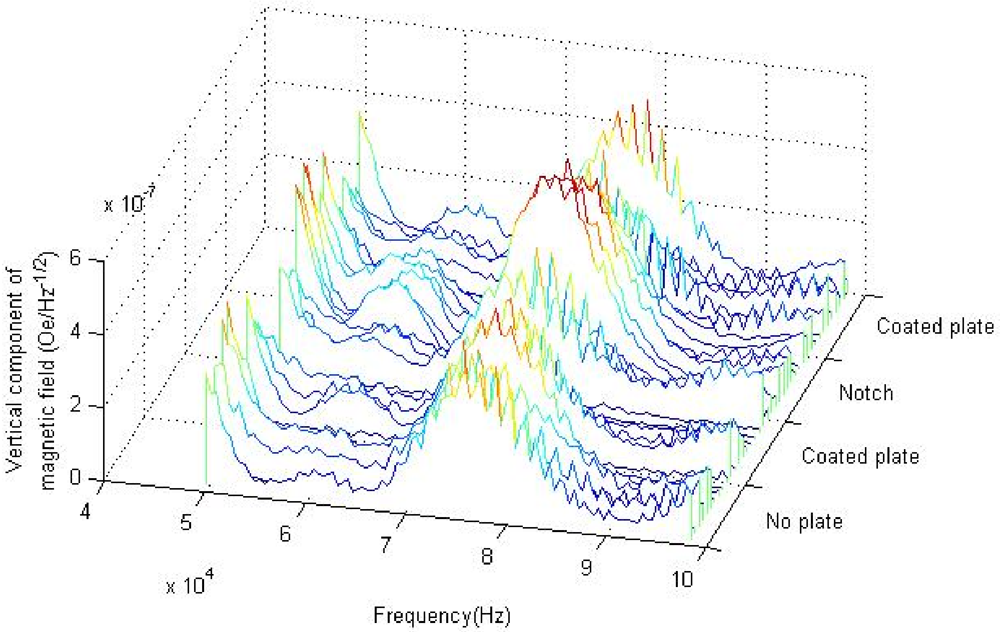

Figure 2. *PSD response over time of aluminum sample in basic solution*

Similar measurements and calculations were done with steel plates. Measurements of the properties from the PSD plots of the steel plates in the different environments however do not show much distinction. The right trend is observed, that is, the magnetic field measurements increase in the corrosive environment over the notch. However, the response is closer to the behavior in other environments, perhaps due to the ferromagnetic nature of steel.

3.2 Active sensing

Active sensing explores the interaction of an imposed magnetic field with a corroding sample. The imposed field was generated by an AC coil with a wide range of working frequencies. The excitation frequencies used ranged from 10 to 60 kHz. Samples used were similar to those of passive sensing, but no coating was used since the interest was to explore the effect of the imposed magnetic field on an actively corroding sample, and not to monitor differences within a sample. During testing, the coil pointed at a fixed angle at the plate and the constructed GMR gradiometer was placed perpendicular to the sample, as shown in figure 1b.

The data acquisition and processing methods were the same as those for passive sensing. The plates were placed in three different environments, and ten data repetitions were taken at each environment and excitation frequency. The plot in Figure 4 shows the average peak value of the PSD plot at the excitation frequency from the ten repetitions taken for each.

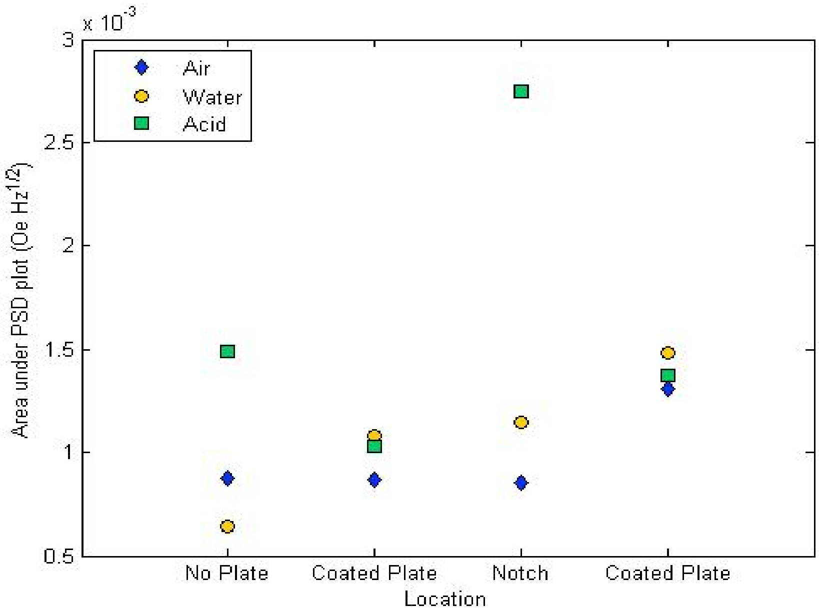

Figure 3. *Area between 70 kHz to 80 kHz under PSD plot of magnetic field signals of aluminum plate in passive (air and water) and corrosive (basic) environments*

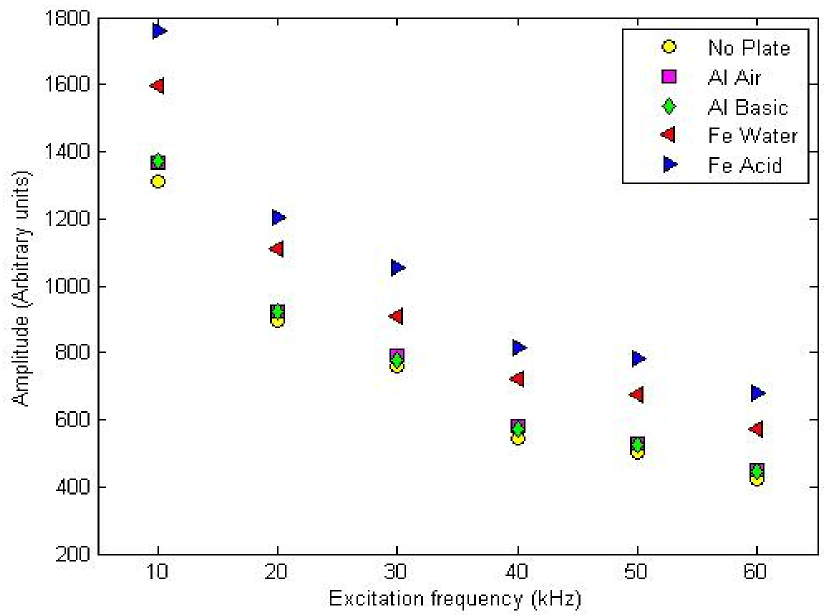

Figure 4. *Magnetic response of passivated and corroding aluminum and steel plates owing to imposed magnetic fields at different excitation frequencies*

From the plots it is clear that the behavior between the steel and aluminum plates can be differentiated, and the presence of either type of plate accentuates the response. The plot also shows that active testing configuration has potential to detect active corrosion in steel. The amplitude of the excitation frequency is significantly higher at all frequencies for the corroding steel plate as compared with the passive steel plate.

4 Conclusions

Magnetic sensing is proposed as a way to overcome limitations of traditional NDE techniques to monitor corrosion. Preliminary tests show some promise for the development of a non-contact approach. Passive sensing measurements with GMR sensors show promise in identifying localized corrosion, particularly for aluminum samples. Active measurements produced better results for steel corrosion. However further testing is needed to verify acquired magnetic field data and improve data consistency.

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References

1. Jones, Denny A. (1996) *Principles and prevention of corrosion*. Prentice-Hall, Upper Saddle River, NJ, second edition.
2. Yunovich, M. and Thopson, N. (2008) "Corrosion of highway bridges – economic impacts and control methodologies", *Concrete International*, Vol. 5.
3. Jenks, W.G., Sadegihi, S.S.H., and Wikswo, J.P. (1997) "SQUIDs for nondestructive evaluation". *Jounal of Physics D: Applied Physics*, Vol. 30, pp. 293-323.
4. Misra, M., Lordi, S., and MacVicar, M.L.A. (1991) " NDE applications of SQUID magnetometry to electrochemical systems", *IEEE Transactions on Power Electronics*, Vol. 27, pp. 3245-3248.
5. Wranglén, Gösta (1985) *An introduction to corrosion protection of metals*. Chapman and Hall.
6. ACI Committee 228 (1998) *Nondestructive test methods for evaluation of concrete structures,* American Concrete Institute.
7. Dawson, J.L. (1996). "Electrochemical noise measurement: the definitive in-situ technique for corrosion applications?", *Electrochemical noise measurements for corrosion applications,* Ed by J.R. Kearns, J.R. Scully, P.R, Roberge, D.L. Reichert. And J.L. Dawson, American Society of Testing Materials, Philadelphuia, PA, pp. 3-35.
8. Pidaparti, R.M., Neblett, E.B., Miller, S.S., and Alvarez, J.C. (2008) "Monitoring the corrosion process of Al alloys through pH induced fluoresnce", *Smart Materials and Structures*, Vol. 17, pp. 1-6
9. Reis, H., Ervin, B.E., Kuchma, D.A., and Bernhard, J.T. (2005) "Estimation of corrosion damage in steel reinforced mortar using guided waves", *Journal of Pressure Vessel Technology*, Vol. 127, pp. 255-261.
10. Clarke, John (1996) "SQUID Fundamentals", *SQUID sensors: fundamentals, fabrications, and applications,* Ed by Harold Weinstock, pp. 1-62.
11. Bellingham, J.G., and MacVicar, M.L.A. (1987) " SQUID technology applied to the study of electrochemical corrosion", *IEEE Transactions on Power Electronics*, Vol. 23, pp. 477-479
12. Juzeliũnas, Eimutis; Ma, Yu Pei; and Wikswo, John. P. (2004) "Remote sensing of aluminum alloy corrosion by SQUID magnetometry", *Journal of Solid State Electrochemistry*, Vol. 8, pp. 435-441.
13. Clarke, J. and Braginski (2006). *The SQUID Handbook: Fundamentals and Technology of SQUIDs and SQUID Systems*, Wiley-VCH.
14. NVE (2008) *GMR sensor catalog*, http://www.nve.com/Downloads/catalog.pdf, last accessed on June 30, 2008.