Enhanced Sensitivity of Low Frequency (LF) RFID Sensor Signal for Structural Health Monitoring (SHM) in High Temperature Environment

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Abstract. Structural health monitoring at high temperature environment is essential particularly in chemical industries where processes conduct at 150°C or more. In such cases, corrosion is a major cause of deterioration to metallic structures and temperature affects the rate of corrosion. Current methods used for inspection of these metallic structures requires removal of thermal insulation layer to gain access to the metallic surface which often requires shutting down of operations and are an expensive process. This paper demonstrates the use of LF RFID sensors for SHM in high temperature conditions. The system comprises of a reader and a tag along with ferrite sheet for higher efficiency sensing of corrosion on metallic samples at high temperatures. This paper studies the response characteristics of commercial RFID tags that are placed on high temperature metallic samples which have significant impedance variation. Also ferrite sheet has been used to enhance the RFID signal sensitivity for accurate corrosion monitoring and to understand temperature influence for the measurement and compensate temperature influence.

Keywords: LF RFID, high temperature, corrosion characterisation, ferrite cores, non-destructive testing and evaluation (NDT&E)

1. Introduction

Online monitoring of metallic structures such as pipes at high temperature for defect classification is the key to many industrial NDT&E (Non-Destructive Testing and Evaluation) demands, such as power generation and the nuclear industry [1-2]. The pipes, usually made of carbon steel or steel alloys, are used to transport a wide variety of chemicals which are operated at temperatures of 150 °C or more [3]. Corrosion testing and detection is an essential area in these industries. Deterioration of infrastructure due to corrosion is not just an economic issue, but can also jeopardise human safety. The ability to inspect defects or classify corrosion without shutdown for unscheduled time has important economic consideration [4] and a method for temperature monitoring at the same time is highly desirable. Recent developments in metallic structures and materials have intensified the requirement for reliable corrosion detection and monitoring methods [5]. Currently there are a number of methods used for the inspection at high temperature. They can apply high temperature material for sensor systems, stand-off distance for non-contact measurement and signal enhancement. For example they include guide waves, laser based interferometry methods and electromagnetic NDT&E methods, namely eddy current based
methods [6-9] amongst others. Laser based methods are usually expensive and are difficult on the surface condition and also require large diameter optics. Also for long term measurements in condition monitoring applications, the use of these systems are impractical. High temperature piezoelectric materials and their potential use in NDT applications are receiving increased attention [10]. Extensive reviews on progresses and challenges on designing piezoelectric ultrasonic transducer for operation at high temperature are shown in [11]. Also laser EMAT configuration can be used for high temperature operations but the temperature of the magnet must be kept below the maximum operating point and the temperature of the coil must be sufficiently low as well in order to avoid damage to coil insulation [12-13]. However, the challenge of corrosion detection in high temperature environment still remains unevaluated.

Recently, electromagnetic NDT&E methods have been used to investigate corrosion detection [14] and Structural Health Monitoring (SHM) [15]. Eddy current (EC) and pulsed eddy current (PEC), are the most commonly used techniques in the field of electromagnetic NDT&E. These techniques have a wide variety of applications including stress measurement [16], flaw detection [17], and corrosion characterisation [18-19]. Majority of NDT techniques are limited when it comes to online in-situ monitoring under thick insulation layer. The passive LF RFID sensors demonstrate the potential of cheap, passive sensing which can be permanently embedded into structures for long term monitoring at high temperatures. Previously passive LF commercial RFID tags have been used to study the monotonic behaviour of corrosion progression using both static [20] and transient features [21]. In this paper, the performance of off-the-shelf high temperature LF RFID tags is studied in order to understand the temperature effect on high temperature RFID tags and also ferrite sheet is used to compensate the temperature causing impedance mismatch and characterise corrosion at higher sensitivity. This paper is an extension of the work carried out in [21].

The rest of the paper is organised as follows. The section 2 describes the corrosion measurement setup at high temperatures along with corrosion progression samples. In section 3, results and discussion are carried out for the experimental studies. Conclusion and future work are mentioned in section 4.

2. Corrosion measurement at high temperature

An RFID tag placed on a metallic structure operating at high temperatures will have an output dependent on not only the corrosion progression but also the temperature variation. Therefore it is essential to compensate for temperature variations in order to have accurate and more reliable corrosion monitoring. In general, an increase in temperature of the metallic sample will lead to an increase in resistivity and decrease in conductivity. The Bolch-Grüneisen formula mathematically represents the relationship between temperature and resistivity for metals.

\[ \rho(T) = \rho(0) + A \left( \frac{\theta}{\theta_R} \right)^n \int_0^{\theta/\theta_R} \frac{x^n}{(e^x-1)(1-e^x)} dx \]

where \( \rho(0) \) is the residual resistivity due to defect scattering, \( \theta_R \) is the Debye temperature and \( A \) is constant. At high temperatures, the metal resistance changes linearly with temperature. Semiconductor components of an RFID tag, such as microchip, also have a temperature dependence given by the Steinhart-Hart equation. The resistivity of semiconductor decreases with an increase in temperature.

\[ \frac{1}{\tau} = A + B\ln(\rho) + C(\ln(\rho))^3 \]
where A, B and C are the Stenhart-Hart coefficients.

Most widely known temperature compensation methods are Optimal Baseline Subtraction (OBS) and Optimal Stretch Method (OSM) [22-24]. In OBS a set of baseline signals covering a range of conditions are used whereas in OSM a single baseline is being stretched or compressed to best match the signal. However, the problem with baseline set acquisition is that, if there is no prior knowledge of temperature during the acquisitions then the set can have many baselines that correspond to the similar temperatures. Also if there is no control over temperature then it becomes harder to cover the whole range operational temperature. Therefore, in order to compensate the temperature influence on the metal and tag, ferrite sheet is used to improve the quality factor of the tag. Fig. 1 below shows the experimental setup of tag with ferrite sheet (0.1mm).

![Fig. 1. Experimental setup using ferrite sheet](image)

2.1 Corrosion progression samples

A set of coated mild steel plates (S275) have been used which have had different duration of atmospheric exposure (1, 3, 6 and 12 months) to create different level of corrosion. The plates have dimensions of 300x150x3 mm (length×width×thickness). A 30×30 mm rectangular patch at the centre of each plate was left exposed to the atmosphere to allow rust to build up. The coating used is epoxy phenolic based paint with a typical thickness of 100 microns.

![Fig. 2. 1 to 12 months coated samples](image)

2.2 Experimental setup

LF RFID (operating at 125 kHz) reader kit has been used to perform the following experimental work. The tag that is used is 231 Volcano LF RFID tag is used in this experiment which has a high heat tolerance and performs best at high temperature environments and is shown in Fig. 3.
As the increase in temperature will cause the resonance frequency to shift, therefore the sweep frequency has been measured using a signal generator from 114 kHz to 132 kHz. This will then measure any change in frequency over various temperature. The tag was placed on the centre of the corrosion patch of 4 different (1 month, 3 months, 6 months, and 12 months) samples from the corrosion progression sample set shown in Fig. 2. Each of the plates was then placed on top of the hot plate (VWR VHP-C7) and the temperature of the hot plate was increased from 50 °C to 200 °C with 50 °C increment. The experiment was carried out with and without ferrite sheet to understand the behaviour of the tag at different temperatures. Fig. 4 and Fig. 5 shows the system setup and system diagram respectively.

The output signal from the RFID reader kit is sampled using 14bit Adlink 2010 DAQ. The data acquisition is controlled in the PC using a LabVIEW program that allows the user to set the sample rate and number of samples to be acquired. The output was sampled at 1 MHz for 0.03 seconds (30,000 data points).
3. Results and discussion

The performance of the LF RFID system on mild steel samples at a range of temperatures was performed using the setup shown in Fig.5. In order to perform the experiment at different temperatures the hot plate heater was used to heat the sample and then FLIR i3 camera was used to monitor the temperature of the sample surface and the tag. The procedure to execute the experiment is as follows; firstly the measurement is taken at room temperature from 114 kHz to 132 kHz; sample is then left on the heater for a certain time until it reached the next desired temperature (temperature monitored using FLIR) and then measurement of the resonant frequency is taken again. This is repeated for all the 4 samples at 4 different temperatures from 50 ºC to 200 ºC with 50 ºC increment.

The peak amplitude from the frequency domain of the measured signal is plotted against temperature change shown in Fig.6. Each of the 5 different colours on each temperature range represents the number of times the experiment was carried out. The result show that the peak amplitude decreasing with the increasing temperature. This is due to increasing levels of resistivity leading to greater losses and less power being absorbed by the RFID tag.

![Fig.6. Peak frequency domain amplitude against temperature increase for tag](image)

An important consideration when performing inspections at high temperatures is the change of signal amplitude as the physical change can lead to large errors if not taken into consideration. Sweep frequency has been studied for all the samples at different temperatures with and without ferrite sheet to see the frequency shift with increasing temperature. Sweep frequency for the 12th months sample is shown in Fig. 7.

![Fig.7. Sweep frequency response (a) without ferrite and (b) with ferrite](image)
The resonant frequency has then been studied for both the experimental setup with and without ferrite over different temperatures and the results without ferrite shows more frequency shift compared to that of the result with ferrite. The results can be seen in Fig.8. The frequency shift was measured keeping 50 °C at 120 kHz. The yellow circled lines are the results without ferrite which show the frequency shift of four corrosion plates from 120 kHz to about 116 kHz which is about 4 kHz lower. However, for ferrite sheet marked in red circle we see a frequency drop of only about 1.5 kHz the lowest from 120 kHz to 118.5 kHz. Also the RFID signal response with ferrite sheet shows higher signal sensitivity to corrosion progression over increasing temperature compared to that of the result without ferrite sheet. These results can be seen in Fig.9.

**Fig.8.** Resonant frequency as a function of temperature for corrosion progression samples with and without ferrite

**Fig.9.** LF RFID tag response at varying temperatures for corrosion progression samples (a) with ferrite and (b) without ferrite

The results in Fig.9 have been taken at the operational frequency for LF RFID i.e. 125 kHz. There are two notable observations that can be made of the results in Fig.9. (a) and (b). The first is that both graphs show a monotonic reduction in signal amplitude with an increase in temperature. Also, the change of temperature can be easily identified. The second notable result is that, using ferrite sheet, not only the frequency shift was reduced but also the
sensitivity of LF RFID signal over corrosion progression samples have been enhanced. As a result, a monotonic relation from 1 to 12 months can be noticed for all the temperature variations with the use of ferrite sheet whereas without ferrite sheet the corrosion progression results are not monotonic and the frequency shift is higher.

4. Conclusion and Future work

A significant progress has been made with the LF RFID sensor system with its main goal, operation at high temperature. It has been shown that it is possible to perform measurements on mild steel samples with surface temperature as high as 200 ºC. The tag’s performance is reliable even at 200 ºC. On the high temperature survivability of the tags, it was found that tags which experienced temperatures in excess of 240 ºC did not survive the first 10 hours heating period. Therefore the experiment was carried out at temperatures less than or equal to 200 ºC which was ideal for the tag. The response to corrosion progression has been studied with and without ferrite sheet at higher temperatures and the result with ferrite sheet outperformed the results without ferrite sheet in terms of both detecting corrosion sensitivity and reducing frequency shift caused by temperature.

Future work involves some fundamental tasks to be accomplished; amongst these the most important is to compensate the temperature effect on the tag by automatically matching the impedance change that occurs due to high temperature while at the same time accurately monitoring the corrosion behaviour.

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References