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Tunnel-magnetoresistive-based Pulsed Eddy Current Probe for Inspection of Corrosion under Insulation

To cite this article: Mohamoud Hussein Mohamed *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1244** 012006

Tunnel-magnetoresistive-based Pulsed Eddy Current Probe for Inspection of Corrosion under Insulation

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Abstract. The problem of corrosion in the industrial oil and gas pipes has been one of the major contributors in catastrophic structural failures. Among the various types of corrosion, corrosion under insulation (CUI) has been known to cause serious problems. Pulsed eddy current (PEC) non-destructive testing has shown its effectiveness in detecting hidden CUI. Most PEC systems have been developed by using an inductive coil as their sensing device, while some use a magnetic sensor which potentially offers better resolution. A new probe design based on a solid-state Tunnel magnetoresistance (TMR) is presented. TMR sensors offer higher sensitivities compared to other commercially available sensors. The performance of the probe is evaluated by using ferromagnetic mild steel plates that have thicknesses in the range of 8mm to 12mm at different stand-offs with a thin aluminium sheet under the probe. The different thicknesses represent different corrosion levels, while the stand-offs and thin aluminium sheet are to mimic the insulation of different thicknesses and the cladding in the real pipeline structure. The results show an overall mean absolute error (MAE) of 0.19 mm, which is better than our existing Hall-device-based PEC probe.

1. Introduction

In oil and gas industry, non-destructive testing (NDT) plays a crucial role in maintaining a safe and continual operation of its infrastructure. Metals are used in various infrastructures and utilities including pipelines and they are potentially subject to corrosion, and it has been reported that about 10 percent of the used metal is lost to corrosion [1].

In pipelines, one of the types of the corrosion that is commonly found is the corrosion under insulation, or CUI for short, which is very hard to detect by NDT techniques as it is hidden under the cladding and thick insulation layer. This corrosion mainly takes place due to the presence of moisture between the pipe and the insulation [2]. Going undetected, the presence of such corrosion in pipes can lead to tragic accidents [3], which unfortunately have happened in the past. For detection of CUI, the ultrasonic NDT techniques can be used, however they need a relatively long time due to the requirements for the insulation removal and surface preparation. These requirements also mean higher costs and, additionally, the removal of the insulation increases the chance of new surface contamination that may lead to corrosion [4] [5]. Therefore, an NDT technique that can detect this corrosion without removing the insulation and cladding will bring benefits to the industry.

PEC NDT uses a transient electromagnetic field to detect and evaluate both surface and sub-surface irregularities in various metal structures, including multi-layered ones. A rectangular or square excitation current is supplied to the excitation coil to generate a transient magnetic field that will, in turn, induce transient eddy currents inside the specimen. A secondary magnetic field is then induced by the eddy currents opposing the primary one. The net field, which is a combination of the field generated by the coil and the field induced by the eddy current, will then be detected by a sensing device [6]. The sensing device is generally located inside the excitation coil. Thanks to its low frequency components, with its high penetration capabilities PEC testing is ideal to be used in detecting CUI overcoming the need for the removal of the insulation. Therefore, this particular NDT technique cuts down the inspection time and costs [7].

The sensors that are commonly used in a PEC probe can generally be categorized into two types, which are inductive coils and magnetic sensors. The drawback for using and inductive coil as the sensor device is that it cannot detect DC magnetic field and it is less sensitive to low frequency fields. Its spatial resolution is also lower than that of a magnetic sensor generally. The inductive coil's output signal is proportional to the rate of change of the magnetic flux. In [8], it was shown that as the optimum sensitivity varies depending on the cross-section area of the coil and it is hard to find the actual sensitivity of an induction coil.

Magnetic sensors offer the benefit of having a better spatial resolution compared to inductive coils generally. There are many types of magnetic sensors, and the most common one among them are the Hall effect sensors [9]. These sensors are mostly used in as sensor to detect the speed in a wheel and the crankshaft detect the magnetic field by the Hall effect that is caused by the Lorenz force. Even Though, hall sensors are cheap and easy to integrate it in a circuit it has a high noise to signal ratio that restricts its sensitivity in a certain level [10].

Magnetoresistance (MR) sensor technologies provide major advantages compared to hall sensors. The flat frequency response of MR sensors, which ranges from DC to hundreds of MHz, makes them especially appealing for low-frequency and multi-frequency applications [11]. MR sensors exploit the magnetoresistive effect that was discovered by Lord Kelvin in 1857 but it was way later that the first MR sensor was introduced.

Magnetoresistance sensors are made up of a magnetic tunneling junction (MTJ) element, which mainly consists of three main layers where two of them are made of ferromagnetic material and the third layer that is an insulator is sandwiched between the other two layers. These sensors use quantum mechanical phenomenon as the electrons can make a quantum leap to tunnel through the insulator layer. The insulating layer is so thin that electrons can tunnel through the insulator layer if voltage is applied between the two metal electrodes across the insulator [12].

Among MR sensors the most common devices are anisotropic magnetoresistance (AMR) and giant magnetoresistance (GMR). They are mostly used in industrial position sensors, automotive sensors, cell phone compasses, and solid-state memories [13]. Nevertheless, the new developed magnetic sensors like tunnelling magnetoresistance (TMR) have been emerging in more applications due to its high sensitivity. TMR is the fourth generation of magnetoresistive made of an Fe/MgO/Fe-type magnetic MTJ [14]. Because of this MJT, TMR can achieve more than 200% of magnetoresistance variation at room temperature as compared to AMR and GMR where only 25% and 70% of magnetoresistance relative are achieved, respectively [15].

As described by Cheng [16], the gradient of the decay part of the signal can be used to infer the thickness of the sample when a magnetic sensor, instead of an inductive coil, is used in a PEC system. A similar signal feature is used in this work to determine the wall thickness, and in turn the performance of the new probe can be evaluated. A finite element model for PEC systems has been previously built to support the work, which has been discussed in our previous publication [17].

The most common sensors used in a PEC system are pickup signal coil and the Hall-Effect sensor, however, the accuracy of these sensors is not sufficient in detecting corrosion, the noise in the signals of the Hall-Effect sensor and the coil sensor are not suitable for industrial applications. Recently, Research towards improving sensitivity as well as analyzing and removing unwanted noise at low frequencies is still ongoing. Therefore, the Application of using TMR sensor inside the PEC probe can detect the thicknesses of ferromagnetic metal will achieve higher accuracy as this sensor compared to order sensors showed promising results with a 200% MR ratio, this new probe makes the PEC test more suitable in detecting CUI.

In the next section, the methodology of the research will be discussed. This includes the design of the probe and the experimental setup. Then, by using the probe's signal data obtained from the experiment, the performance of the probe is assessed. Finally, the conclusion is provided at the end of the paper.

2. Methodology

2.1. Probe design

The designing of a circular probe was carried out by using Solidworks CAD software. The excitation coil has inner and outer diameters and height of 7.73 mm, 10.57 mm, and 12.0 mm, respectively. It has 200 turns. The probe's coil and sensor holder were fabricated by using a 3D printer. In the middle of the probe, the TMR sensor is inserted into a special slot made to hold the sensor and its PCB. Figures 1 and 2 shows the 3D drawings and picture of the probe (without the TMR sensor holder), respectively.

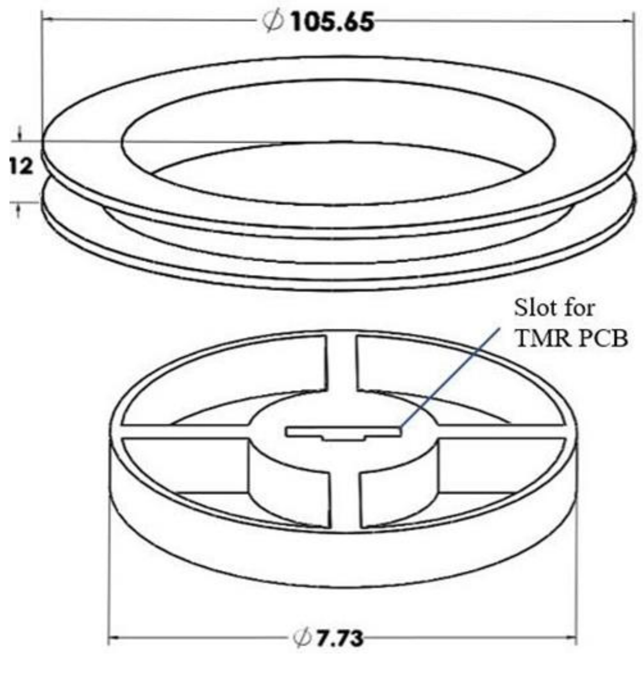


Figure 1. 3D drawing of our TMR-based PEC NDT probe. The top one is the coil former and the bottom one is the holder of the TMR PCB to position the TMR sensor at the centre of the coil. The holder will sit inside the coil former.

Figure 2. The fabricated PEC NDT probe with a slot at the centre where the TMR PCB will be inserted in order to place the sensor as centred as possible.

2.2. Data Acquisition system

A Sony Vaio PCG-41216W portable computer is used to implement the PEC system and to test the performance of the TMR sensor. An NI USB-6218 is used to for data acquisition which captures the TMR sensor's signals and the excitation coil's current at a sampling rate of 100 kS/s.

2.3. TMR SENSOR

TMR 2001 sensor that has a sensitivity of 80mV/V/mT is used in the probe. It comes in a chip size of 3 mm x 3 mm x 1.45 mm. A printed circuit board (PCB) has been designed by using an electronic design automation (EDA) software called Eagle. Figure 3 shows the PCB designed in Eagle. In this project, the PCB is used to mount the TMR sensor. The TMR sensor has a directional sensitivity as shown the figure and it should be vertically placed in the centre of the probe to get a positive reading. A 5V DC supply is used to power up the TMR sensor.

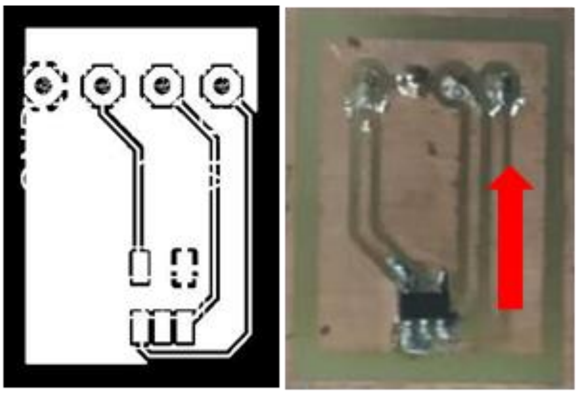
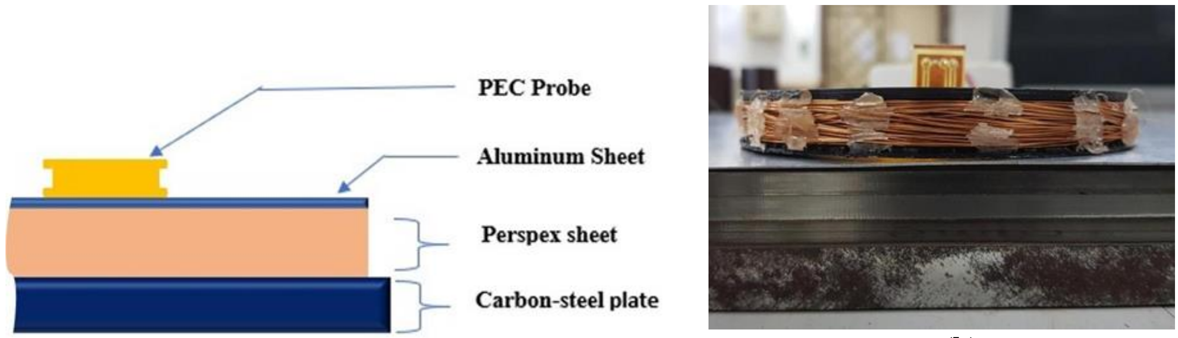


Figure 3. PCB for holding and connecting the TMR sensor was designed in Eagle Software, while the red arrow indicates direction of applied field that generates a positive output; (a) the PCB design and (b) a picture of the PCB

2.4. Experimental set-up of PEC and associated electrical systems

To evaluate the TMR sensor performance an experimental setup is devised. This setup consists of the power source and the excitation circuit, the probe, DAQ device, the specimen. In this experiment the PEC system is used to measure the thickness of ferromagnetic mild steel sheets. Figure 4(a) illustrates the structure of the experimental setup, while figure 4(b) display a picture of the setup. The probe is positioned on the aluminium sheet that represents the aluminium cladding in the real pipe structure. Its thickness is approximately 0.5 mm. Under the aluminium sheet, a Perspex sheet is used of the insulated pipe and how a PEC probe is positioned on the cladding. Perspex sheets have been used to represent the insulator layer in the actual pipe structure. A few Perspex sheets can be used and stacked to create thicknesses of 5 mm, 10 mm, and 15 mm.

Under the Perspex sheet, we have a mild steel sheet. In this experiment, five different mild steel sheets with the thicknesses of 8 mm to 12 mm with an interval of 1 mm have been used to evaluate the performance of this PEC prototype in detecting CUI. The 12-mm thick mild steel sheet is representing the sound pipe wall that has no corrosion. Corrosion will cause the change of the effective thickness and, therefore thinner sheets are used to simulate pipe walls with different levels of corrosion. The worse the corrosion the lower the thickness of the sample.



(a) (b)

Figure 4. The experimental sample setup: (a) Illustration of the experimental setup. The alumimum sheet simulates the aluminum cladding, the Perspex sheet simulates the insulation, while the carbon-steel plate is representing the wall of the pipe, (b) a picture of the actual setup.

The excitation circuit is used in this project to provide the excitation coil with pulses of excitation current. The external DC power source supplies a continuous 60V DC to the excitation circuit. Capacitors are used to assist the DC power supply to supply the required high current to the excitation coil. To generate the pulsed excitation current, a MOSFET controlled by the USB-6218 is used as a switch. Figures 5(a) and (b) illustrate the system block diagram and the overall experimental setup of the PEC system, respectively.

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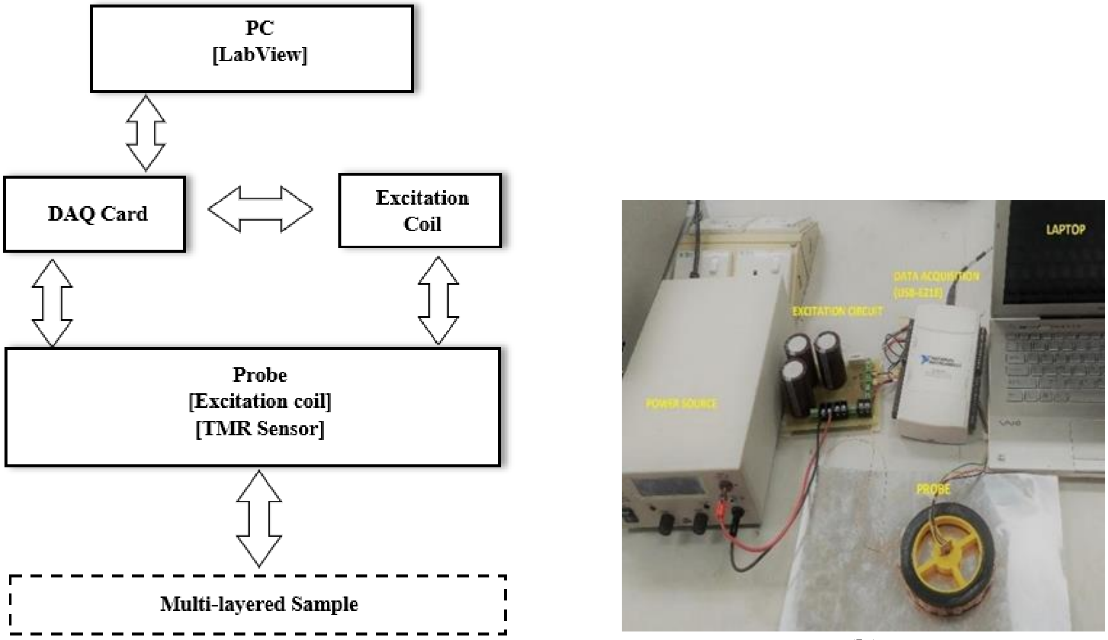

(a) **(b)**

Figure 5. The experimental setup of the TMR-based PEC NDT system (a) the block diagram, (b) a picture

2.5. Signal processing

The developed LabVIEW code running in the PC controls the data acquisition system to get the sensor's signal data and store them in the hard drive for further off-line analysis. To allow evaluation of the system, 120 readings for each mild steel sheet have been obtained, making a total of 600 readings. The position of the probe was varied randomly between each reading. Later, a signal averaging will be carried out to achieve the prediction of the thicknesses of the mild steel plates. To predict the thicknesses, a feature based on the decay signal, called the decay coefficient, is calculated from each signal. The decay coefficient (λ) of the signal is defined as the reciprocal of the gradient of the signal in the logarithmic scale [17]. This is the signal feature that will be used in this work to infer the sample thickness.

3. Results

Figure 6 shows the comparison of two different thicknesses of ferromagnetic plates, which are 8 mm and the 9 mm, where stand-off was varied at 1, 10 and 15 mm for each ferromagnetic plate. As shown in the graph there are significant differences in the signals between the two thicknesses of the two ferromagnetic plates, while on the other hand, the changes in the lift-off does not have a great effect on the signal of that specific ferromagnetic thickness. The other three mild steel plate thicknesses also show similar patterns. These results underline that this decay property can be used for getting the thickness of the plate relatively consistently despite the variation of the stand-off.

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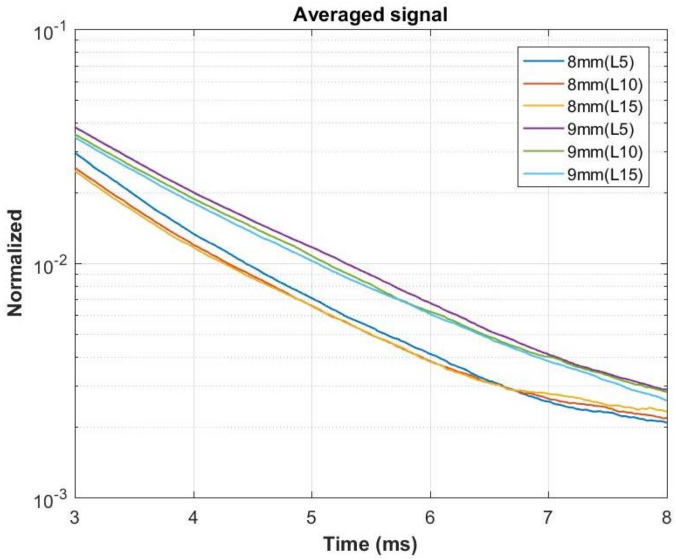


Figure 6. Comparison of the averaged signals from 8-mm and 9-mm-thick plates with stand-offs of 5 mm, 10 mm, and 15 mm.

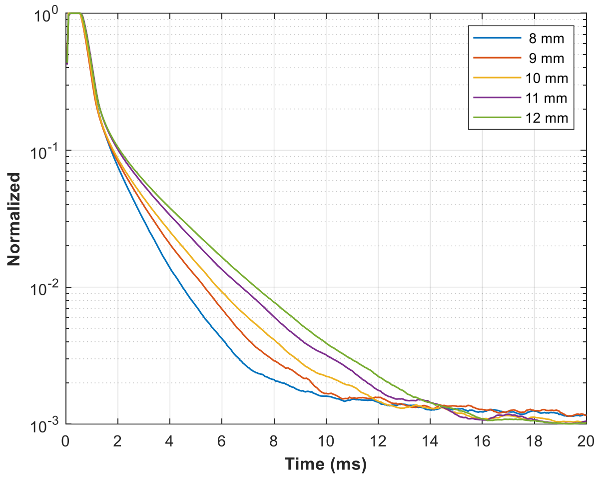
Figure 7(a) shows the averaged signals in the logarithmic scale, only the falling edge part will be used to compute the thickness of the ferromagnetic sample. As shown in the figure and described in the previous paragraph, there are significant differences between the different thicknesses, on the other hand, the change in the lift-off does not have a great effect on the signal of that specific ferromagnetic thickness. The plots suggest that the gradients in the signal in the time window starting from 2 ms up to 6 ms approximately can be used for good discrimination and determination of the thicknesses. Figure 7(b) shows the zoomed-in of this segment of the signal to show more clearly the differences in the signals and that they demonstrate relatively straight lines.

Figure 8 illustrates the decay coefficients of the averaged signals that were obtained from the sensor against the carbon steel plates thicknesses. Again, the plot shows that the lift-off has negligible effects on the decay coefficient. The relation between the decay coefficient and the thickness can be used to predict the thickness when the decay coefficient of an acquired signal has been obtained.

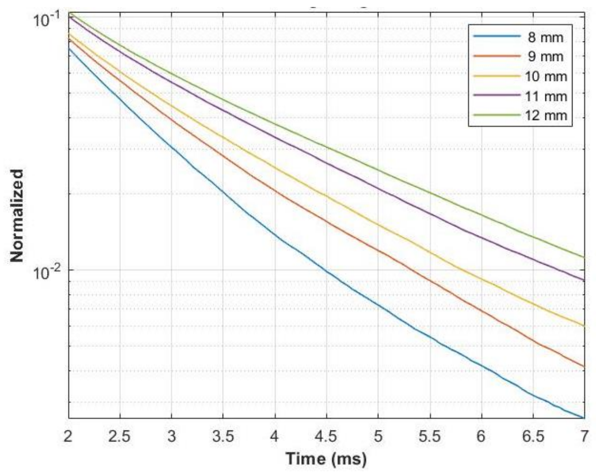
From the one-to-one mapping of the decay coefficient and thickness of the carbon steel sample, we derived the following quadratic equation:

$$\boldsymbol{T} = 187.192\, \boldsymbol{d}^2 + 128.477\, \boldsymbol{d} + 29.886 \tag{1}$$

where $\boldsymbol{T}$ is the thickness in mm and $\boldsymbol{d}$ is the decay coefficient, which is 1/gradient of the signal's segment.



(a)



(b)

Figure 7. Average signals of different thicknesses carbon steel plates with different lift-offs: (a) the original signals (b) the segment of the images whose gradients are used for determining the thickness of the sample under test.

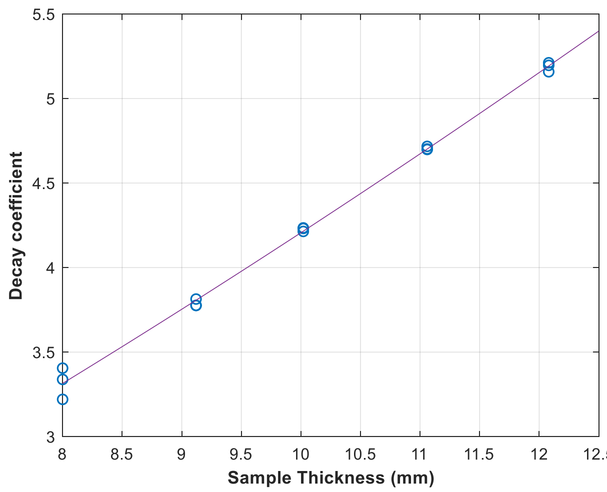


Figure 8. Plot of calculated decay coefficients for different thicknesses and lift-offs vs sample thicknesses

Table 1 and Figure 9 show the performance metrics of the new probe. They show that the probe has been successfully producing signals that can be used to predict the thickness of the sample, which represents a pipe wall with different corrosion levels. The mean absolute error (MAE) and the standard deviation of the errors have been found to be 0.20 mm and 0.25 mm respectively, while the overall MAE is 0.19 mm, which is better than what we have seen before with our Hall-device-based probe that has a MAE of 0.35 mm [17].

Table 1. Performance test results

Actual Thickness (mm)	Mean Predicted Thickness (mm)	Mean Absolute Error (mm)	Standard Deviation of Error (mm)
8.1	7.8	0.26	0.28
9.1	8.4	0.25	0.29
10.0	9.4	0.16	0.19
11.1	10.7	0.14	0.17
12.1	11.6	0.16	0.20
	Overall	0.19	0.25

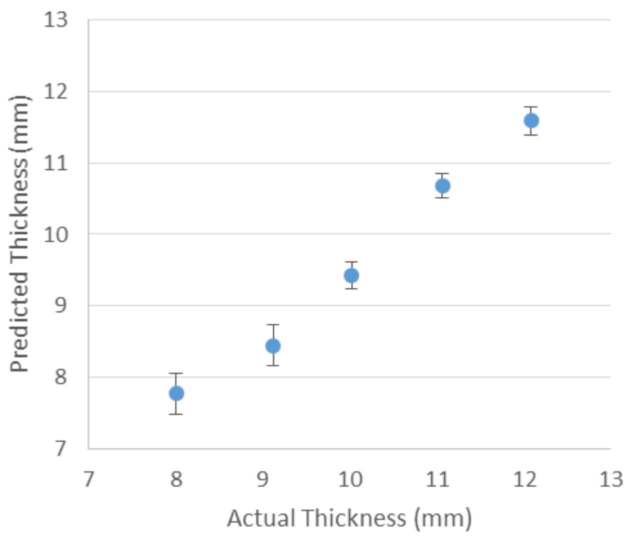


Figure 9. Plot of predicted vs actual thicknesses. The error bar represents the standard deviation of the errors.

4. Conclusion

Corrosion under insulation (CUI) presents a challenging problem for NDT, especially if the test is to be done without removing both the cladding and insulation. Pulsed eddy current (PEC) NDT has been identified the most effective technique todays. In this paper, a new PEC probe design that uses a TMR sensor that has a high sensitivity has been presented. To the authors' knowledge, the use of a TMR sensor in such a PEC NDT system is the first one that has been reported in a research article. The results are very promising, especially when they are compared to those obtained by using Hall devices that we have reported previously. A relatively low mean absolute error (MAE) of 0.20 mm for the TMR- based probe has been found in this study. This is potentially exploited in the future work to implement a PEC NDT system that can be used in the real industrial setting.

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