

# Effects of Coil Diameter in Thickness Measurement Using Pulsed Eddy Current Non-destructive Testing

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**Abstract.** Non-destructive testing (NDT) techniques are used in industry to evaluate the properties of a material, component or structure without causing any permanent damage. Among the techniques, pulsed eddy current (PEC) NDT is regarded as a new technique where a broadband pulse excitation is used, as opposed to single frequencies employed in conventional eddy current NDT. In this study, a 2D axisymmetric electromagnetic model of a PEC probe has been developed and it has been used to study the effects of the excitation coil diameter on the performance of PEC probes in sample thickness measurement. A PEC system has also been built to validate the model. Aluminium plates are used as the sample and they can be stacked up to replicate thickness from 1 mm to 10 mm. The results show that there is a very good correlation between the simulation and experimental results, with an average error of less than 10%. The results also suggest that the larger the diameter of the excitation coil, the deeper the penetration and therefore the larger the thickness measurement range. It has also been shown that although the larger diameters have deeper penetration, the smallest diameter has the highest sensitivity if normalization is not used. These conclusions indicate that coil diameter is an important parameter in a PEC probe design for thickness measurement applications.

## 1. Introduction

Non-destructive testing (NDT) technologies are widely used in various types of industries such as aerospace, manufacturing, automotive, construction, military, oil and gas to characterize material properties, detect and characterize the flaws in structures or materials. NDT applications assure that the tested materials are not damaged during the testing so that their future usage is not affected. Safety, quality and operational costs benefit greatly from the use of NDT.

Pulsed eddy current (PEC) is in general still considered as a new emerging technique in non-destructive testing and evaluation (NDT&E). Being a member of eddy current testing (ECT) family, PEC shares the advantages of ECT, such as reliability and minimal preparation of samples. PEC has been employed in detection and characterization of defects, measurement of stress and measurement of thickness, among others [1]. The advantage of the PEC technique comes with its wide bandwidth of excitation frequencies that are excited simultaneously.

An example of the work in PEC for thickness measurement is [2], where Q235 steel plates with a thickness of up to 30 mm was measured. Shin et al. also investigated thickness measurement for different materials, including copper and titanium [3]. Röntgen Technische Dienst's PEC system is capable of measuring the wall thickness made of low alloy carbon steel of up to 65 mm [4]. Other works done on thickness measurement for wall thickness of pipes include [5], [6], [7], and [8].



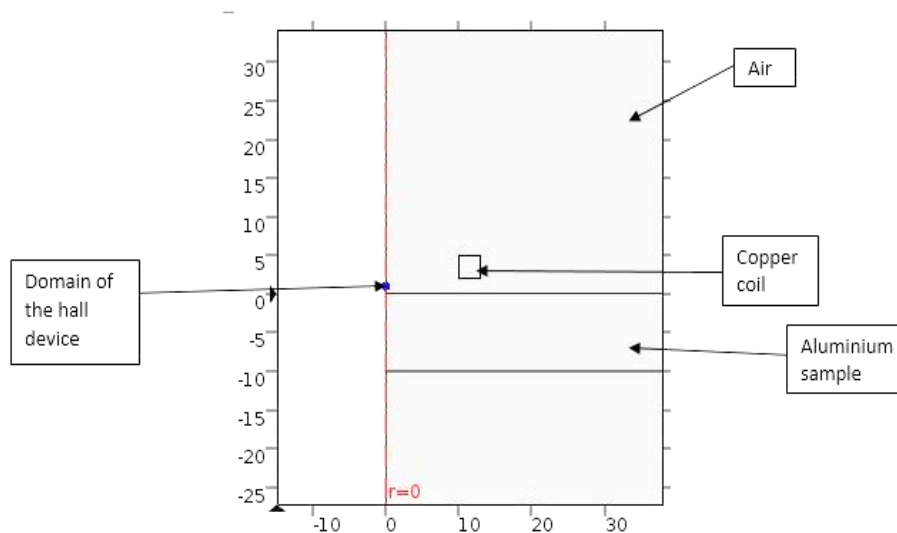
The success of thickness measurement by using PEC depends on the depth of penetration of the induced eddy currents, which is affected by many factors, such as the height of the coil, the number of turns and the lift-off. The understanding on the effects of these parameters is paramount for designing an optimum PEC probe. The depth of penetration is increased when the height of the coil is increased although the magnetic field density is decreased at the surface of the material. The number of turns of the coil is very important in determining the strength of the magnetic field generated by the coil. However, it has been reported that the number of turns does not affect the depth of penetration [9]. Only the strength and sensitivity will be affected by varying the number of turns of the coil. The effect of another parameter, which is the lift-off, on depth of penetration has been studied by Janoušek [10], who found that the larger the lift-off, the higher the depth of penetration but results in lower sensitivity.

The aim of this work is to investigate the relation between PEC's excitation coil diameter and the depth of penetration and the sensitivity in thickness measurement of non-ferromagnetic metallic samples. The study will be carried out through both finite element modelling and experimental tests. In the following sections, the modelling, experimental setup and results will be described. Discussion and conclusions are presented subsequently.

## 2. Modelling

In this study, a 2D axisymmetric finite element model has been built by using Comsol, as illustrated in figure 1. The model includes an excitation coil and an aluminium plate as the sample that has an electrical conductivity of  $26.33 \times 10^6$  S/m. The number of turns is fixed at 144 turns while the coil current is 3A. The sample's thickness is varied from 1 mm up to 10 mm with an increment of 1 mm. The dimension of the plate is 130 mm x 130 mm. The magnetic flux density is measured at the coordinate (0, 1) mm.

Initially, the simulation was started with 20 mm diameter of coil with sample thickness of 1 mm. Then, the thickness of the sample was increased by 1 mm until it reached 10 mm. Subsequently, the same steps were repeated for coil diameters of 30 mm and 40 mm.

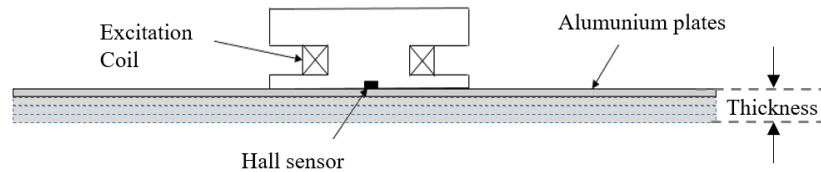


**Figure 1.** The Geometry of the 2D axisymmetric Model

## 3. Experimental Setup

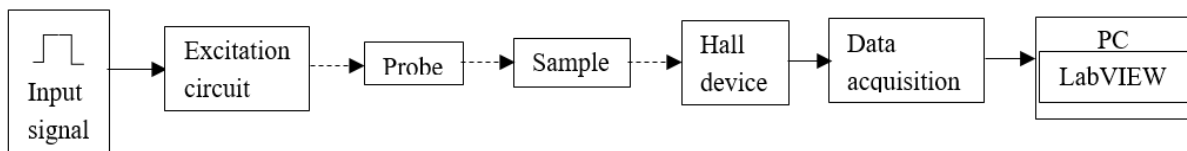
A PEC system has been implemented for the experimental setup that will be used to gather data for validating the built model. The steady-state excitation current is 3 A. Probes of different diameters have been built, where each of them contains an excitation coil and a sensing device. The coil bobbin was made by using a 3D printer. The excitation coil windings use copper wire and have 144 turns. A Hall-device (A1324) with a sensitivity of 5mV/G has been used in each probe. Figure 2 shows the

illustration of the probe and the sample. For the specimens, aluminium plates have been used whose dimensions are 130 mm x 130 mm x 1 mm. Different sample thicknesses were achieved by stacking the plates up accordingly.



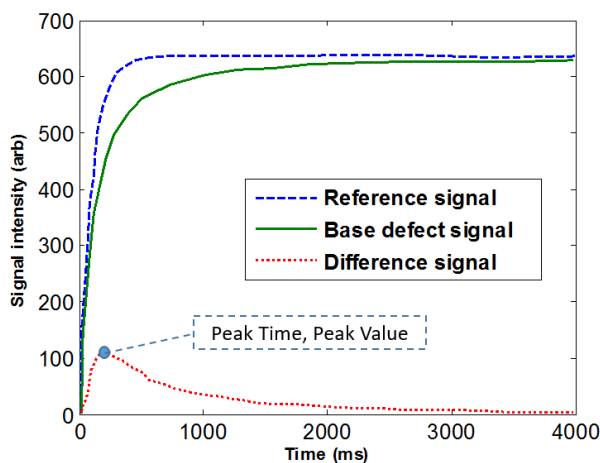
**Figure 2.** Set-up of the Experiment

For acquisition of the transient magnetic field signals, a data acquisition (DAQ) system was used with a sampling frequency of 50 kHz. The data of the magnetic flux density has been recorded for each variation of thickness by using a LabVIEW-based application. Figure 3 shows the block diagram of the overall system. The DAQ card was also used to generate the excitation signal with 1 Hz frequency and 0.5% duty cycle. The low duty cycle was chosen to minimize the heating effects of the coil and the components within the excitation circuit.



**Figure 3.** System Block Diagram

For thickness measurement in this study, the parameter to be used is the peak value of the differential PEC signal [1], which is illustrated in Figure 4.



**Figure 4.** Typical PEC Signals: Base, Reference and Differential

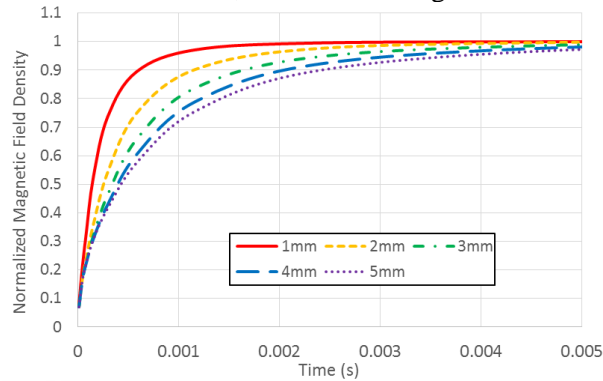
#### 4. Results and Discussion

In order to compare the trend of the peak values for different thicknesses, normalization of the measured magnetic field signals has been used to reduce the effects of the excitation current variations during the tests. The normalized PEC signals were calculated as

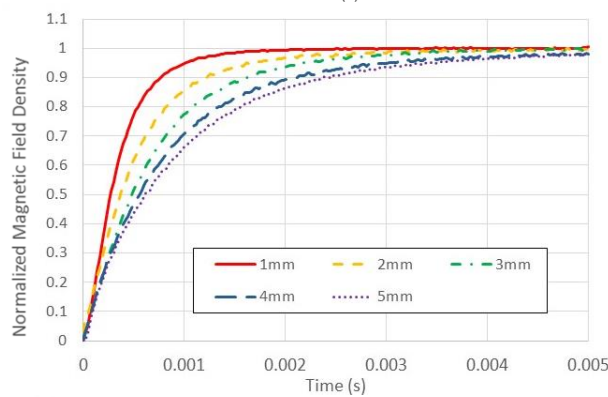
$$B_{norm}(t) = \frac{B(t)}{B_{ss}} \quad (1)$$

, where  $B_{norm}$  is the normalized magnetic field density,  $B$  is the measured magnetic field density and  $B_{ss}$  is its steady state value. Signal normalization is commonly used in PEC.

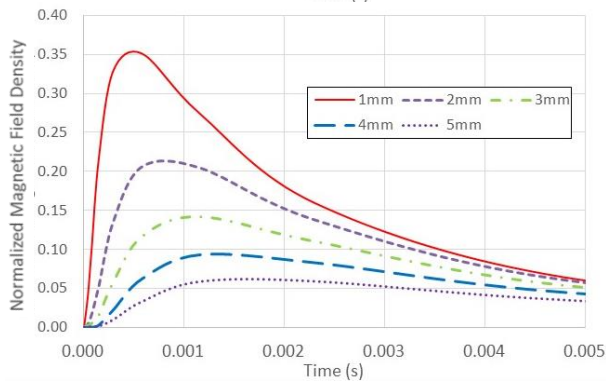
Figures 5 and 6 show typical normalization results obtained by using both simulation and experiment, which show that both sets of results show similar trends in the transient magnetic field density. The rate of change of the magnetic flux density decreases when the thickness of the plate is increased. However, the rate of change increases when the coil diameter is increased.



**Figure 5.** Normalized Signals from the 30-mm-Diameter Probe (Simulation)



**Figure 6.** Normalized Signals from the 30-mm-Diameter Probe (Experiment)

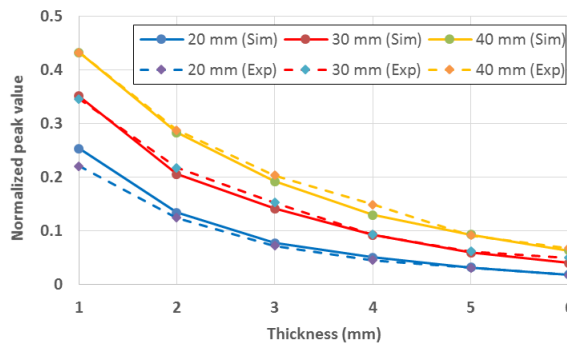


**Figure 7.** Examples of the Resulting Differential Signals (Simulation)

Figure 7 shows typical differential signals, which were derived by subtracting the normalized reference signal from the normalized response signal. The reference signal used was the signal obtained from the sample thickness of 10 mm. It can be clearly seen that the intensity of the differential signal is higher for lower thicknesses.

#### 4.1. Model Validation

The peak values were then extracted from the differential signal obtained through both experiment and simulation, which are plotted in Figure 8 and tabulated in Table 1, which also highlights the good correlation between the simulation and the experiment with most of the errors are less than 10%. This result indicates that the developed model is reliable to be used in further analysis and prediction of thickness measurement and depth of penetration.



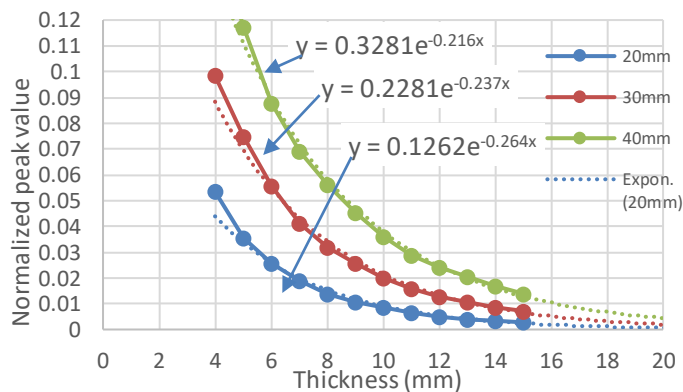
**Figure 8.** Normalized Peak Values vs. Sample Thickness for Different Coil Diameters (Simulation and Experiment)

**Table 1.** Peak Values from Both Simulation and Experiment

		Normalized Peak Value (no unit)								
Probe diameter →		20mm			30mm			40mm		
Method →		Simula- tion	Experi- ment	Error (%)	Simula- tion	Experi- ment	Error (%)	Simula- tion	Experi- ment	Error (%)
Sample Thickness (mm)	1	0.254	0.220	-13.0	0.351	0.346	-1.4	0.432	0.432	0.0
	2	0.134	0.124	-7.6	0.206	0.218	5.8	0.283	0.288	1.6
	3	0.078	0.073	-6.7	0.142	0.153	7.9	0.192	0.203	5.8
	4	0.051	0.046	-9.6	0.093	0.093	0.3	0.130	0.149	14.8
	5	0.032	0.031	-3.9	0.060	0.062	4.4	0.093	0.092	-1.7
	6	0.019	0.018	-6.9	0.041	0.050	23.8	0.064	0.068	6.8

#### 4.2. Range of Thickness Measurement

By using the model, the relationship between the normalized peak value and the thickness was derived for each coil diameter, as can be seen in figure 9.



**Figure 9.** Plots of the Peak Values vs Thicknesses with their Exponential Curve-fittings (Based on Simulation Results)

In order to determine the range of measurement, a signal-to-noise ratio of 3 was assumed. Due to different field strengths of the coils, the minimum normalized for each coil diameter is different and shown in table 2. The table shows that the range of measurement gets higher as the diameter is increased. It shows that if the area of induced eddy currents is larger on the surface of the sample, then the eddy currents penetrate deeper into the sample.

**Table 2.** Prediction of the Maximum Measurable Thickness

Coil Diameter	20 mm	30 mm	40 mm
Steady State Value (T)	0.0219	0.0155	0.0123
Min Peak Value (V), SNR = 3	0.0106		
Min Peak Field Density (T), SNR = 3	0.00021		
Min Normalized Peak Value, SNR = 3	0.0097	0.0136	0.0171
Predicted Max Thickness (mm)	9.7	11.9	13.6

#### 4.3. Sensitivity

Although the largest diameter has the largest measurement range, the smallest diameter looks to have the highest sensitivity for thinner sample measurement when normalization is not used. This can be seen from the change in the measured field density when the thickness is changed from 1 to 2 mm, which shows the 20-mm-diameter coil has the highest change, as can be seen in Table 3. This is in contrast to the thickness change from 6 to 7 mm, where the 40-mm-diameter coil has the highest output change. Therefore, it can be concluded that the sensitivity of the probe does not only depend on the diameter, but only on the measured thickness range.

**Table 3.** Sensitivity in Different Thickness Ranges

Thickness change →		$\Delta B$ (T)	
		1 mm - 2mm	6 mm - 7 mm
Coil diameter (mm)	20	0.00276	0.00012
	30	0.00235	0.00022
	40	0.00185	0.00027

#### 5. Conclusion

A few conclusions can be drawn from the results obtained in this work. Firstly, the 2D axisymmetric model has been validated by the experimental results with an average error of less than 10%, indicating that it is a useful and reliable tool for predicting the performance of a PEC probe design in sample thickness measurement. Secondly, the larger the diameter of the excitation coil, the deeper the penetration and therefore the larger the thickness measurement range. Thirdly, although the larger diameters have deeper penetration, the smallest diameter has the highest sensitivity if normalization is not used. Overall, the work shows that coil diameter is an important parameter the optimization of a PEC probe design.

#### References

- [1] Sophian A, Tian G and Fan M 2017 Pulsed Eddy Current Non-destructive Testing and Evaluation: A Review *Chinese J. Mech. Eng.* **30** 500–14
- [2] Huang C and Wu X 2015 An improved ferromagnetic material pulsed eddy current testing signal processing method based on numerical cumulative integration *NDT E Int.* **69** 35–9
- [3] Shin Y-K, Choi D-M, Kim Y-J and Lee S-S 2009 Signal characteristics of differential-pulsed eddy current sensors in the evaluation of plate thickness *NDT E Int.* **42** 215–21
- [4] Robers M A and Scottini R 2002 Pulsed Eddy Currents in Corrosion Detection *NDT.net* **7**
- [5] Chen X and Lei Y 2014 Time-domain analytical solutions to pulsed eddy current field excited by a probe coil outside a conducting ferromagnetic pipe *NDT E Int.* **68** 22–7
- [6] Xu Z, Wu X, Li J and Kang Y 2012 Assessment of wall thinning in insulated ferromagnetic pipes using the time-to-peak of differential pulsed eddy-current testing signals *NDT E Int.* **51** 24–9
- [7] Xie S, Chen Z, Takagi T and Uchimoto T 2015 Quantitative non-destructive evaluation of wall thinning defect in double-layer pipe of nuclear power plants using pulsed ECT method *NDT E Int.* **75** 87–95
- [8] Park D G, Angani C S, Kim G D, Kim C G and Cheong Y M 2009 Evaluation of Pulsed Eddy Current Response and Detection of the Thickness Variation in the Stainless Steel *IEEE Trans. Magn.* **45** 3893–6
- [9] Majidnia S, Nilavalan R and Rudlin J 2016 A numerical study of the depth of penetration of eddy currents *Insight - Non-Destructive Test. Cond. Monit.* **58** 129–34
- [10] Janoušek L 2012 Impact of selected parameters on eddy current attenuation in conductive materials *2012 ELEKTRO* 419–22