

2.5D Finite Element Analysis of Differential Coils

Bobby T.R. Freer

Faculty of Applied Design & Engineering, Mount Pleasant Swansea University of Wales Trinity ST David
Phone: +44(0)1792 481000 (UWTSD) Non-Destructive Testing & Evaluation.
bfreer.141566@student.uwtsd.ac.uk

Abstract

This paper describes the use of a differential eddy current coil finite element software package, FEMM used to simulate how differential coils will react when encountering material defects. The setup used a standard differential coil setup with a 100 turns on each coil inspecting a 2.5mm thick plate. Two scenarios were examined as to how the setup reacted when encountering two different sizes defects of 1mm and 1.5mm depth. Mesh optimisation is examined to find a trade-off is made between accuracy and time of simulations. Data was then recorded and graphically plotted where it was found that the original set up had a standard depth of penetration of 470mm, to adjust for this the equation used was rearranged for frequency to see what the optimal frequency of a 1.5mm defect response would be. It was then determined that to get accurate results for the relationship between frequency and depth of penetration in differential coils further equations and more complex mathematics may be needed.

Keywords: MFL, Magnetic Flux Leakage, Coil, Inspection, Eddy Current, Finite Element Simulation, FEMM, Current Density, Mesh Optimisation, Saturation, Magnetization, Finite Element Analysis, 2.5D

1. Introduction

Differential coils are used in Non-Destructive Testing (NDT) to detect small sized flaws and material discontinuity. This paper discusses a finite element analysis study for a simulated differential coil eddy current inspection using two coils with the same amount of turns and diameter. Prior to the analyses of the differential coil mesh-optimisation was ran to gauge a trade-off between data-accuracy and computational time, this gave the most efficient mesh density to run.

The simulation of how a defect will influence the differential coils at different regions will be analysed and how the coils will give different readings. Also, optimum frequency and phase angle changes will be evaluated to determine who to get the most from the set-up.

2. Informative Literature

2.1 Differential Coils

Differential eddy current probes have two active coils typically wound in opposition, when these coils are located over an area of continuity (or a flaw free area) there will be no differential signal between the coils and both coils will give the same response as one another. But, when a defect is introduced into the region of one of the coils there will be a difference in readings, due to one coil experiencing material continuity and the other coil experiencing influence from a defect, hence the name differential coils.

Differential coils are very sensitive to defects, yet insensitive to slow changing geometry's and temperature variations. But on the other hand, a disadvantage of differential coils is that signals can be difficult to interpret if the flaw in question is larger than the space in-between the coils, in this scenario only the leading and trailing edges of the defect would be detected

as both coils will be reading the same discontinuity between one another. Therefore, this approach of testing will require a prior knowledge as to what defects one may find (www.nde-ed.org, 2015).

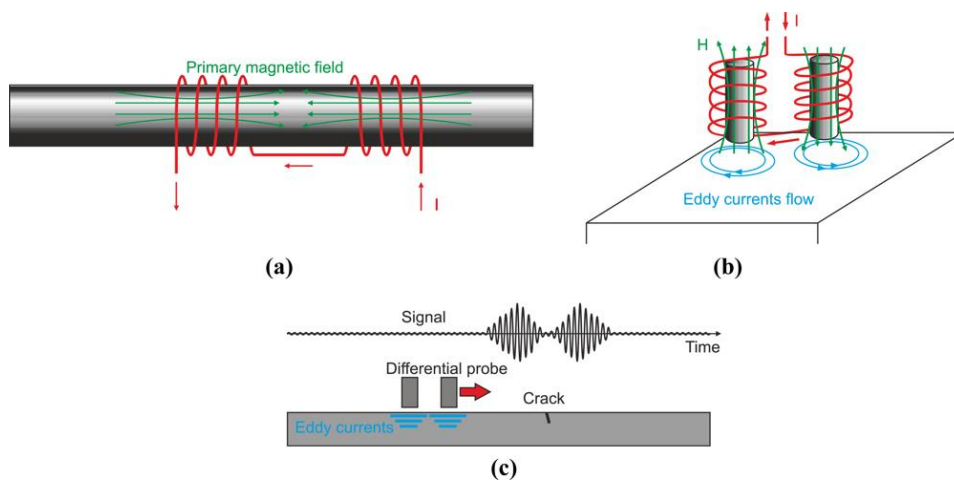
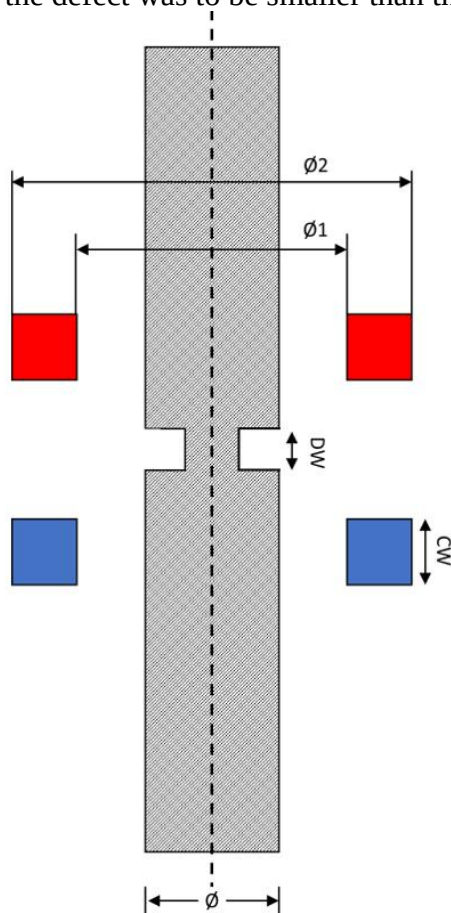


Figure 1 Differential Coils
(www.mdpi.com, 2016)

3. Model Configuration

The model created represents an axisymmetric model as the figure below displays. The coils were spaced 2mm apart, which meant that there would be differential readings from the coil as the defect was to be smaller than the distance between the coils.



Materials;
Coils: Copper Wire
Rod: Titanium

Coil Parameters:
Turns: 100
Current: 1A
Frequency: 20Khz

Dimensions:
 $\varnothing$: 5mm
 $\varnothing 1$: 6mm
 $\varnothing 2$: 12mm
CW: 4mm

Defect:
DW: 0.5mm
Depth of 1mm & 1.5mm

Figure 2 Model Configuration

3.1 Coil Check

Before looking to run simulations on the set-up created the coil configuration would be checked, as is the nature of differential coils one must first know that when the coils are encountering a material with continuity that they will give the same readings.

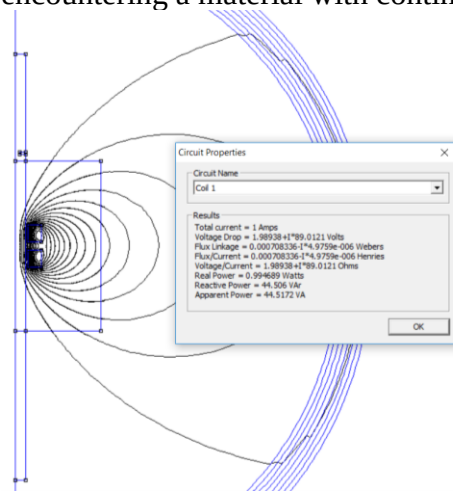


Figure 3 Coil Equilibrium Reference

	Coil 1	Coil 2
R	1.98938	1.98398
XL	89.0121	89.0121

Here it was found from taking readings on both coils that they read the same values of R and XL, therefore displaying the configuration is set-up correctly.

3.2 Mesh Optimisation

Mesh optimisation will give graphical comparison of mesh density sizes on a given model to evaluate the accuracy of results produced by the software and the computing time taken. For this comparison a boundary was created around the differential coil model (section 3.2), within this boundary layer areas of interest were decided to have a finer mesh applied than other areas which are not of interest, i.e. the air around the outside of the boundary. After changing the mesh density and running simulations at different densities data was recorded in the form of tables and then converted into a graphical representation.

From running simulations with the stated setup, the mesh density was changed on each simulation then plotted against the magnetic field energy to evaluate a trade-off between computational time and accuracy. Results from this are displayed in Table 1 below.

It is displayed in figure 4 that when we reach a mesh density of 0.1 we do not see the results significantly increase, but near flatline with only computational time increasing rather than accuracy. Therefore, a mesh density of 0.1 was chosen for the simulations.

Table 1 Recorded Simulation Data

Mesh Density-Nodes	Mesh density	Magnetic field energy (Joules)	Time (minutes)
7871	1	1.62070E-04	1 second
15533	0.5	1.62130E-04	1 second
161581	0.1	1.62256E-04	5 seconds
393729	0.08	1.62258E-04	30 seconds
509403	0.07	1.62259E-04	1 minute
687771	0.06	1.62260E-04	3 minutes

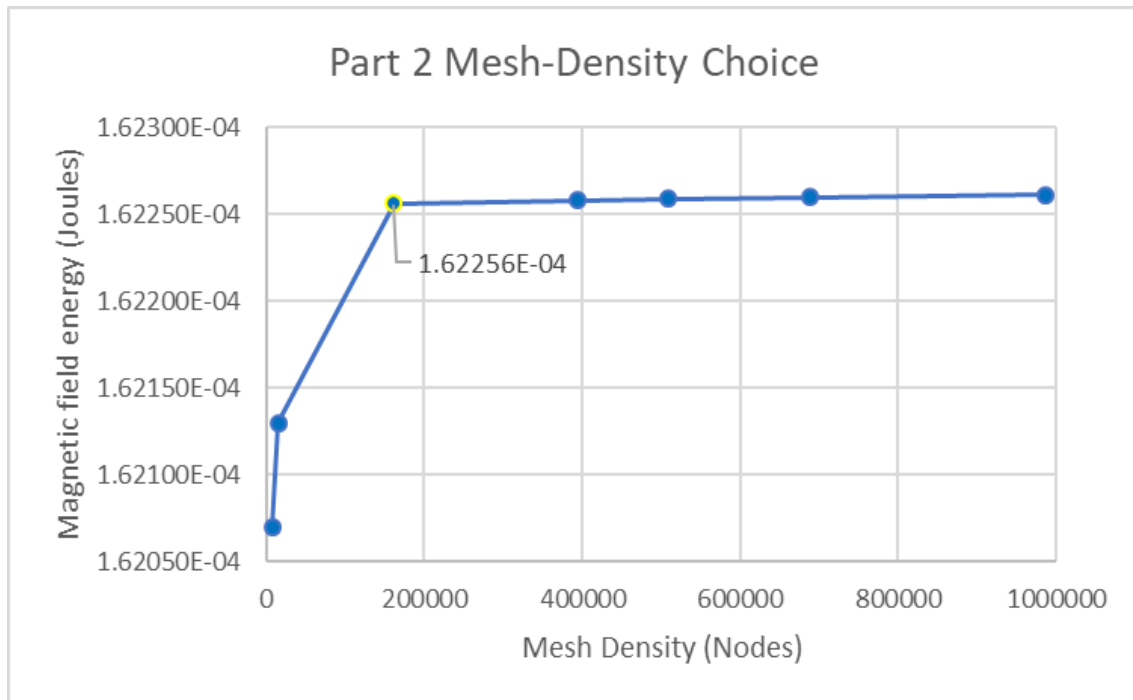


Figure 4 Mesh Density

3.2 Mesh Boundaries

A box was created around the region of interest of dimensions, 40 x 20 mm. This box size was created as this is where the lines of flux dropped off (see appendix 1). The software also created its own boundary of which to concentrate a mesh density, this boundary created by the software was set to a given triangulated coarse mesh size as it was agreed it would not affect the results which is in the box created.

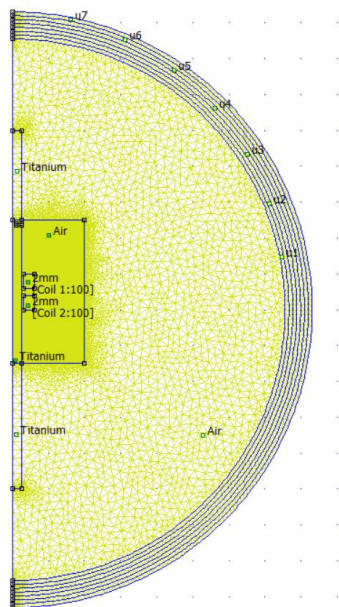


Figure 5 Mesh Boundaries Example 1

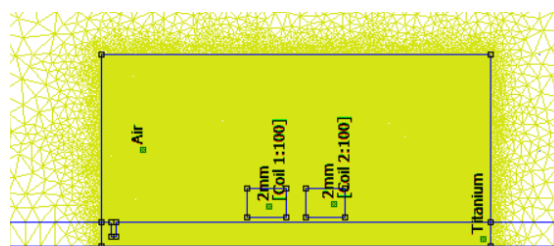


Figure 6 Mesh Boundaries Example 2

4. Results & Analysis

4.1 Resolution Chosen

For the first set of simulations the defect was placed 1mm inside the 40x20mm box. Using a resolution of 2mm increments, then once the coils begin to see influence a 1mm resolution was used. The decision to change to 1mm increments came when the coils stopped giving the same readings of XL (AC resistance) and R (resistance), once this happened it was clear that one of the coil was being influenced from the defect.

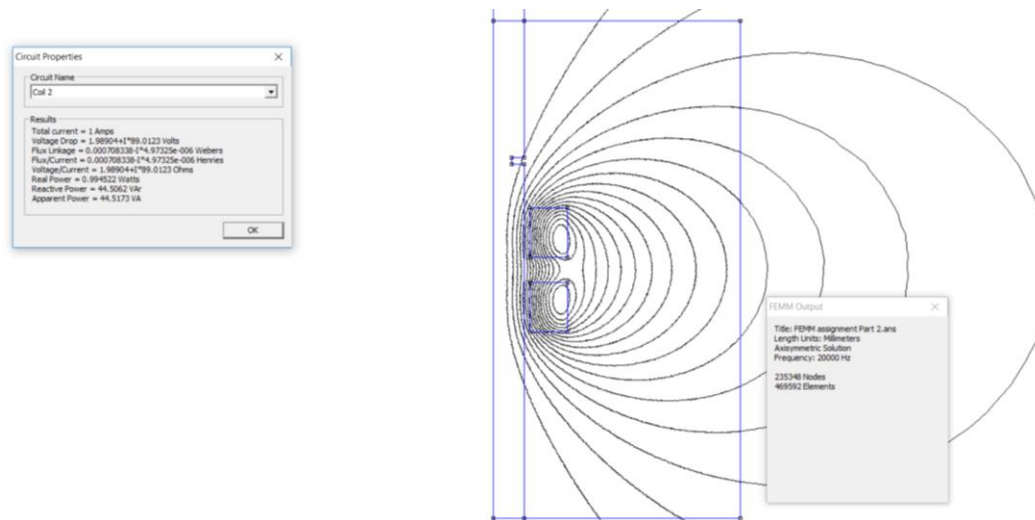


Figure 7 Resolution Choice

The figure above shows where the defect is starting to enter the field the coils are producing, therefore some influence on the coils readings could now be expected in this region.

When running the second defect it was decided to pick the most important points that were graphed from the first defect. So rather than again run 26 simulations which gave a lot of unnecessary data, it was decided that only 16 of these points were valid to give a graphical solution, therefore just these points were ran (see appendix 2).

4.2 1mm Defect

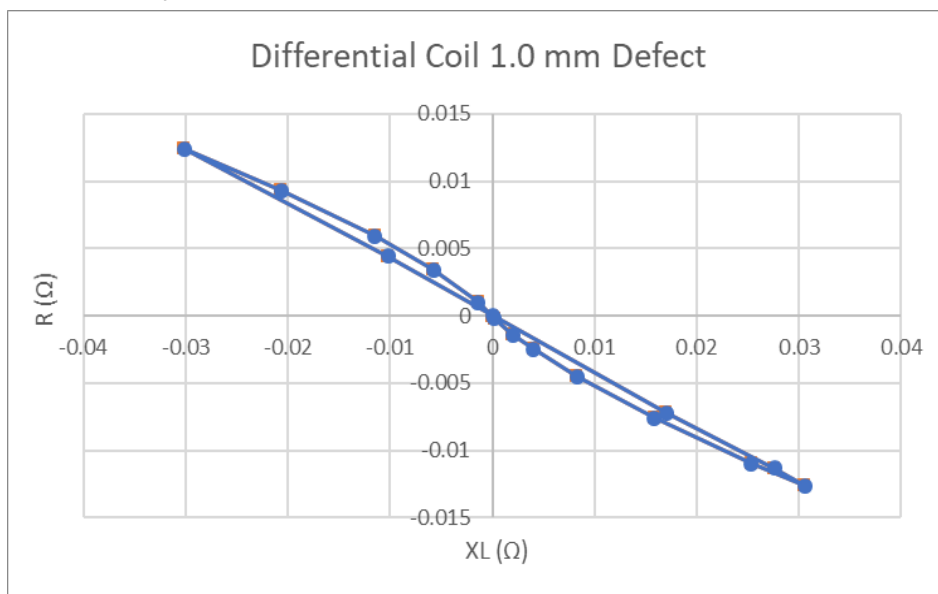


Figure 8 1mm Defect Response

Figure 8 shows the differential coil readings over the 1mm defect. Here a narrow figure of eight has been produced due to the fact that at the zero point of the graph the defect is directly between the two coils, and as previously stated the defect being smaller than the two coils meaning that at some point where the defect is between the coils there will be a reading of 0 as both coils are giving the same reading.

4.3 1.5mm Defect

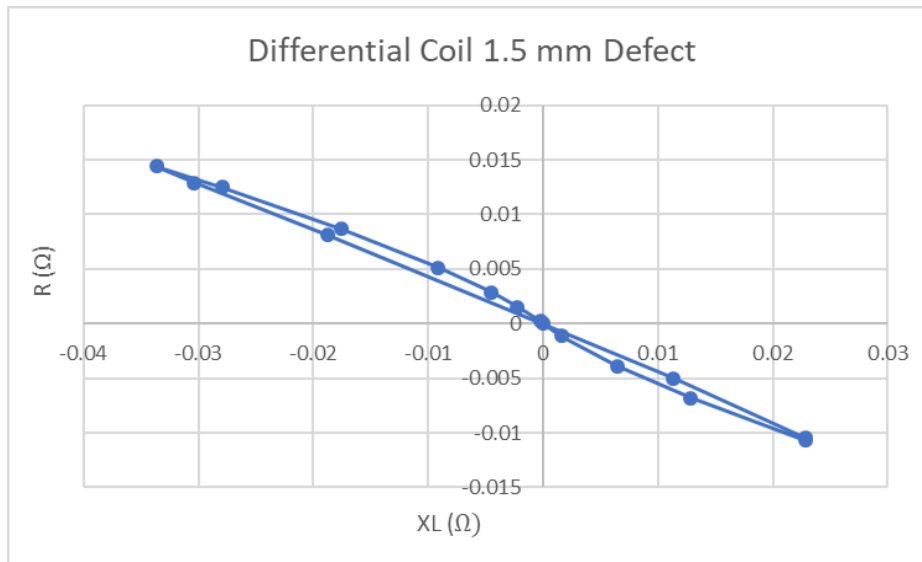


Figure 9 1.5mm Defect Response

Figure 9 above shows the slightly deeper 1.5mm defect, from this graph a similar pattern can be seen where there is a point that the defect travelling between the coils has read zero. There is also wider readings of XL and R which was expected in this deeper defect as there was to be more differentiation in the readings between the coils in comparison to the 1mm defect.

4.4 Defect Comparison

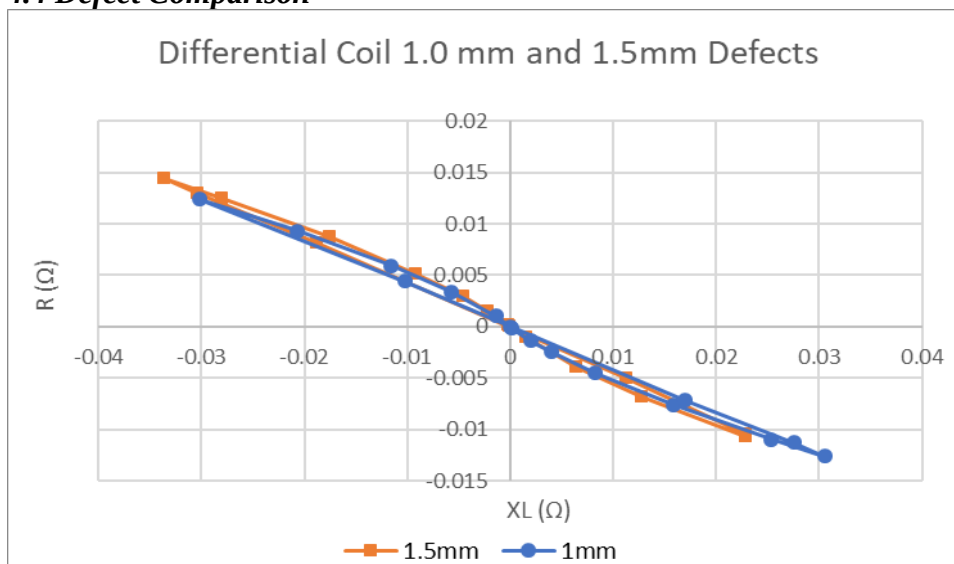


Figure 10 Defect Response Comparison

Figure 10 above shows the comparison of the of the two defect responses. Although there is not large variation it can be noticed that the deeper defect has gave higher signal response.

4.5 Standard Depth of Penetration & Frequency

To check whether the set up is running the optimum frequency a simple calculation of *depth penetration* of can be rearranged. First the penetration for the current setup can be calculated to see what is the range of defect depth that will be visible;

δ =Standard Depth of Penetration (mm)

f = Test Frequency (Hz)

μ_r = Relative Permeability (dimensionless, = 1 for non-ferrous materials)

σ = Electrical Conductivity (% IACS)

$$\delta_{mm} = \frac{661}{\sqrt{f \mu_r \sigma}}$$

$$\delta_{mm} = \frac{661}{\sqrt{(20 \times 10^3) * 1 * 98.6}} = 470.70 * 10^{-3}$$

Therefore, the standard depth of penetration is 470mm. As there is only a 2.5 mm thick piece of plate being tested it shows that the current setup is over calculated. If the frequency is changed taking into account, the largest possible defect size of 1.5mm a more reasonable standard depth of penetration can be found in the setup;

$$(\delta_{mm})^2 = \frac{661^2}{f \mu_r \sigma}$$

$$f(\delta_{mm})^2 = \frac{661^2}{\mu_r \sigma}$$

$$f = \frac{661^2}{(\delta_{mm})^2 \mu_r \sigma}$$

$$f = \frac{661^2}{(2.25)(1)(98.6)} = \frac{661^2}{(2.25)(1)(98.6)} = \frac{661^2}{221.85} = 1969\text{HZ}$$

Now figures 11 and 12 on the next page show a comparison of the density plots for the 20khz and the 1.96khz recalculated.

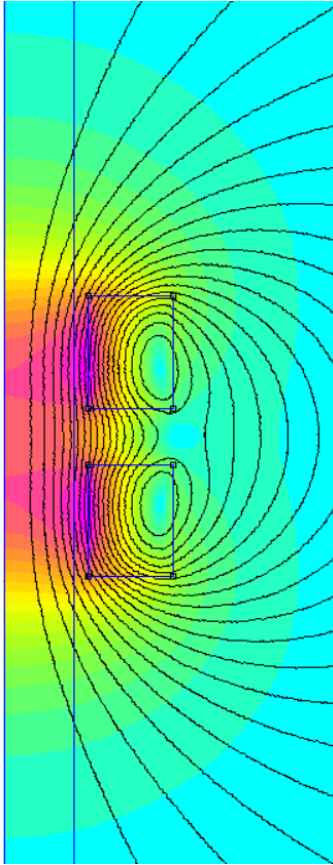


Figure 11 20kHz Setup

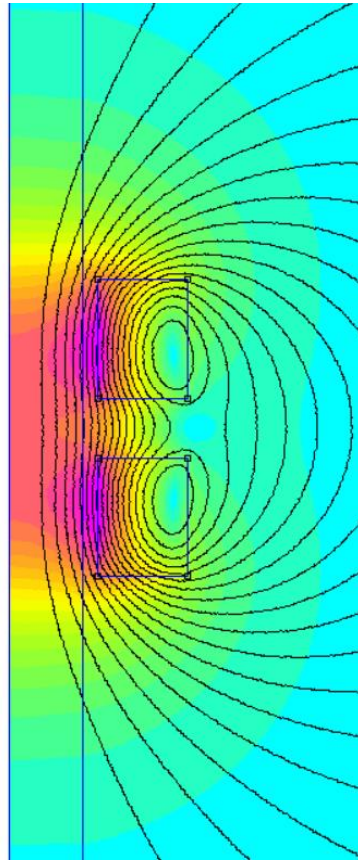


Figure 12 1916kHz Optimised Setup

From the figures above, it can be seen that the optimised density plot shows less deep purple around the coils indicating that the depth of penetration has been reduced here. A set of simulations was now run with the 1.5mm defect with this optimised frequency as displayed in the figure below.

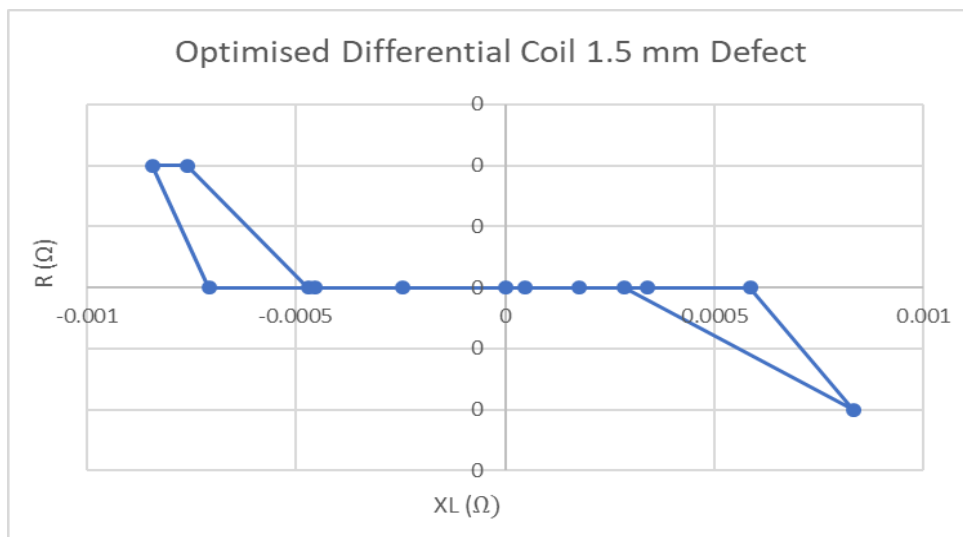


Figure 13 Optimised Frequency Setup

The figure above displays that there is a loss of reading over the coils and that the only time there was differentiation in the reading was when the defect was either side of the coils. A reason for this will likely be that the recalculated coils frequency is now too low

4.6 Phase Lag

Phase lag is a parameter of the eddy current signal that makes it possible to obtain information about the depth of a defect, it can be described as the shift between eddy current response from a defect on the surface and a disruption at a distance below the surface. Disruptions in the eddy currents away from the surface will produce more phase lag than disruptions near the surface. Therefore, the lesser the degree of phase lag the nearer the surface the defect is. Phase lag can be calculated with the following equation;

θ = Phase Lag (Degrees)

x = Distance Below Surface (mm)

δ = Standard Depth of Penetration (mm)

$$\theta = \frac{x}{\delta} * 57.3$$

Phase lag was now plotted graphically for two different standard penetrations of both defects 1mm and 1.5mm. These graphs could be used to give indication of the depth of a defect on what would be the response in a correct setup.

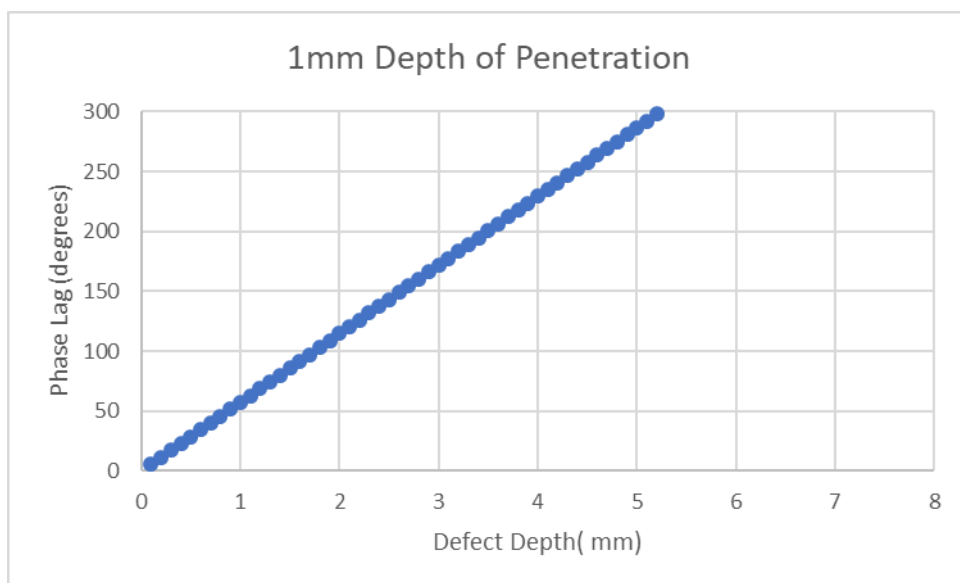


Figure 14 Phase lag 1mm Penetration

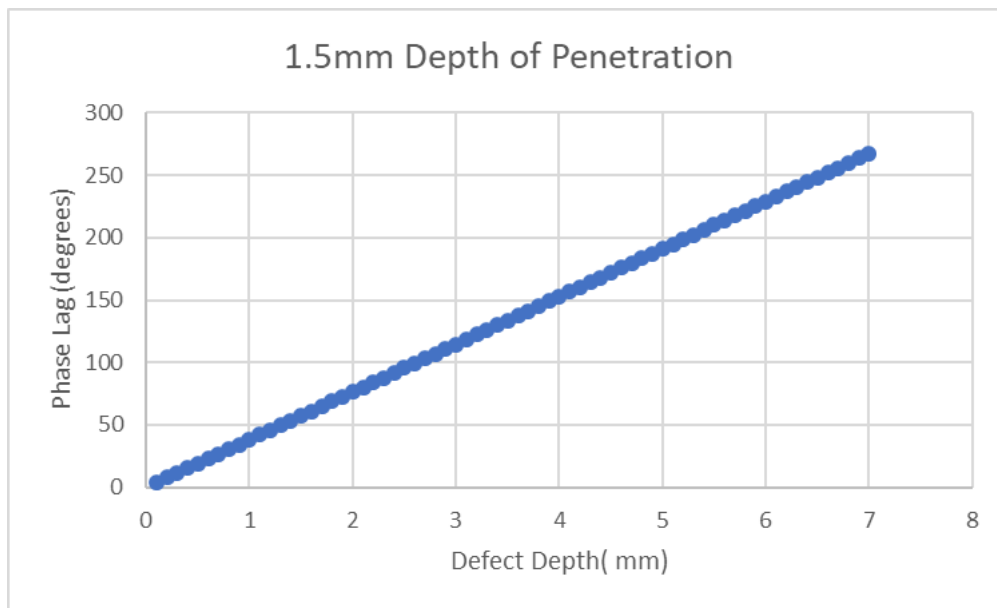


Figure 15 Phase Lag Response 1.5mm Defect

5. Conclusion and Future work

5.1 conclusions

Two sizes of defect have been estimated for their signal responses, as well as investigation into changing frequency and how phase lag could be used to estimate defect size.

The depth of where the defect lies, and the position of the defect has a direct influence on the response from the differential coils. When the coils give the same response, it is assumed that the defect is in-between the centre of the coils, as there is the same amount of defect for each coil to pick up meaning continuity is still registered.

Response levels were affected by the depth of the defect as the 1.5mm gave a greater response. After using some basic equations to calculate the standard depth of penetration it was found that the system designed was looking to penetrate 470mm, as the plate in question was only 2.5mm the equation was then rearranged for frequency to see what the optimum frequency would be, once this frequency was found that related to the 1.5mm defect depth a set of simulations were run to see how the response would change. It was found that the new lower *optimised* frequency did not give any signal response when directly over the coils, only response when it was either side of the coils.

Phase lag was then plotted in relation to specific standard depths of penetration with graphs being created. The graphs created gave indication of how phase lag could indicate the depth of a defect.

5.2 Future work

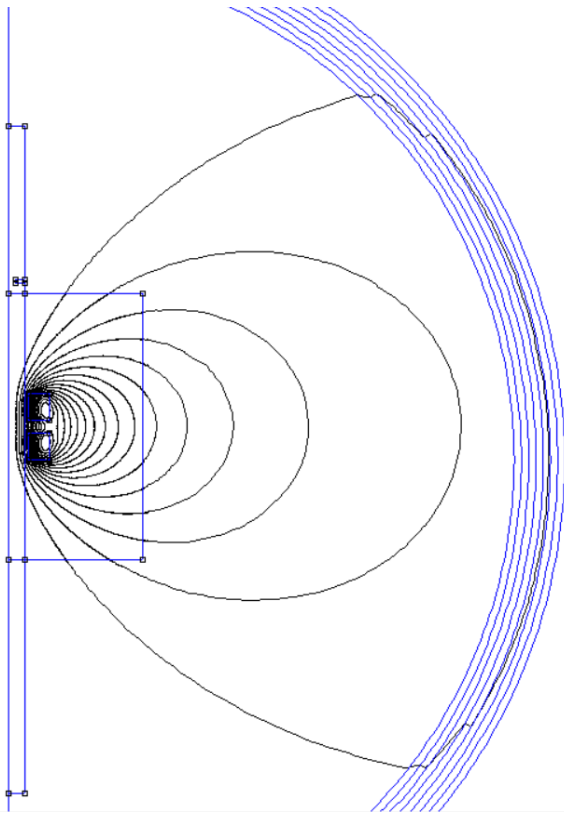
To find the optimum frequency for which the differential coils must run at to give the best trade off between signal response and depth of penetration would need further investigation, and possibly more complex equations to determine this.

References;

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Appendix

1.



2.

Simulation 1

Defect 1 (0.5x1)				
Y-Position	Coil 1		Coil 2	
	XL	R	XL	R
0	89.0121	1.98936	89.0121	1.98937
2	89.0121	1.98934	89.0121	1.98936
4	89.0121	1.9893	89.0121	1.98935
6	89.0122	1.9892	89.0121	1.98932
8	89.0125	1.98887	89.0122	1.98926
10	89.0133	1.98764	89.0123	1.98904
11	89.0143	1.98598	89.0125	1.98879

12	89.0162	1.98258	89.0128	1.98833
13	89.0192	1.97595	89.0133	1.98748
14	89.0235	1.96532	89.0142	1.98601
15	89.0275	1.95505	89.0154	1.98389
16	89.0293	1.951	89.0169	1.98115
17	89.0282	1.95481	89.0186	1.97784
18	89.0251	1.96351	89.0207	1.97375
19	89.022	1.97108	89.0235	1.96768
20	89.0196	1.97593	89.0268	1.95893
21	89.0177	1.97957	89.029	1.95199
22	89.0161	1.9826	89.0287	1.95204
23	89.0147	1.98504	89.0257	1.9597
24	89.0137	1.98683	89.0213	1.97102
25	89.013	1.98797	89.0175	1.9797
26	89.0126	1.9886	89.0151	1.98458
27	89.0124	1.98894	89.0138	1.98695
28	89.0123	1.98913	89.013	1.98812
29	89.0122	1.98922	89.0126	1.98869
31	89.0121	1.98931	89.0123	1.98914

Simulation 2

Defect 2 (1.5 x 0.5)				
Y-Position	Coil 1		Coil 2	
	XL	R	XL	R
0	89.0121	1.98936	89.0121	1.98937
10	89.0135	1.98744	89.0124	1.98901
12	89.0168	1.98179	89.0129	1.98822
13	89.0203	1.97445	89.0135	1.98728
14	89.0252	1.96277	89.0145	1.98565
16	89.025	1.96277	89.0145	1.98565
18	89.0271	1.96066	89.0221	1.97198
20	89.0208	1.97441	89.0289	1.95566
21	89.0186	1.97849	89.0315	1.94811
22	89.0167	1.98185	89.0311	1.94819
23	89.0152	1.98456	89.0277	1.9566
24	89.014	1.98656	89.0227	1.96903
25	89.0132	1.98781	89.0183	1.97868
26	89.0127	1.98851	89.0156	1.98402
27	89.0125	1.98889	89.014	1.98667
31	89.0121	1.98931	89.0123	1.98913