

2.5D Finite Element Analysis of Smart Pigging

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Abstract

This paper describes the use of the open source magnetic finite element software package, FEMM used to simulate a Magnetic Flux Leakage system in a pipeline wall. 2.5D axisymmetric finite element analysis is explained as to how this pipeline can be simulated without 3D software. Two scenarios were first examined as to how the setup reacted when we implemented two different sizes defects from a ball end cutter. Mesh optimisation is examined to find a trade-off is made between accuracy and time of simulations. Data was recorded and graphically plotted where it was found that the deeper 40% defect caused more flux leakage in the plate and when directly over the sensor caused two separate paths of flux leaking out which resulted in the graph displayed a crown shape in this area. Redesign of the setup resulted in less reluctance in the circuit, therefore determining methods of how improvements could be made for particular situations.

Keywords: MFL, Magnetic Flux Leakage, Tube Inspection, Finite Element Simulation, FEMM, Current Density, Mesh Optimisation, Saturation, Magnetization, Finite Element Analysis

1. Introduction

Magnetic flux leakage (MFL) has become the most commonly used Non-Destructive Testing (NDT) method for pipeline inspection. This paper discusses a finite element analysis study for a simulated pipeline inspection using permanent neodymium magnets in a brush set-up.

Prior to the analyses process mesh-optimisation was undertaken to gauge a trade-off between data-accuracy and computing time, this gave the most efficient mesh density to run.

The simulation of how a defect will influence the MFL sensor at different proximities is analysed and used as a reference for resolution. Also flux in the pipe and its relationship with saturation levels is analysed. It was investigated how avoiding having saturation in the bridge of the standard pig setup with some re-design of the component sizes could be accomplished.

Simulations on the changing magnet and plate sizes were run to investigate how this dimension change would influence the levels of saturation. With these changes in dimensions being analysed a judgement could be made as to whether pole sizes should be increased or decreased when dealing with a given thickness of pipeline wall.

2. Informative Literature

2.1 MFL PIG Systems

PIG systems are used in NDT to inspect pipelines, they are especially useful as when a pipeline is underground the range of possible inspection techniques are limited without digging up the pipeline. Pigs can be used to both inspect and clean the pipeline, being used continuously in pipe line sections long as 1055KM before.

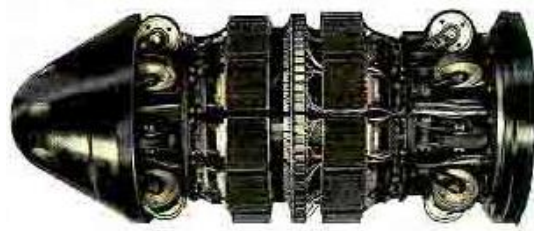


Figure 1: pig

(www.nde-ed.org, 2015)

Magnetic flux leakage (MFL) pig systems work by creating a strong magnetic field in the pipe wall, here magnets such as powerful neodymium magnets as in this study will be used to create the magnetic field. As the figure below shows damaged or flawed areas of the pipe will be picked up by the sensor finding a change in the magnetic flux which has been created, here damaged areas will not be able to hold as much flux as the consistent areas of the pipe therefore causing the flux to go around the damaged area as the figure below is displaying.

The sensor picking up the changes in magnetic flux will be a hall effect sensor, hall effect sensors are activated by changes in magnetic field density (B). When subjected to a magnetic field (caused by the defect), the sensor responds with an output voltage proportional to the magnetic field strength which can then be read on the testing equipment.

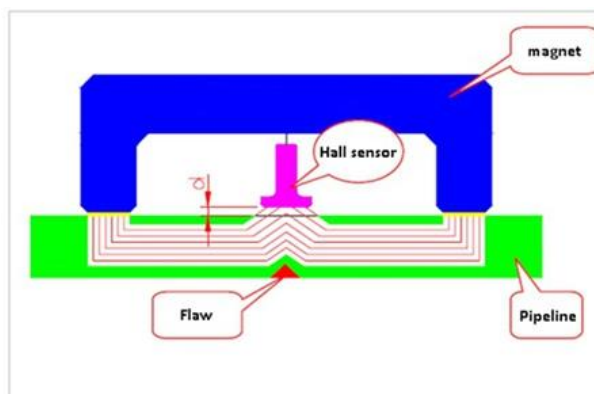


Figure 2: pig example set-up (sensing.honeywell.com, 2011)

2.2 Materials & Saturation

B/h curves, Saturation and Reluctance

We will be looking to *saturate* the pipeline wall with flux in order to get clear readings from the hall sensor in magnetic flux leakage testing. Saturation can be defined as a point where a material can absorb almost no more flux from a magnetic field, which then causes *reluctance* where the pipeline will oppose magnetic flux lines.

For this we will have to understand the materials permeability, and how the material will react on the B/H curve. Permeability describes the ease at which a material can establish magnetic flux within itself. A B/H curve is a graphical representation of the materials permeability as shown in the graph below. The graph below describes the four distinct regions which soft iron will go through on it's way to reaching saturation.

Four distinct regions involved in the materials magnetization;

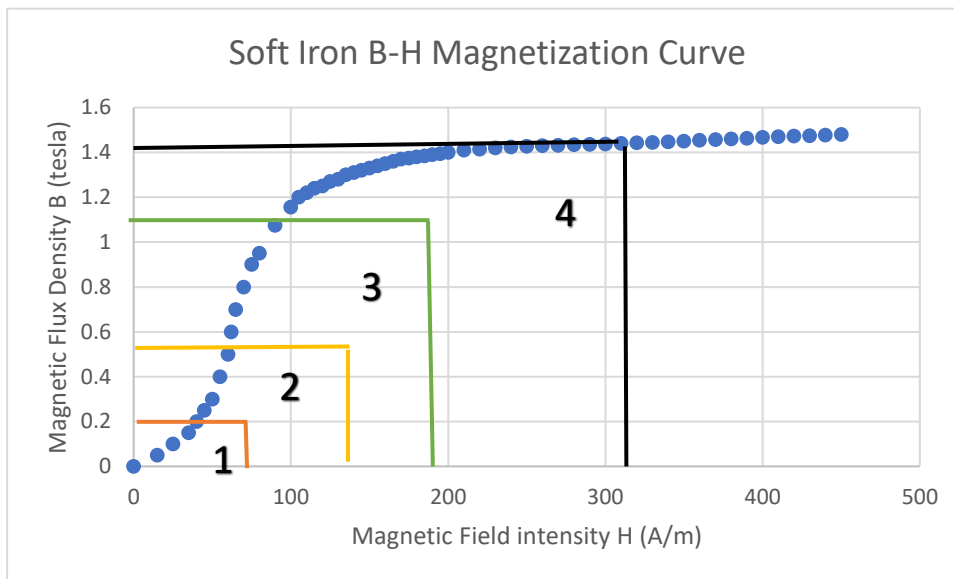


Figure 3: B/H Curve Saturation Regions

1. Reversible growth



The magnetic domains within the materials atomic structure have started out in the iron randomly aligned as shown in to the left. The magnetic field is starting to increase as is shown in the graph above, but not to the point where there is enough flux within the iron for the magnetic domains to turn in the direction of the field. At this point if the field was taken away the domains would go to random alignment

Figure 4: Magnetic Domains

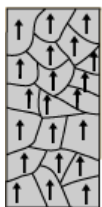
2. Irreversible growth

At this point the magnetic domains have started to grow to a point where they would not return to their original state naturally

3. Rotation

The magnetic domains have started to rotate in the direction of the magnetic field, aligning with the field more and more as the material is getting nearer to the saturation point

4. Saturation



All magnetic domains have aligned in the direction of the applied field; the iron can take no more magnetic flux within itself and all magnetic domains are aligned. It has now reached the same permeability of free space as it can take no more magnetisation.

Figure 5: Magnetic Domains Aligned (hyperphysics.phy-astr.gsu.edu, 2006)

3. Pig Model

The pig model was sketched axisymmetric, meaning that the model has rotational symmetry, therefore we can represent the whole pipeline-pig set-up using the 2D software.

Materials used;

Materials
Magnet Assembly (bridge and bushes): M50 Mild Steel
Pipe Wall: Cold Rolled Low Carbon Steel
Permanent Magnets: NdFeB 40

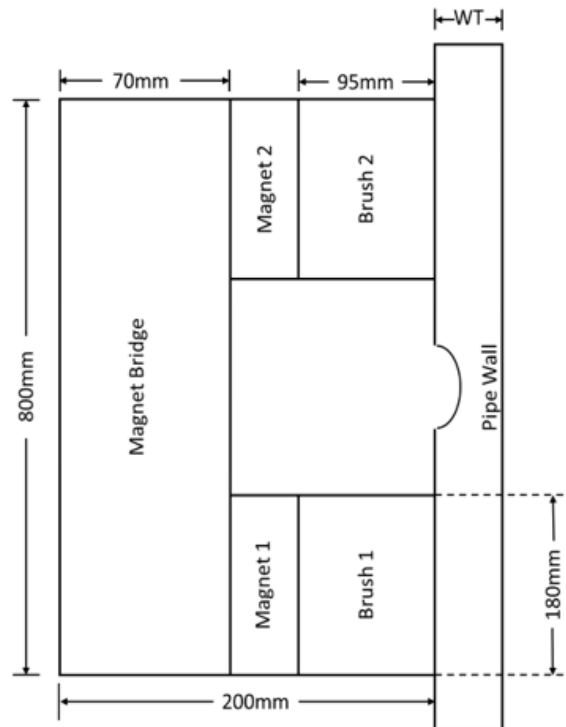


Figure 6: Standard pig Set-Up

Wall Thickness: 25mm
Pipe Diameter: 1 Meter
Sensor Position: Directly between the brushes at 2mm above the inspection surface

The figure above shows the original design of the pig configuration. Here a defect from a 22mm ball end cutter was placed at 20% then at 40% through the pipe wall to run simulations on.

3.1 Mesh Optimisation

Mesh optimisation allows for graphical comparison of mesh density sizes on a given model to evaluate the accuracy of results produced by 'Finite Element Analysis' software and the computing time taken for the machine used to run the 'Finite Element Analysis'. For this comparison a boundary was created around the PIG model (see appendix 1), and within this boundary layer areas of interest were decided to have a finer mesh applied than other areas which are not as interesting to us, i.e. the air around the outside of the pig was decided to run a coarser mesh in comparison to the model itself. 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.

This now allows for the optimal point to be selected between mesh size and computational time. The results from the optimisation are displayed in Table. 1 and Figure 7 below. We can see that when we reach a mesh density of 1 that we do not see the results significantly increasing, but we computational time does start to increase. From the table and graph below, it was decided that a mesh density of 1 gave sufficient results with an acceptable computational time.

(Charlton & A Pullen, P Charlton, 2015)

Mesh density- Nodes	Mesh density	Magnetic field energy (Joules)	Time (minutes)
16544	5	1324.72	1
42914	2.5	1322.2	1:40
103691	1.5	1320.73	3:30
225861	1	1319.74	5
585383	0.6	1319.44	8:15

Table 1: Mesh Density

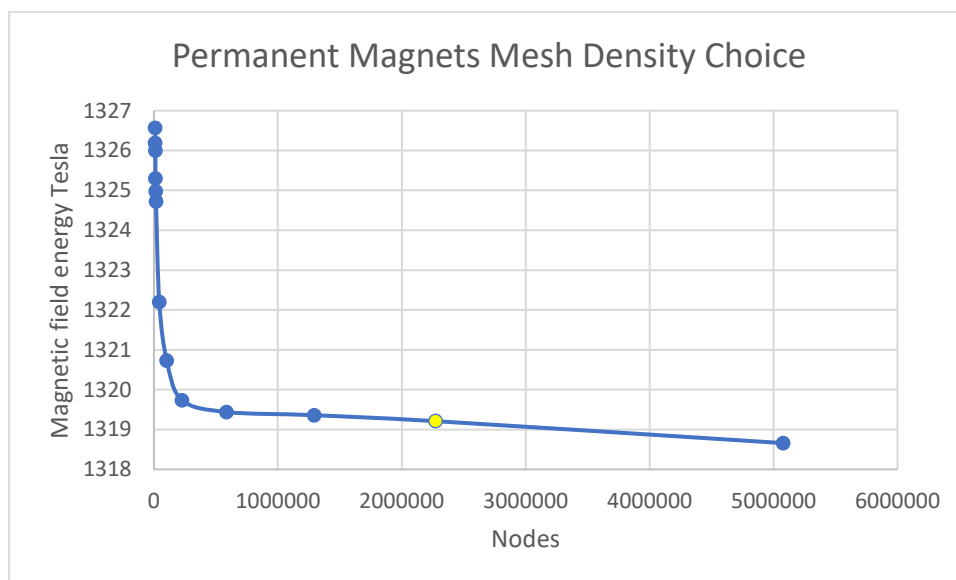


Figure 7: Mesh Optimisation

3.2 Mesh Boundaries

The mesh boundaries set as shown in appendix 1 improved computational time, the software chose the boundary which would be outside of the axisymmetric model. This allowed for increased mesh densities within a localised area, and gave the option to change the air within the boundary to designated coarse mesh which would not interrupt with computational time.

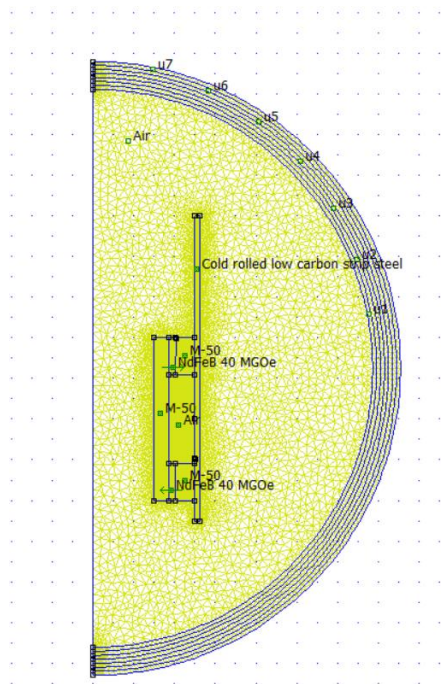


Figure 8: Mesh Density Simulation

Figure 8 above displays how specific areas of interests within the boundary have been concentrated on, where we can see the air within the boundary having a coarser mesh than the pig components.

4. Results & Analysis

4.1 Saturation

Figure 9 below shows the model with no defect. We can see the flux density at certain points within the setup, the highest regions of flux density are in the bridge and the plate between the magnets.

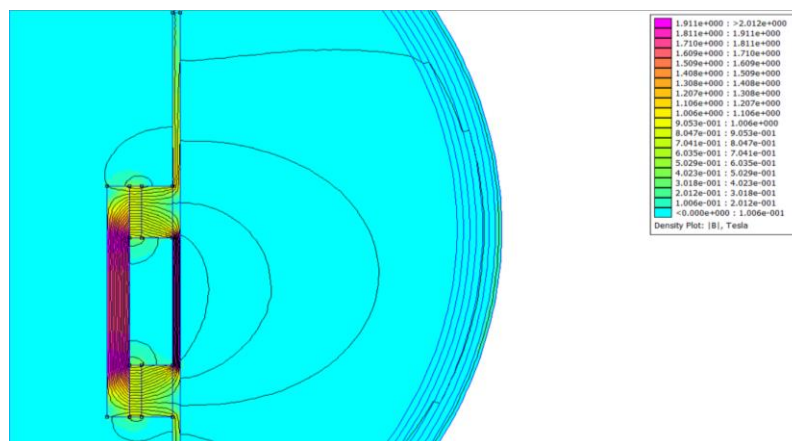


Figure 9: Flux Density

We can see here that the bridge is becoming saturated as well as the plate in-between the permanent magnets, we can visually see that the plate is in saturation not just from the flux density chart but also as the lines of flux do not want to travel through saturation as there is now high reluctance here.

As there is high reluctance in the plate we can see that the bridge has started to become saturated, we don't want the bridge saturated because it will start to take flux away from the plate and essentially cause more magnetic reluctance within the circuit.

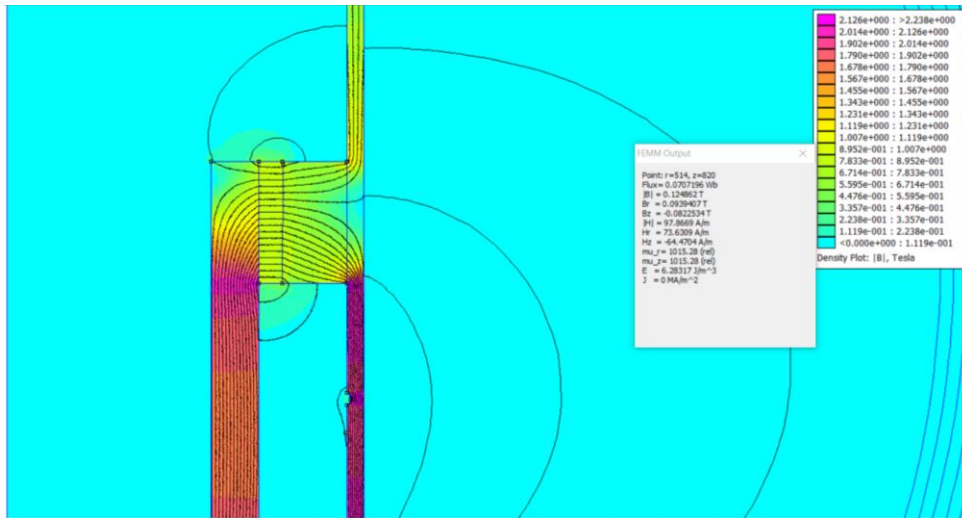


Figure 10: Flux Density

4.2 20% defect

A defect was created that represented a cut from a 22mm ball end cutter by creating a circle of diameter 22mm. We then placed this circle in at 20% of the pipeline wall depth as displayed in the figure below.

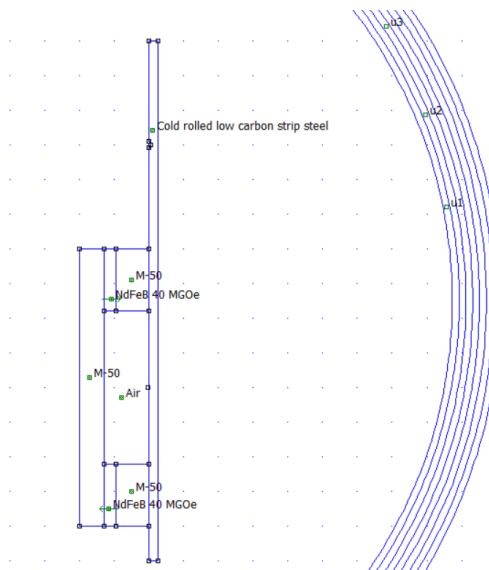


Figure 11: Pig Defect

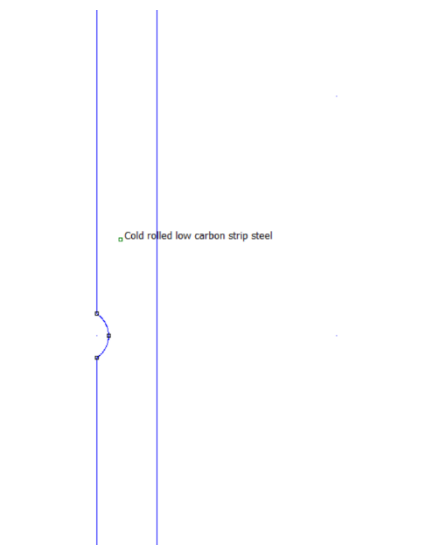


Figure 12: Close-Up 20% Defect

A node was now set half way between the two magnetic poles at 2 millimetres above the cold rolled low carbon steel plate (see appendix 2), from this node we would take three different readings of flux. These will be B_r (normal flux density), B_z (tangential flux density) and of $|B|$ (the magnitude of B_r and B_z) node will now be described as the probe.

To understand the readings taken of the values mentioned we must first look to see graphically where they are being taken from. Having this understanding will allow to make judgments when the data is graphically plotted.

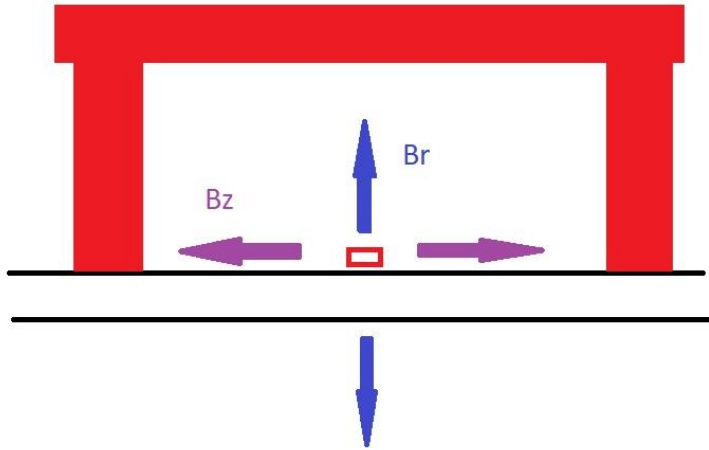


Figure 13: Flux Directions

The diagram above shows how B_z is taking a horizontal measure of the flux, whereas B_r is taking a vertical measure of the flux. $|B|$ is the magnitude of the two readings, where $|B|$ is defined from the equation below. It was important to understand these flux direction readings as we were using an asymmetrical model geometry needed to be understood.

$$|B| = \sqrt{B_r^2 + B_z^2}$$

It was decided to move the defect in incremental steps then run simulations to take the readings rather than move the pig assembly. We started with the defect at a point where it would have no influence on the *probe* which we would call *zero y position*, we then would move the defect until we could graphically start to see an influence on the probe.

It was found from the first simulation that the *zero y position* that was chosen (which was above the leading pole piece) had no influence on the probe (as displayed in figure 14 below with $|B|$). This was realised by drawing a line from the probe to near the leading pole (see appendix 3), then graphically plotting values of $|B|$, B_r and B_z , from this line. Figure 14 below shows results of $|B|$, we can see from figure 14 that there is no influence from a defect just a rise from the magnet pole as more intense flux is found nearer the leading pole of the setup which is why we see the curve.

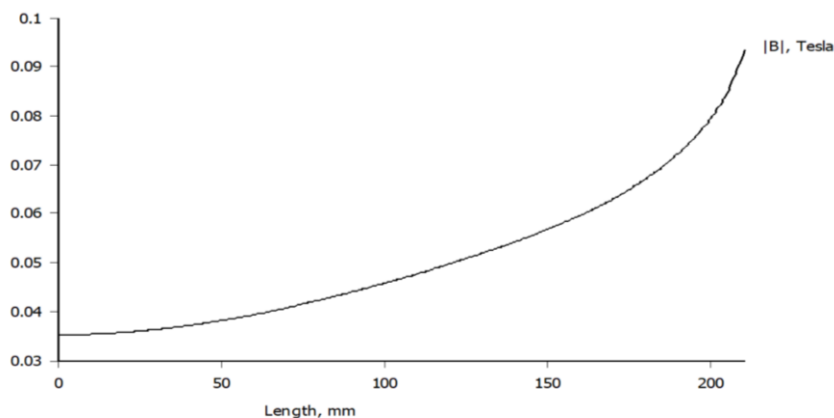


Figure 14: Resolution Justification

The figure below shows the same plot taken from the same coordinates as above, but we can now see that the defect is influencing the plot, here we can see the defect influence is roughly 75mm away.

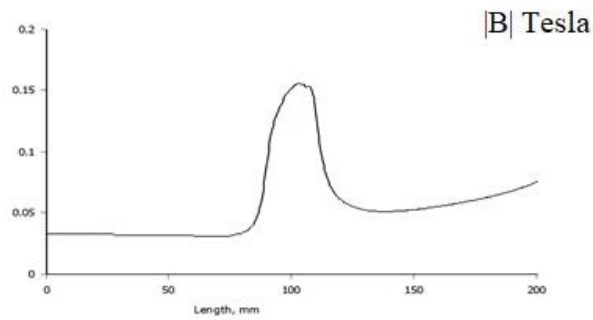


Figure 14: Resolution Justification

This gave justification for having a crude resolution at the start of the simulations (moving 25mm). Once we could see that we are close to encountering direct influence from the defect we can look at making the resolution finer. If we look at the graph above we can see that we are roughly 75mm away from direct defect influence, therefore from these screenshots we were able to make justification on resolutions used.

We also used these screenshots as a way to validate the graphs that we would plot from the recorded values, for example we would expect the same kind of bell curve produced from the excel as what was found from the graphically plotted line graph above for $|B|$, and likewise with the B_z and B_r values displayed below.

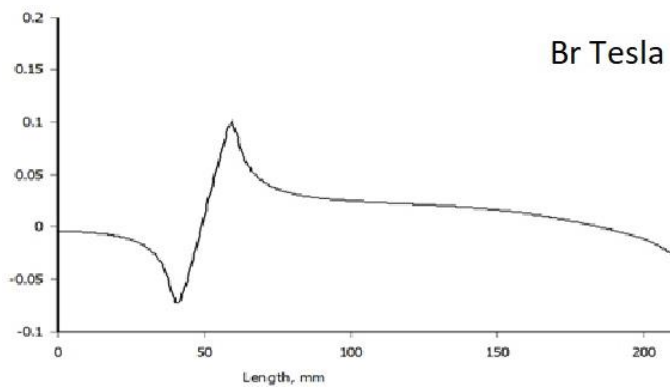


Figure 15: Resolution Br

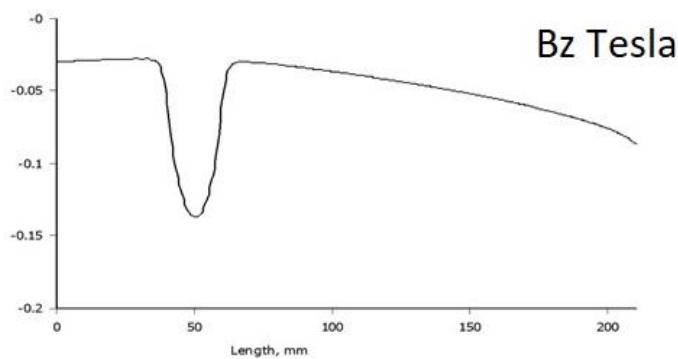


Figure 14: Resolution Bz

Table 2

Y Position	Bz	Br	B
355	-0.03165	0.000822	0.03166
380	-0.03018	0.004349	0.030491
405	-0.02805	0.017352	0.032986
410	-0.02767	0.024509	0.036967
415	-0.028369	0.0392312	0.0484135

Table above shows how data from simulations was recorded, this was taken from the probe position. The table also displays the point where the resolution was made finer as we graphically started to see some defect influence on the probe, we changed from using a resolution of 25mm to 5mm when we came into defect influence region.

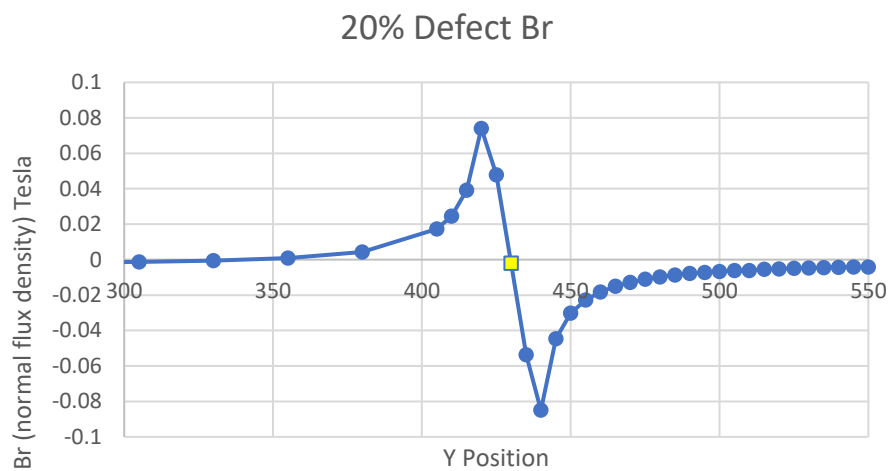
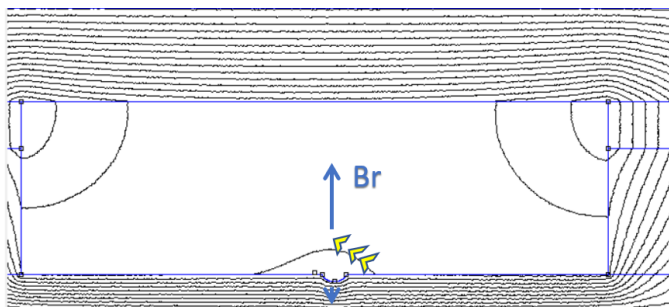
**Figure 16: Recorded Br**

Figure 16 above displays the graph of Br values created from the recorded data displayed in table 2 above. We can see a spike has been created as the defect has travelled directly over the probe between y positions 400 to 500, the Br values are measuring flux vertically therefore we can assume that the point where the graph has dipped back down to the normal line (highlighted with a yellow marker) displays where the defect is directly over the probe position.

The reason for this can be explained in the following figures. If we are aware that we will only get a Bz reading when some kind of vertical flux path is influencing the probe as in the figure below, we can expect change in the graph when there is change in vertical flux direction (shown here is yellow).

**Figure 17: Flux Direction**

Now look at a similar screenshot below when the center of the defect is not 10mm from the probe, but in line with it we can now see that the flux direction has levelled out and there is no longer vertical change. Therefore, at this exact point we have no reading of B_r .

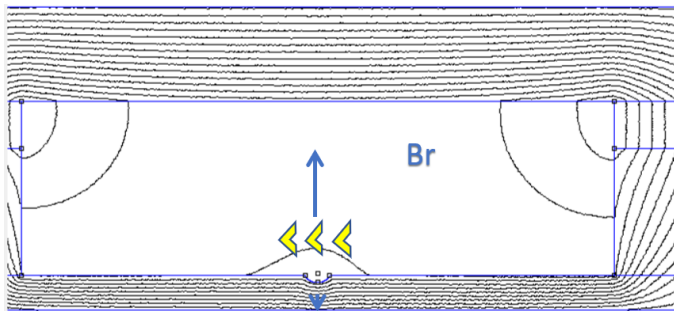


Figure 18: Flux Direction

The spike and dip in the graph has formed from as we are bringing the defect closer to the probe there has been a bulge of a flux path leaking from defect (which is seen in the two figures above) the probe has then been influenced from both the raise and the dip of this flux bulge caused by the defect.

The graph of B_z displayed below again shows at which position the flux leakage from the defect influenced the probe. Referring back to the graph previous of B_r we could start to see that the probe was influenced by the defect as early as 375 y position, here for B_z we get very gradual influence until we reach 415 where even though a finer resolution has been used there is still large degrees of influence.

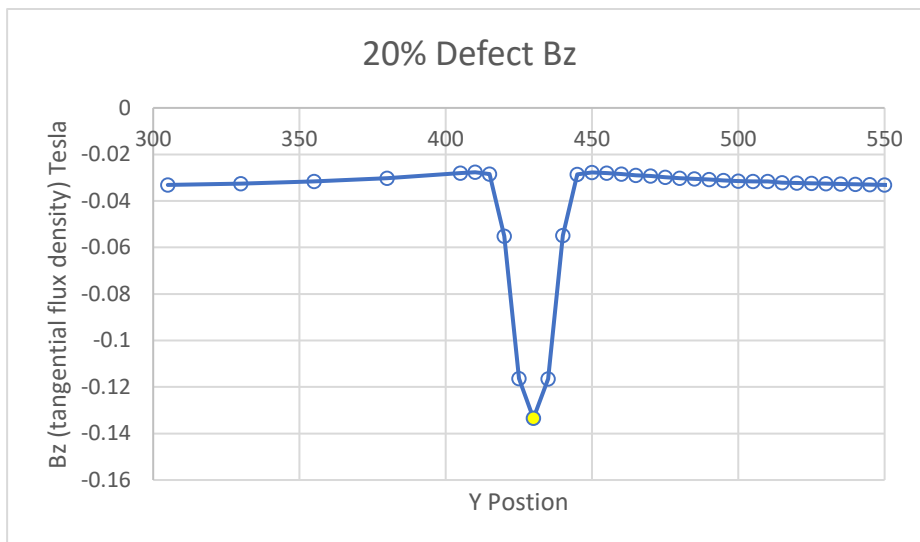


Figure 19: Recorded Bz

Again, the point of y position 430 has been highlighted yellow as we can now see here that in terms of B_z (horizontal flux path) is recorded a maximum value when the defect center is directly over the probe. Figure 19 displayed is when the greatest change in horizontal flux is recorded.

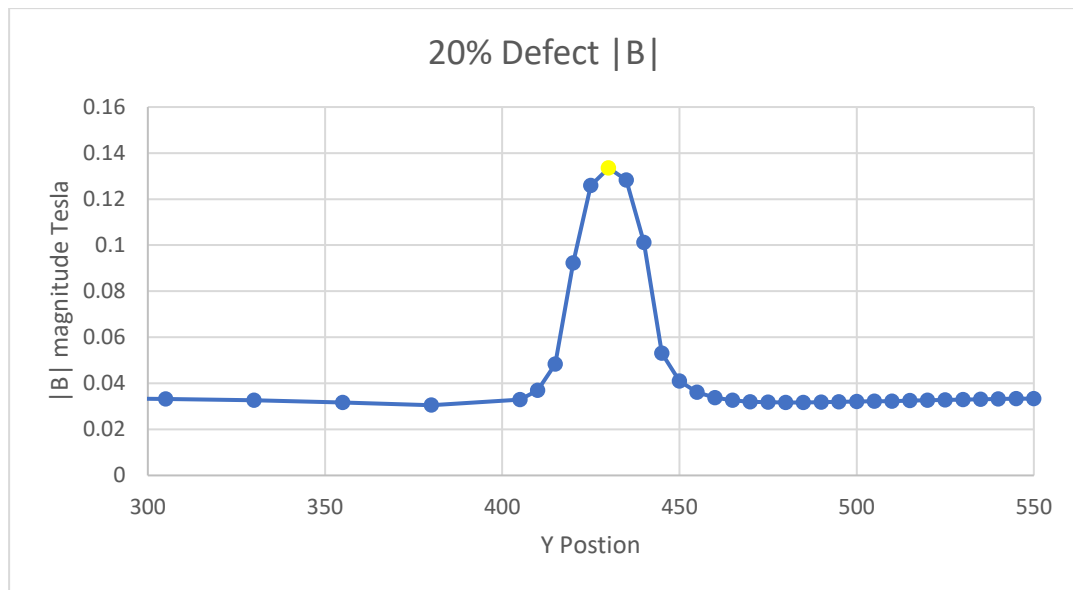


Figure 20: Recorded |B|

The $|B|$ magnitude graph above is a combination of both B_r and B_z values. We see it has represented the graphed line plotted in figure 20 indicating data has been recorded accurately.

4.3 40% defect

The same variables such as mesh density and boundaries were used as when we had a 20% defect, the difference now being that we have the 22mm ball end cutter defect at 40% deep into the pipeline wall.

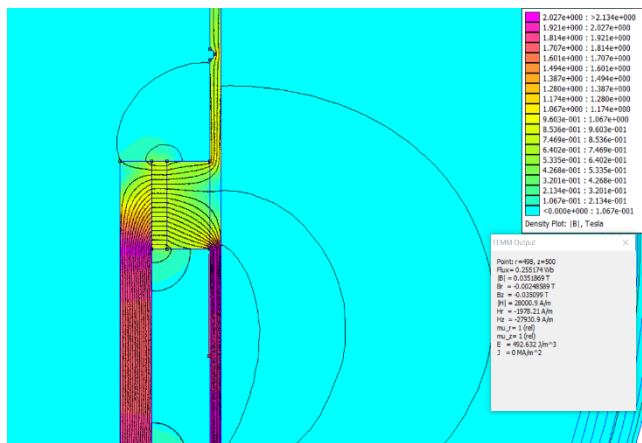


Figure 21: Flux Density 40%

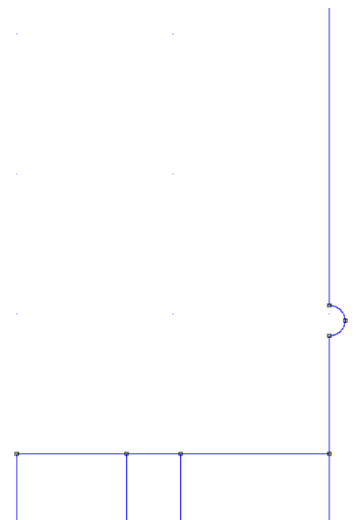


Figure 21: 40% Defect Close Up

The same procedure was used to verify what resolution to use. Again, we would take movement with larger incrementation then use a finer resolution when we start to see influence from the defect. As figure 21 above shows we again have started in a region where the defect has no influence on the probe, when we again plotted the line from the defect to near the leading pole piece we looked at the B_t values the defect gave, this was used as a reference as to what resolution we should be using, but also what the data we record should look like when it is graphically plotted as the defect moves over the sensor.

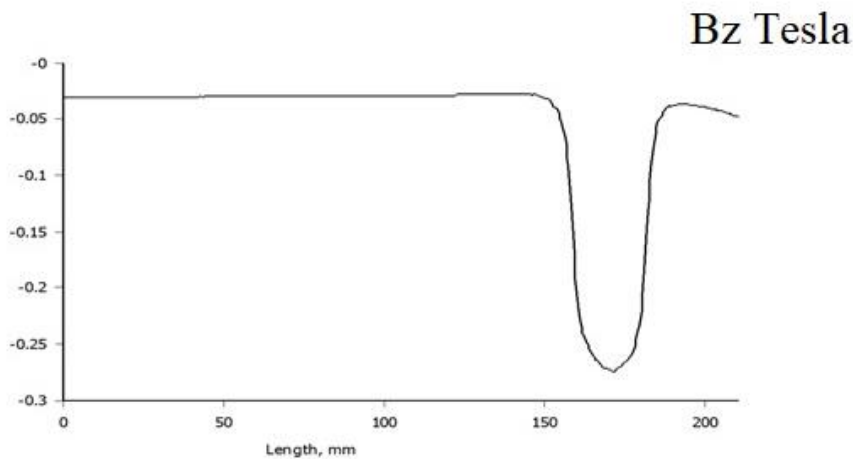


Figure 21 Bz Plotted Line

From the plotted line graph above we can see greater values of Bz recorded as expected in comparison to the 20% defect. This figure above shows that we had roughly 150mm until we would be under direct influence from the defect.

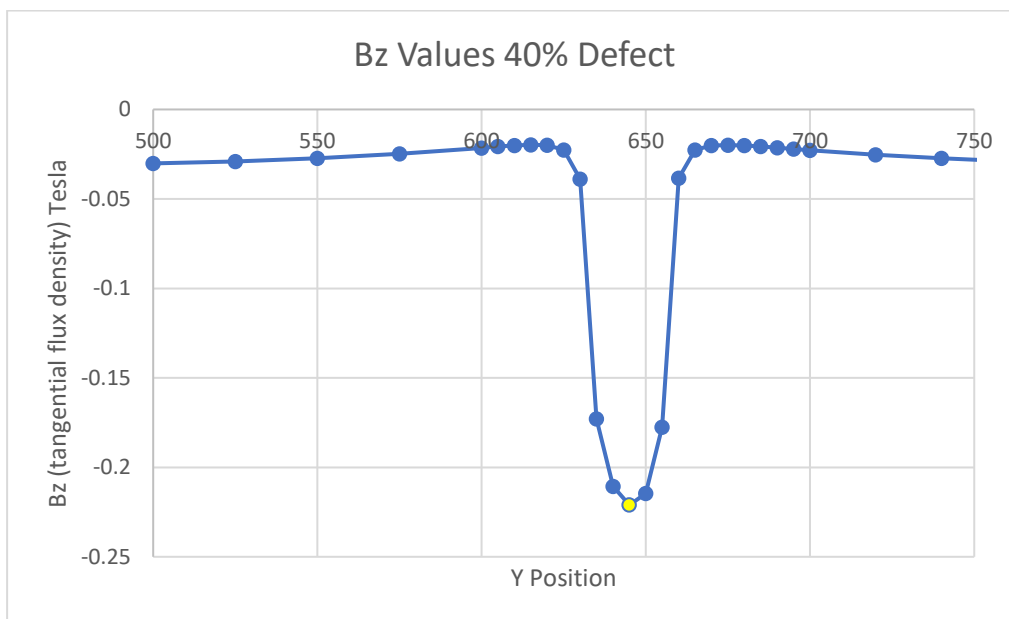


Figure 22: Recorded Values

The recorded Bz values above shows the point where there is the greatest amount of horizontal flux is at point 645, again the same as the 20% defect the values have followed the bulge of flux leakage which is why we have produced this reverse bell curve.

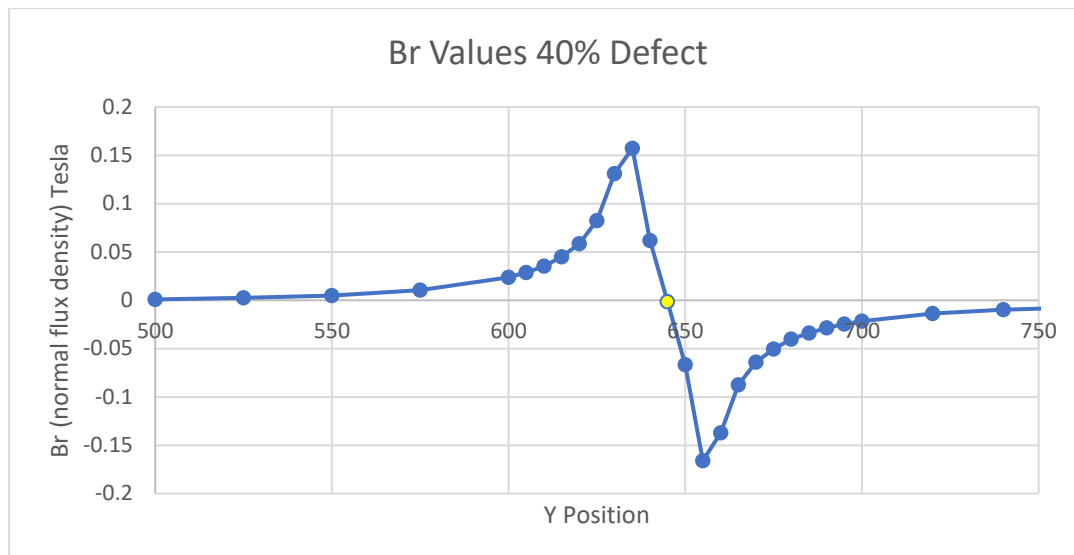


Figure 23: Recorded Br

The peak of the Br spike for the 20% defect measured at 0.074 Tesla, here above we have a close relationship between the size of the defect doubling (to 40% depth) and the new Br value being 0.157 (almost double). We again see the point where the defect is directly over the probe being y position 645, as explained in the previous defect size this is where the flux path hits a horizontal point.

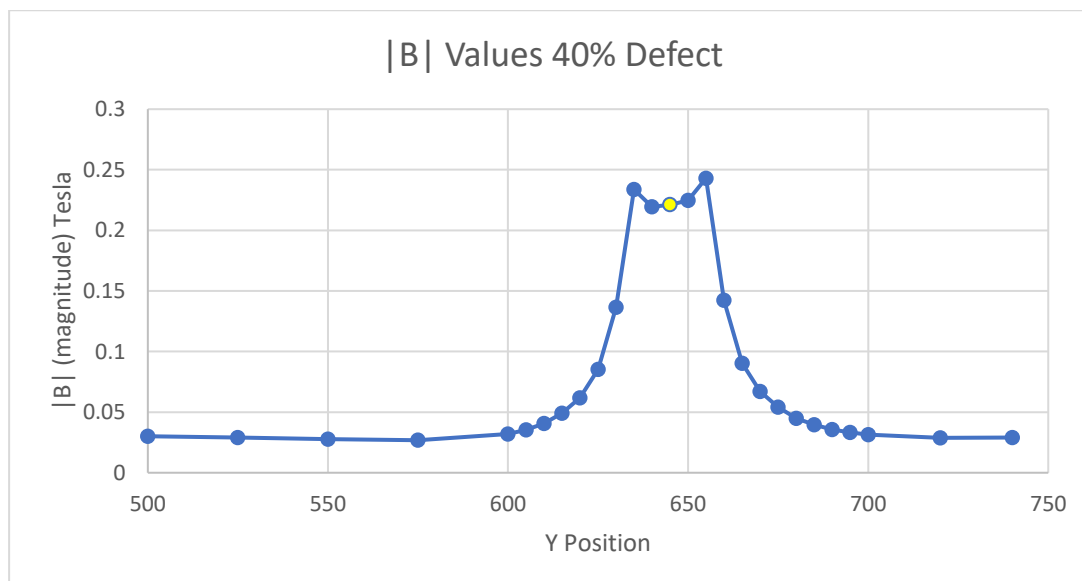


Figure 24: Recorded |B|

Here on the 40% defect we can see a crown has been created as the defect has passed over the probe, we can still see our center of the defect represents the center of the crown highlighted in yellow again. It was not seen on the 20% defect, it was assumed to be happening because a gap had been created in what was once just one flux path from the 20% defect now being two flux paths creating a slight air gap between the flux paths therefore resulting in some reluctance, causing the crown to appear. But looking at figure 25 and 26 on the next page it shows that with the deeper defect a new flux path has been created in the defect from leakage in the plate finding an area of least resistance, this is what is found to have cause the crown.

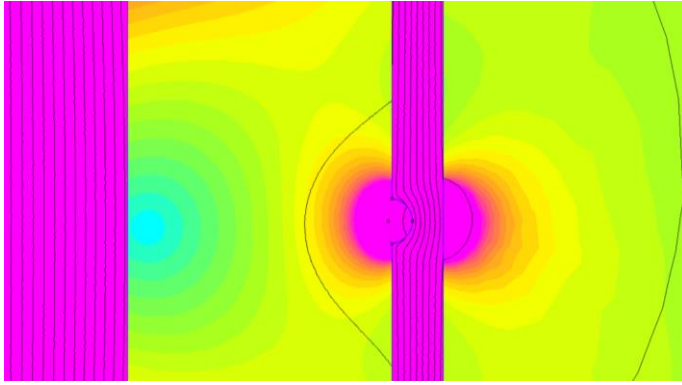


Figure 25: Defect Flux Leak

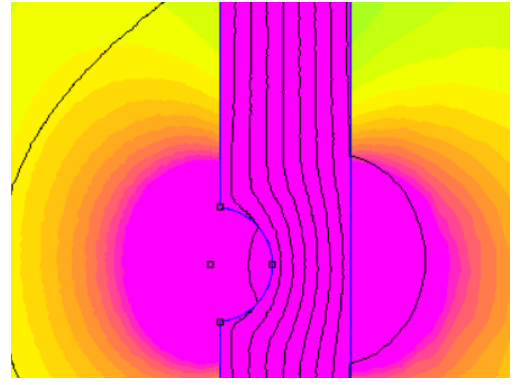


Figure 26: Defect Flux Leak Close up

4.4 Graphical $|B|$ Defect Comparison

Now comparing the values of $|B|$ from the 20% and 40% defects, below we can see as expected there is greater values of $|B|$ recorded in the 40%, it can be seen also how close the lower point of the crown is to the bell curve of the 20% defect.

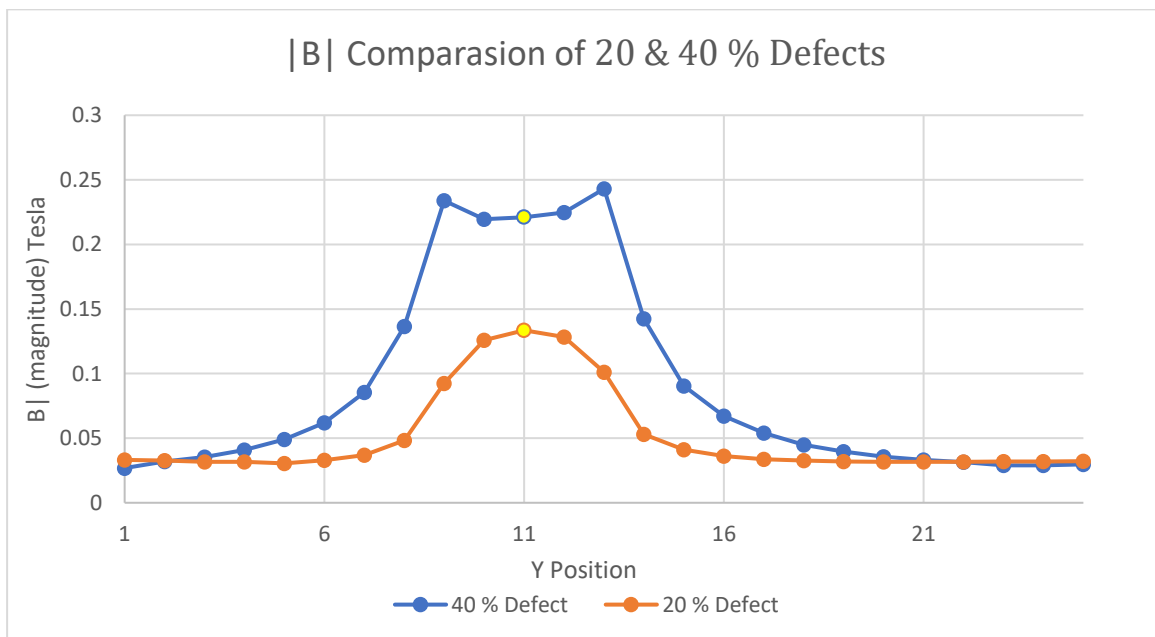


Figure 27: Graphical Comparison of $|B|$ Values

Between the two defect centres there is a difference in readings of 0.088 Tesla, indicating there is no relationship between the bottom of the crown in the 40% defect and the top of the 20% defects. We can also see that the 40% defect starts to have a faster rate of change in the readings taken due to the greater influence from more leaked flux.

4.5 Redesign of magnet assembly and altering plate thickness.

4.5.1 Altering plate thickness

In this section the redesign of the magnet assembly is experimentally undertaken based on its limitations identified in the previous study of defects depths and typical B_r and B_z responses. As seen in section 4.1 the magnet bridge is saturated. This causes a high reluctance path limiting flux induced into the plate. Increasing the bridge thickness would reduce the reluctance resulting in the ability to saturate larger plate thickness.

Taking the original design, the figure below shows a flux density chart to observe areas of saturation. The boundary conditions for the density plot were set between 1 and 2.4T, with 2.4T being the maximum recorded level of magnetic flux below the defected area.

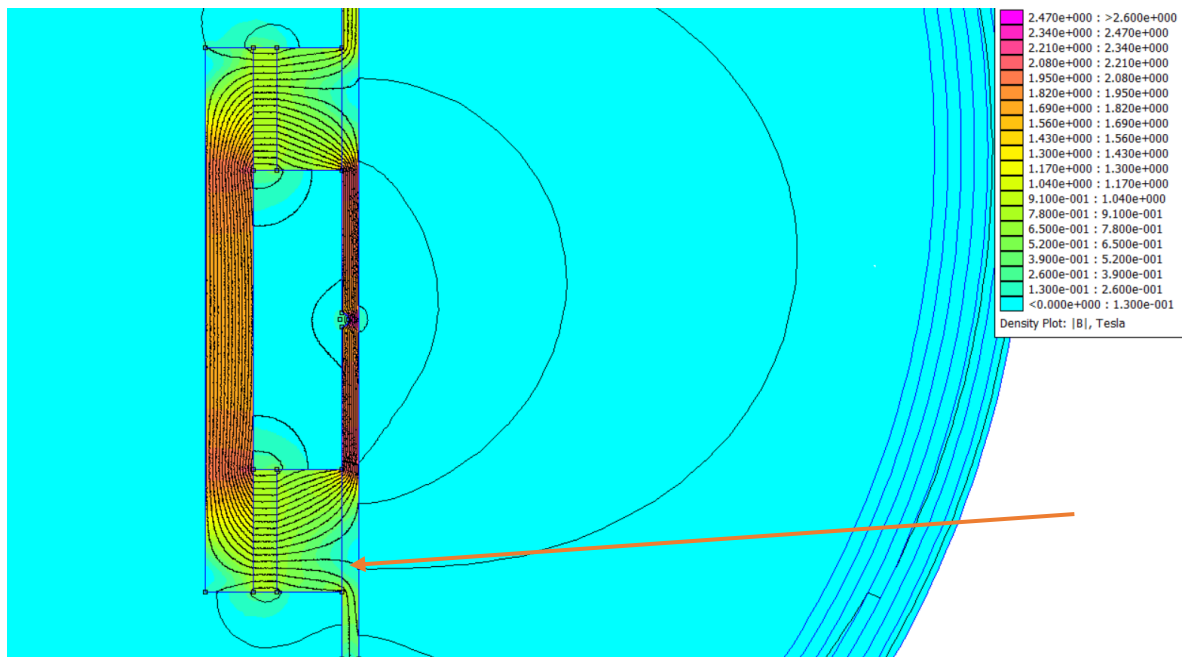


Figure 28: Flux Density Chart

Now it can be seen in the trailing and leading poles that there is enough reluctance to cause the lines of flux to take a new path of least resistance. We will now look at how increasing plate size may cause less reluctance at these points, therefore possibly indicating that this setup could be used to scan thicker plates. The plate lies in saturation which is desired for MFL inspection, but we would hope that as plate size is increased bridge reluctance will decrease. Taking all of this into consideration the plate thicknesses will first be increased to identify the limits of the current set up.

4.5.2 Results of Increasing Plate Thickness

It was decided to increase the plate thickness by, 5,10,20 and 30mm. Then we would compare results and see whether as we expect flux to decrease around the plate as there is now more volume of material to be saturated.

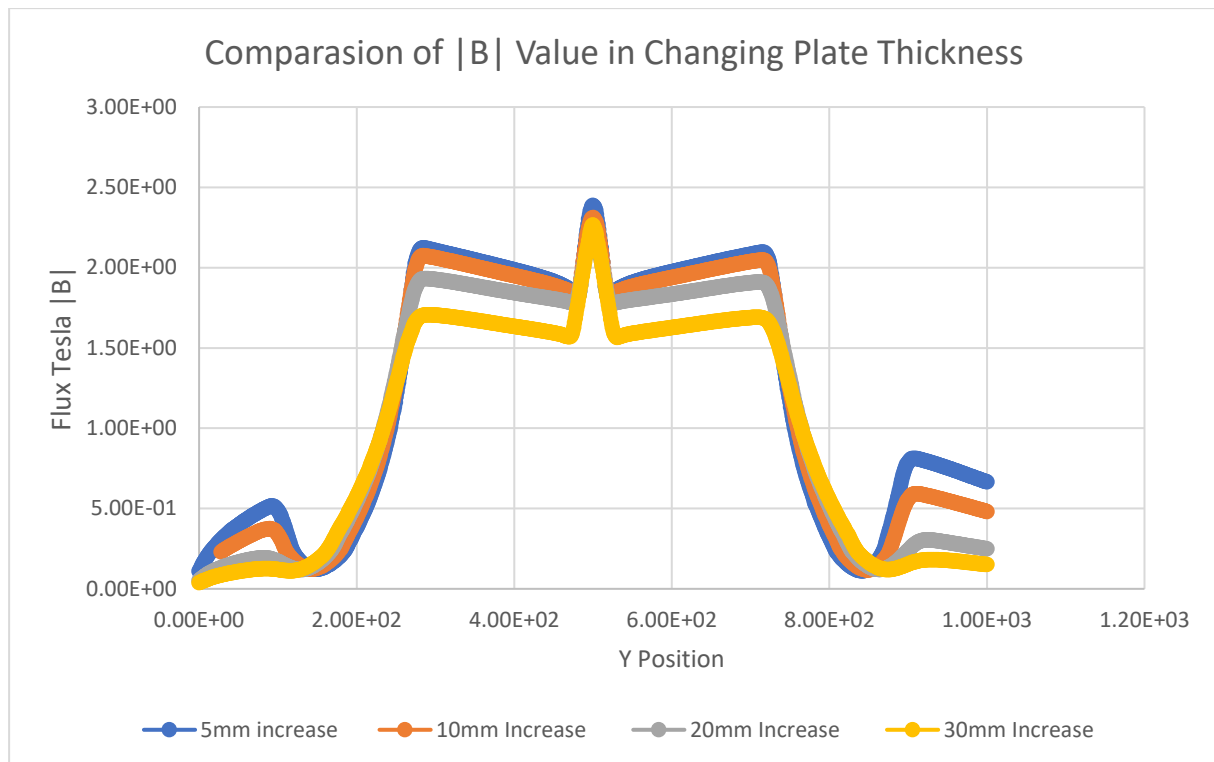


Figure 29: Plate Thickness Variation

When the plate thickness is increased to 30mm a reduction in flux density within the plate occurs, this is because there is now a larger area to saturate. As we know flux is a dimensional measure that takes volume into account the results justify themselves, as the bigger the volume of material the more flux will be needed to saturate it. It is also observed that the levels of flux density within the bridge have increased as the figure below shows, this having a negative effect on the applied flux into the plate as more reluctance is caused in the setup again.

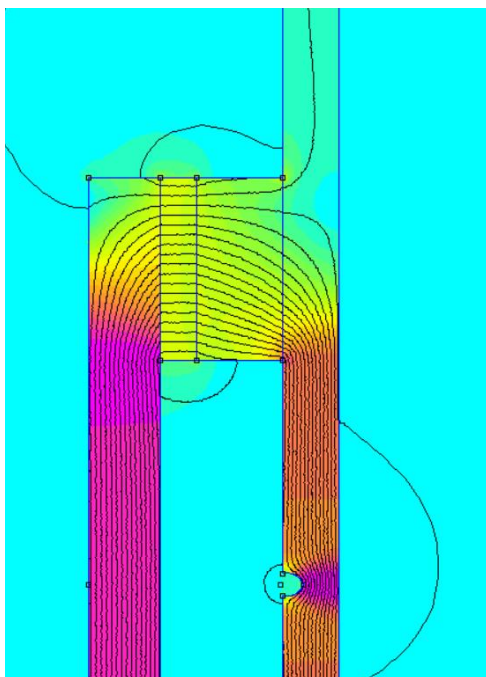


Figure 30: Improved Flux Path Direction

4.5.3 Optimising bridge design

Using the same plate thickness of 30mm the bridge is now widened by 10mm in order to reduce reluctance within the circuit at the bridge. This allows for increased levels of flux to be applied to the plate thus increasing its flux density as the figure below displays.

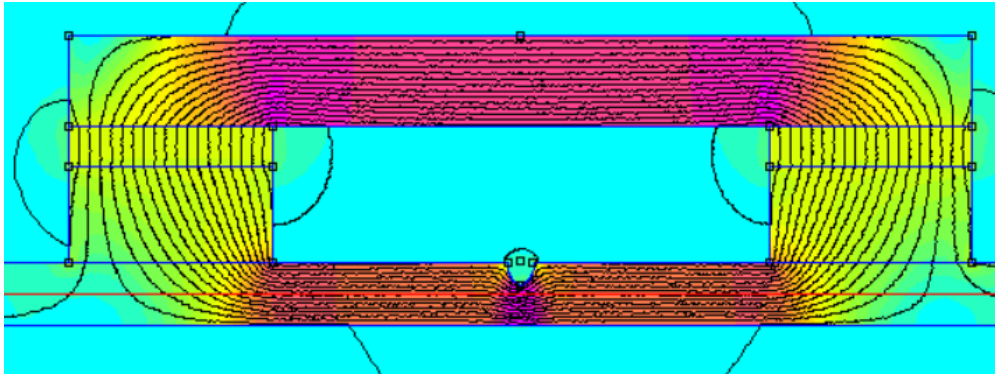


Figure 31: Improved Flux Path Direction Due to Bridge Change

Here in the figure above it can be seen that more lines of flux not being diverted away from the edges of the leading and trailing pole pieces as there is not such high levels of reluctance in these areas as we had previous.



Figure 32: Comparison of Plate and Bridge Flux Changes

Comparing this new re-design to when the plate thickness was simply increased it can be seen that the levels of flux have actually slightly raised in the plate, therefore proving that the increased bridge sized gave less reluctance in the circuit allowing more flux to flow to the plate.

5. Conclusion and Future work

5.1 conclusions

Two sizes of circular defect have been estimated for their signal responses, as well as pig design saturation investigation both using FEMM finite element analysis. The circular defects gave predictable signal responses and gave desired results for graphical analysis.

The position of where the defect lies, and the depth of the defect has a direct influence on the response from the probe sensor. The closer the defect is to the probe the greater the results of magnetic field change will be read from the sensor, and likewise the deeper the defect the more change will be seen in magnetic field.

Saturation levels were affected by the sizes of the defect, as the bigger the defect the more magnetic flux we had leaking from the plate, meaning less saturation occurred in the 40% defect as was found in the 20% defect. It was observed in the 40% defect for the values of $|B|$ that a crown appeared at the center of the defect, this was found to be because the larger defect created not one but two paths of flux with less intensity in the middle, therefore creating this crown in the recorded results.

When it was decided to graph results of a redesigned setup it was found that thicker plates could have been tested with the strength of the current set up, as there was really more magnetic strength than was needed for the task. When the size of the plate and bridge was increased it was found that the flux had less reluctance around the pole pieces than what was occurring in the standard setup, therefore creating an improved design with less reluctance in the circuit.

5.2 Future work

An interesting future study would be looking into how a fully optimised magnet design including pole pieces for differing plate thicknesses could be approached, and to statistically graph what specific setup would work best for a particular thickness of plate.

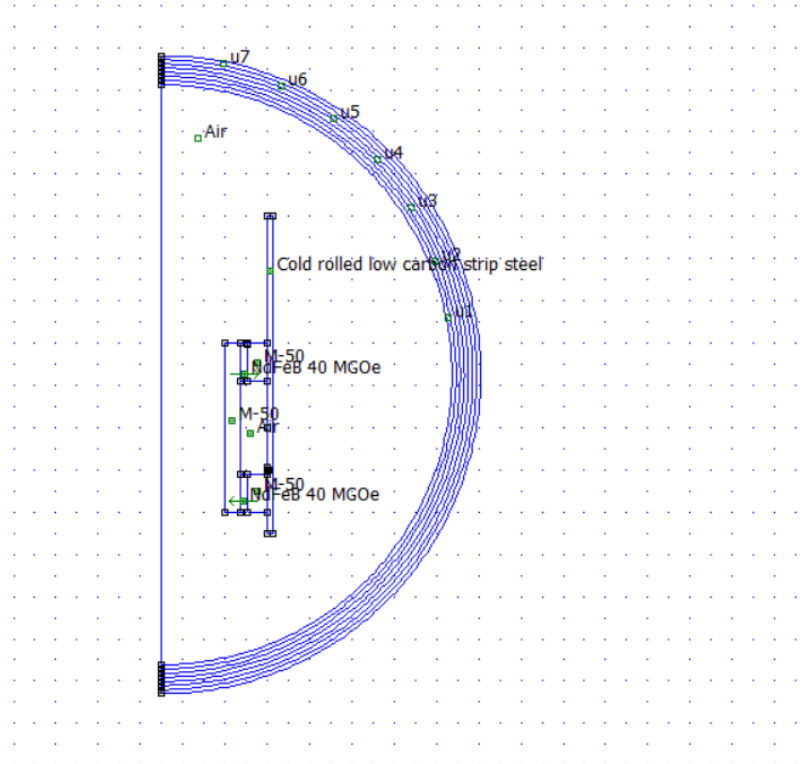
References

Bibliography

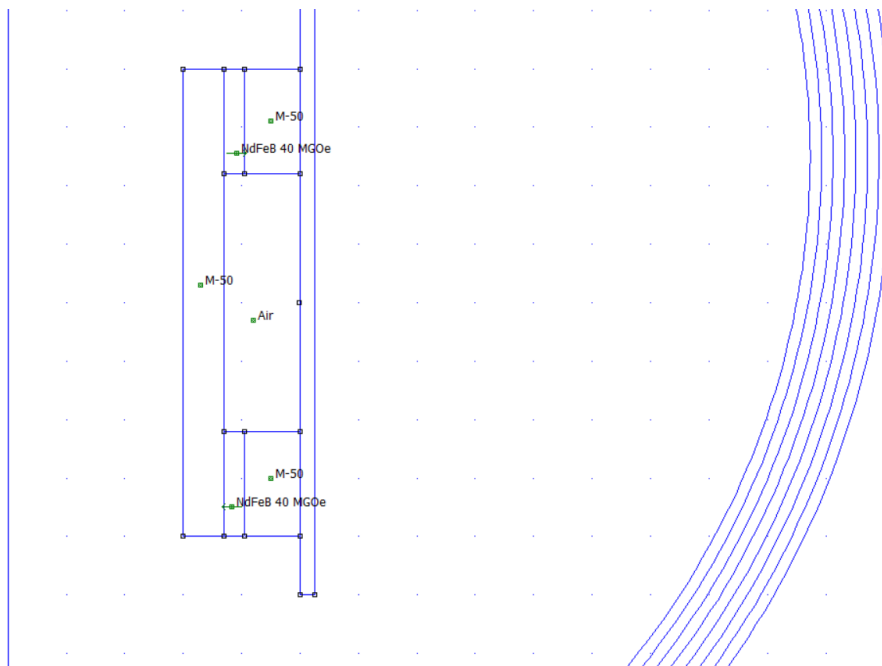
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Appendix

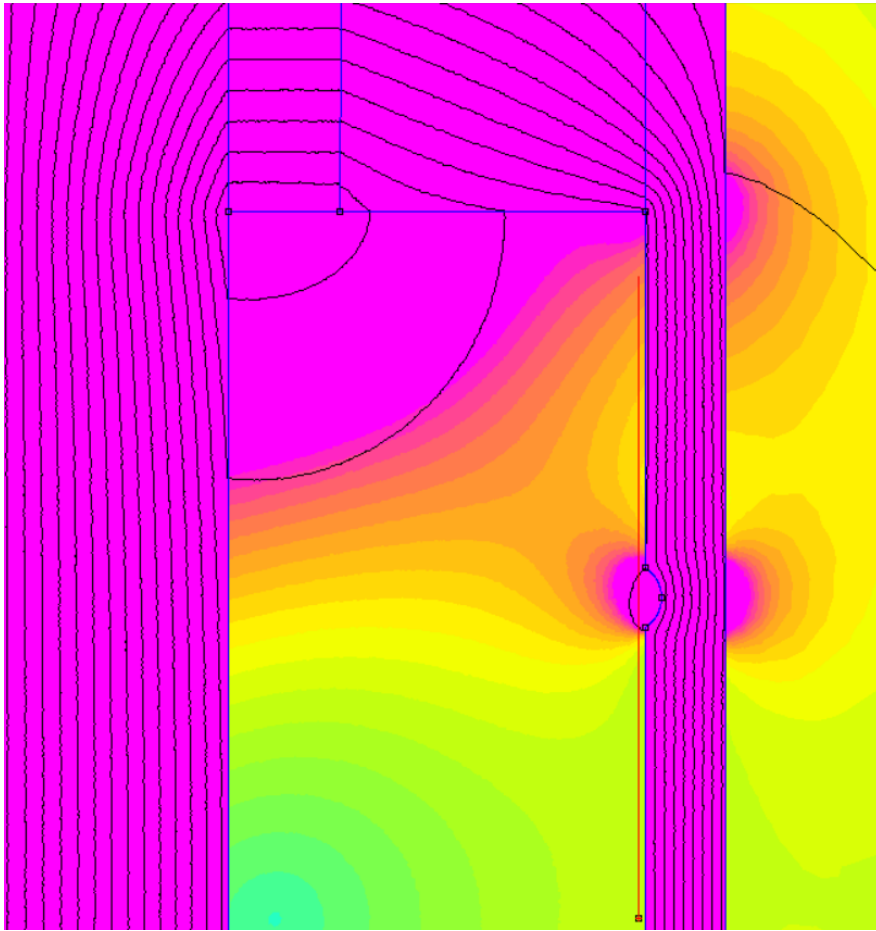
1. Boundary box



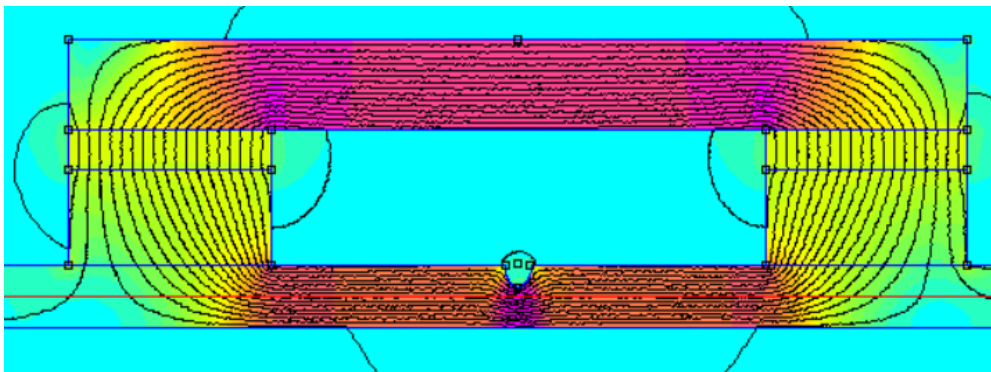
2. Sensor node



3. Producing graphs from a line



4. Optimisation Comparison



5. Magnetic Flux Paths

