SECURING THE BEST PERFORMANCE ENTITLEMENT FROM MFL TECHNOLOGY

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INTRODUCTION

The art of designing Magnetic Flux Leakage (MFL) tools for the inspection of pipelines has been established over the past 40 years. This paper investigates the science behind the art, and describes the fundamentals of MFL magnetiser design, focusing on the effects that various design options have on magnetic performance. Comparisons are drawn between a magnetiser bar design (hereafter referenced as "magbar") and solid core bristle design (hereafter referenced as "sweep's brush") including variations upon each. The study was carried out through the combined use of Vector Fields 3D & 2D finite element modelling and analysis software.

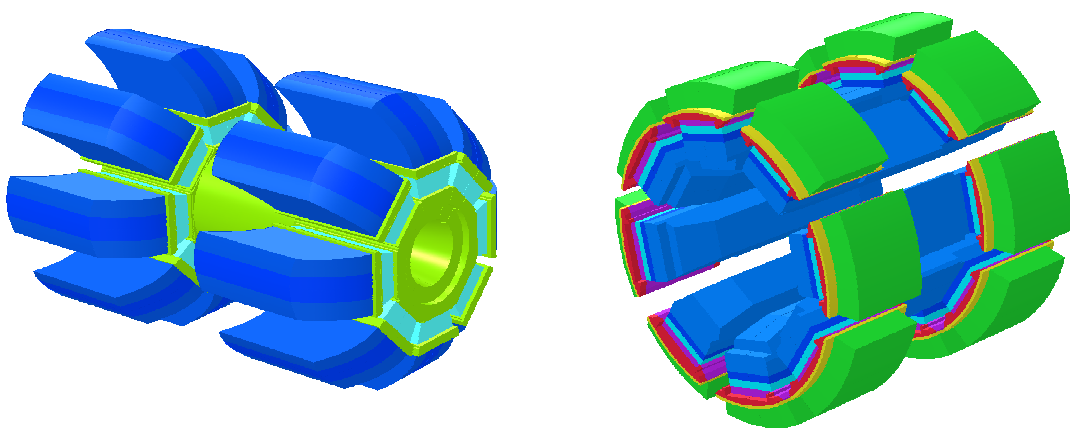

Figure 1 *– Example magnetiser models created in Vector Fields Opera 3D FEMM package. Solid Body Sweep's Brush (Left), Magbar (Right)*

The basic design of sweep's brush and magbar approaches are shown in Figure 1. Essentially, a sweep's brush magnetiser design consists of a solid or annular carbon steel body with magnets arranged around the circumference at each end. The magnetic circuit is completed through the use of ferromagnetic bristles mounted onto the magnet material in order to transmit the flux to the pipe-wall. This is a relatively simple design with few moving parts, yet it has proven itself extremely effective both in magnetic and mechanical performance in a wide variety of pipelines.

A magbar design is achieved through the use of distinct return paths (RP) with magnets attached to the ends of each. These bars are sprung off a small central body, which is not integral to the magnetic circuit. This allows the magnet material to ride much closer to the pipe-wall, reducing the magnetic circuit length and eliminating the need for high reluctance bristles. These designs tend to have shorter poles, which are able to transmit magnetic flux more effectively into the pipe. The magbar arrangement however, has annular gaps due to requirements for radial restriction, which can result in an uneven flux distribution within the pipe-wall. Sweep's brush designs do not suffer from the same effect since long bristles distribute evenly over the inner circumference.

Mechanical Considerations
Magbar designs require more complex mechanisms due to the required radial freedom of the each distinct return path. At any step in pipeline inner bore, the mass of the return path with magnets must be rapidly accelerated inward as the pig travels over the obstacle. In the case of the sweep's brush design the long bristles will 'flick' easily over them while maintaining contact. Bend and bore passing require additional considerations & detailed design for magbar designs. Sweep's brush magnetisers are very straightforward and can more easily deal with varied pipeline geometries such as 1.5D bends while maintaining a stronger magnetic circuit as discussed later.

Drag & Clamping Forces
Magnetic clamping forces are directly proportional to local flux magnitudes and the gap between the pipe-wall and the magnetiser coupling. Larger and varying clamping forces increase and influence tool drag and overall dynamic ride through the pipeline, affecting data quality and inspection. Velocity and dynamic influences are significant to magnetic response and inspection performance. Optimally, designing a coupling to a target field level with minimum variance, such as with steel bristles, will allow for a known and predictable dynamic performance.

REQUIRED FIELDS FOR OPTIMUM INSPECTION

It has always been a subject of debate as to what pipe-wall field levels are required for top specification inspection. One important factor in achieving the best quality inspection is ensuring saturation of the entire pipe-wall. If we consider the BH curve of pipe-steel (figure 2), which is a continuous function, there is no clear boundary above which saturation is achieved. The American Society for Testing and Materials [1] define magnetic saturation as, *"That degree of magnetization where a further increase in magnetization force produces no significant increase in the magnetic flux density (permeability) in a specimen".* Hence, as a target, figure 2 shows the region above 6.4kA/m in saturation where the curve has become approximately linear. This BH curve is an average of a number of modern X-grade pipe-steel samples dating back to the 1970's. Since there will inevitably be variability in the interpretation of a BH curve saturation region, real defect data must be considered in order to consistently determine inspection capability. Limits need to be placed through comparisons between defect sizing from inspection, pull-throughs and excavations in order to find a realistic acceptable field level.

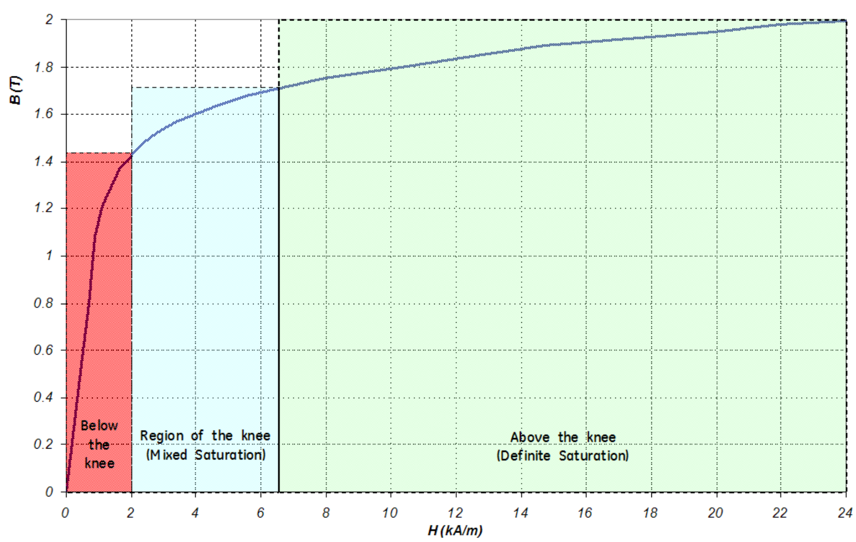

Figure 2 *– Example pipe-steel BH curve created from an average of a number of samples.*

An example of such data is shown in figure 3 where the same external defect was inspected first using an MFL vehicle in full magnet and subsequently half magnet build. This study provided a direct comparison of inspection capability for a real tool at various pipe-wall fields whilst reducing the influence of other sources of variability. It is clear that both traces are ‘clean’ with the higher field trace being slightly cleaner and yet the 10x10mm x 42% external defect is still clearly defined and hence the sizing will be exactly the same in either case.

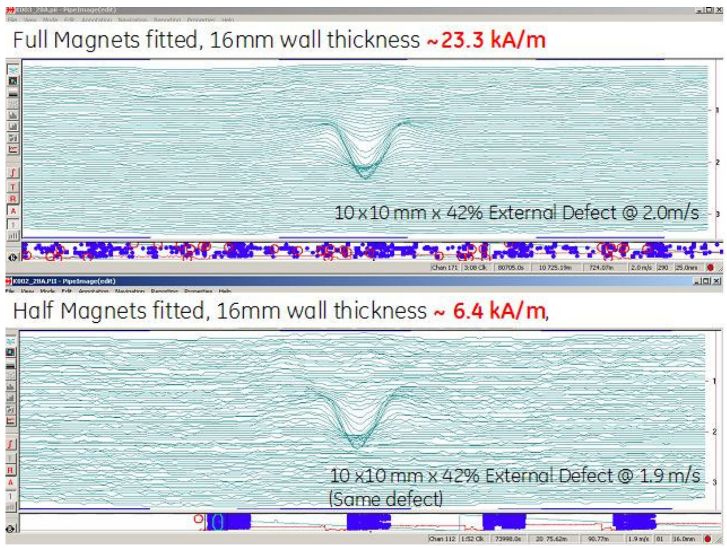

Figure 3 *- 10x10mm x 42% external defect inspected at pipe-wall fields of 6.4kA/m (80 Oe) and 23.3kA/m (293 Oe) in 16mm WT by sweep’s brush magnetiser with full/half magnet build*

This example demonstrates that whilst high field levels are preferable, it should not be an overriding design target. Magnetiser designs should be a balance between achieving sufficient field for the highest specification inspection and producing uniform field profiles in order to reduce noise due to the harsh pipeline environment. The data of figure 3 was recorded by a sweep’s brush magnetiser designed specifically to reduce all sources of noise experienced in a pipeline. However, a short pole magnetiser designed solely to achieve high field levels would be likely to show more noise during an inspection since the sensor will be moving across large field gradients as it experiences vibration. Even if it is operating far above the ‘knee’ on the inner wall, on the outer wall the fields will be a great deal lower at velocity and hence the flux leakage will be subject to large variation.

It is accepted that operating below the ‘knee region’ of the BH curve will result in increased responses from material variations and hence inspection should still be possible but at a lower inspection confidence level. Conversely some magnetiser designs claim to exploit the sensitivity to material effects in this mixed region in order to perform in-line stress detection but are subject to the same impact on reported inspection confidence.

VELOCITY EFFECTS

It is well known that magnetiser performance is susceptible to speed-dependent influences. It is generally noted that shorter return paths/magnetic circuits are able to yield higher peak fields statically (i.e. at zero speed) in a pipe-wall, however there are other effects to consider such as the uniformity of the pipe-wall field distribution as well as response to velocity-induced eddy current effects. Additionally, the effects of magnetiser and sensor lift off on defect signals can also be important.

Faraday's Law states that a changing magnetic flux with time will generate an emf (ε) in an electrical conductor (equation 1). According to Lenz's law, this induced emf will generate a magnetic field, called the induced field, which will act to oppose the field that created it.

$$\varepsilon = -\frac{dB}{dt} \qquad (1)$$

If these laws are applied to a magnetic pig passing through a pipeline then a number of issues become apparent. A section of pipe will experience a change in magnetic flux as a pig passes over it, and since pipe-steel is a good electrical conductor, an emf will be generated in the wall. This will exhibit itself as eddy currents circulating in the pipe-wall and in turn (according to Lenz's law) these will generate magnetic fields opposing those generated by the pig. The greater the velocity of the pig and the conductivity of the pipe-steel, the greater the eddy current effect will be.

$$\bar{J} = \sigma \bar{v}_C \times \bar{B} \qquad (2)$$

The current density, **J** generated in the pipe is determined by equation 2 where $\mathbf{v_c}$ is the velocity of the conductor relative to the field **B** and $\boldsymbol{\sigma}$ is the electrical conductivity of the material in question. Hence, current density will be at a maximum when field and velocity vectors are orthogonal. In the case of a pig passing through a pipe, its velocity is in the axial direction and therefore current densities will be at a maximum where radial fields are high within the pipe (circumferential fields are negligible). The maximum radial pipe-wall fields are experienced at the points of bristle/pole contact and hence this is where we would expect the highest current densities (figure 4 [left]). These regions are where the eddy currents will be strongest and where the highest opposing fields will be encountered. This will act as a shield against the applied magnetic field and attenuate radially across the pipe-wall. Hence, with increasing speed, the axial field levels around the sensor position will drop on the outer diameter and increase on the inner diameter of the pipe as the field is channelled away from the outside wall. This effect is demonstrated in figure 4 (right), which shows a selection of axial field contour plots at various speeds.

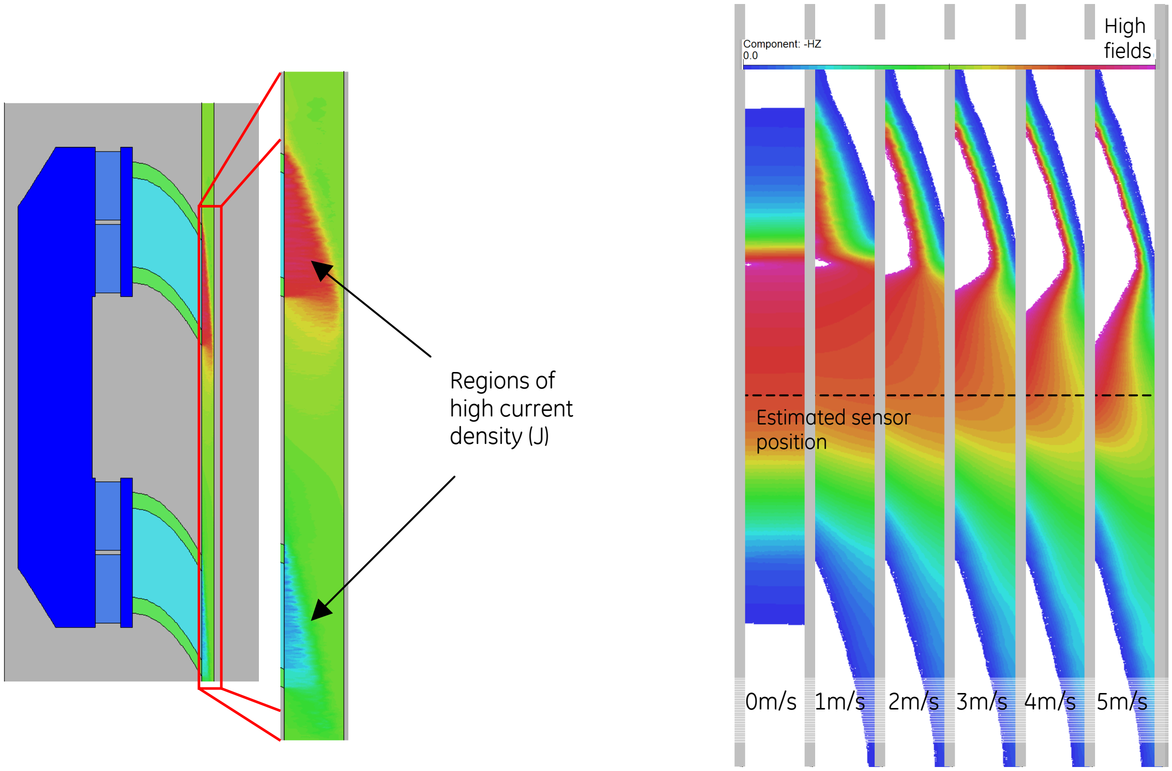

Figure 4 *– 2D finite element contour plots, current density analysed at 5m/s (Left) and axial pipe-wall fields across the velocity range 0-5m/s side-by-side (Right)*

In figure 4 (right) the ideal situation is encountered at 0m/s where the pig is stationary and hence not generating eddy currents in the pipe-wall. In this case, for any given axial sensor position, the field across the wall thickness is homogeneous. However, at higher velocities the effect of the eddy currents and induced field become apparent. These field gradients across the wall thickness create a number of issues. Since the applied fields will always be higher on the inner wall than the outer, some degree of post-processing compensation will be required to correct the signal amplitudes produced by defects. Also, more importantly, field levels on the outer wall may have decreased to a level where inspection is no longer possible and hence external defects may be missed entirely. Magnetiser design and performance is based on the weakest level obtained in the worst "magnetic" operating conditions such as at high speed or increasing wall thickness. Moreover, as a design practice, this "weakest" magnetic point is considered and optimised against our defined saturation levels, so as to confirm the confidence and accuracy in the inspection performance.

Another issue will be in the recording of the pipe-wall field. Axial field is continuous across the pipe-air boundary and hence it is easy to obtain a good measure of the field on the inner pipe-wall. However, it is clear from figure 4 that the fields on the outer wall can be significantly lower that those recorded by a sensor riding on the inner wall and hence non-static in-line data predictions will not represent the behaviour across the entire wall thickness.
A clearer view of the pipe-wall field behaviour with speed is shown in figure 5. The attenuation across the pipe-wall is shown clearly at 3m/s as the fields are reduced to 0 on the outer wall near the front bristle stack. This data was taken from a relatively long return path magnetiser; hence the effect would be more severe even at low velocities for a short return path design (demonstrated later in this paper). So even in this case at 3m/s a measure of the pipe-wall field taken from the internal sensor will overestimate the field on the outer wall by approximately 20%. This value will increase to 55% at 5m/s. It is for this reason that correction factors are derived and understood through both finite element modelling and database pull-throughs across the velocity range in order to give an accurate picture of pipe-wall field levels.

As pipe-wall field levels are now becoming more of a consideration for pipeline operators running MFL tools it is important that all inspection vendors define where field level predictions/measurements are taken with respect to the inner/outer wall and under what conditions, consistent with standards such as POF [2].

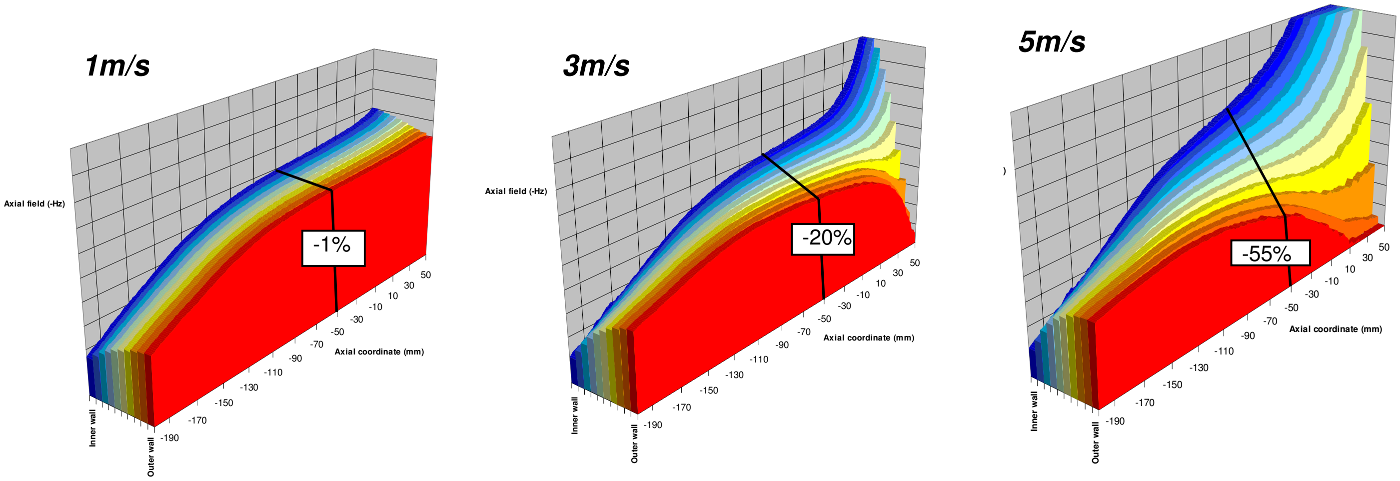

***Figure 5** – 3D axial pipe-wall profile plots between magnetiser poles analysed at 1, 3 & 5m/s. Estimated 2/3rds sensor position indicated by black line with percentage drop in field across pipe-wall shown at this axial coordinate.*

EFFECT OF POLE SPACING

A realistic representation of a sweep's brush magnetiser design was modelled and analysed through FEM. The spacing between the bristle stacks was then decreased in increments and hence an additional 3 designs were created.

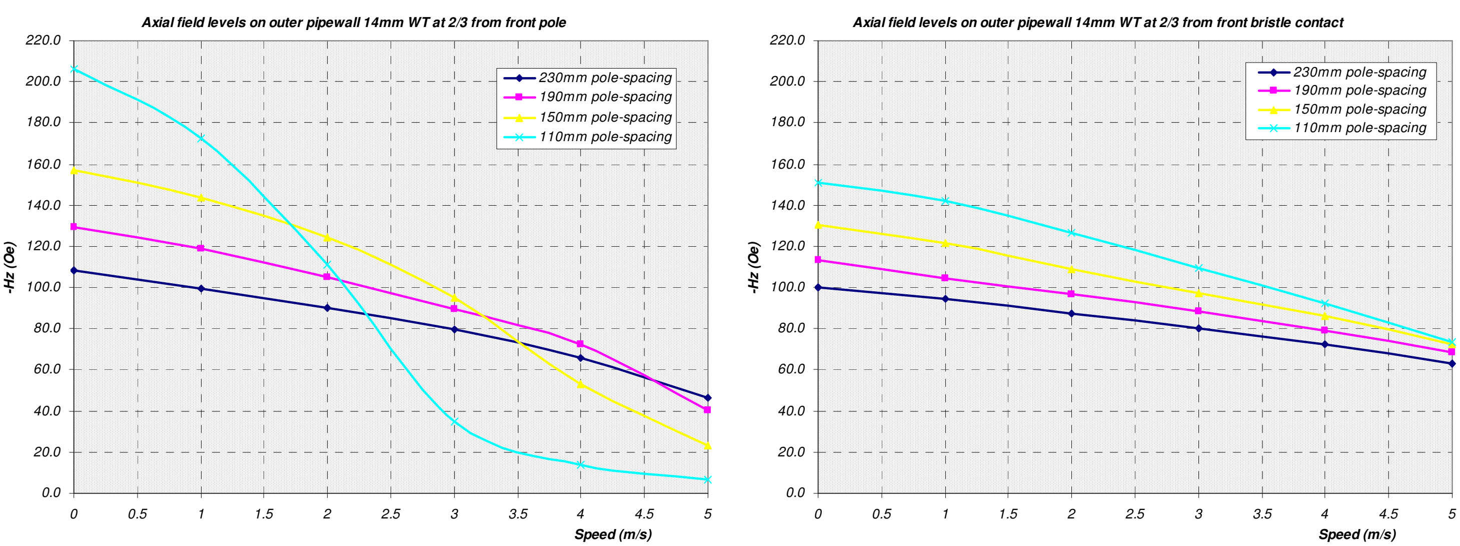

***Figure 6** – Axial field recorded at estimated sensor positions (2/3 back from front pole/bristle) across a velocity range 0-5m/s in 14mm wall thickness*

Long pole-spacing designs are not able to rival the fields generated by short versions at low velocities. However, as they are more stable and better able to maintain field across the velocity range it is likely that they will out-perform in a number of other important respects. The effect of eddy currents is shown very dramatically for the 110mm model (figure 6 [left]) where an inflection is clearly shown in the field values around 2m/s. Beyond 3m/s the field has collapsed and external wall inspection may no longer be possible. A more suitable sensor position would be at 2/3^{rds} back from the point where the bristles contact the wall (figure 6 [right]). At this location the field behaviour of the short magnetiser has changed significantly compared to the long version, which has barely altered. This demonstrates the sensitivity to sensor movement of magnetiser designs where the drawbacks of using short pole spacing in order to achieve high fields at low velocity have not been addressed. Also, in general, long pole spacing will allow more physical space for sensors and supporting instrumentation within the magnetiser pole area.

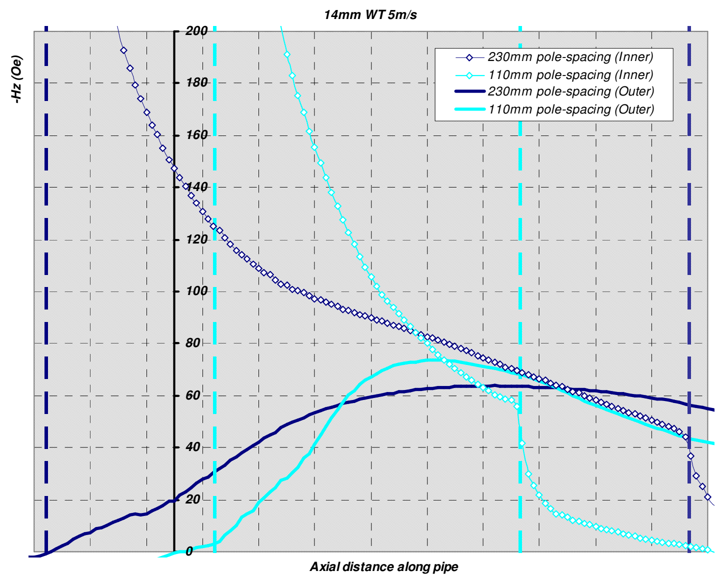

Figure 7 *– Axial field profiles on inner and outer pipe-wall for comparison at 5m/s in 14mm wall thickness*

Finite element modelling provides key insight into identifying the ideal or ‘sweet spot’ sensor position. This position will be highly dependent on design targets. Ideally the sensor should be placed in a region of uniform field both axially along the pipe and radially through the wall thickness. It should also be in a position where variation in field level across the speed range is at a minimum but absolute field levels are still high. Since it is very unlikely that all of these targets will intersect a single point on the field profile, there must be some prioritisation. Then, whilst also considering mechanical constraints, a suitable sensor position can be found.

Field gradients across the wall thickness demonstrated in figure 5 are displayed in more detail for this example in figure 7 at 5m/s. As discussed earlier one of the criteria for the ‘sweet spot’ sensor position is a uniform distribution across the wall thickness. These positions are shown in figure 7 as crossover points where the field on the inner wall is equal to that on the outer. It is obvious here that a long pole spacing will be more forgiving in this positioning since the field gradients are much lower than that of a short magnetiser. Sensor position is crucial since field levels can be more than twice as high on the inner wall.

MAGBAR VS. SWEEP'S BRUSH DESIGNS

In order to compare magbar and sweep's brush designs, two realistic models were created and analysed. A number of designs were created and varied from actual dimensions of existing tools in order to compare the sensitivity and performance of each through FE simulation.

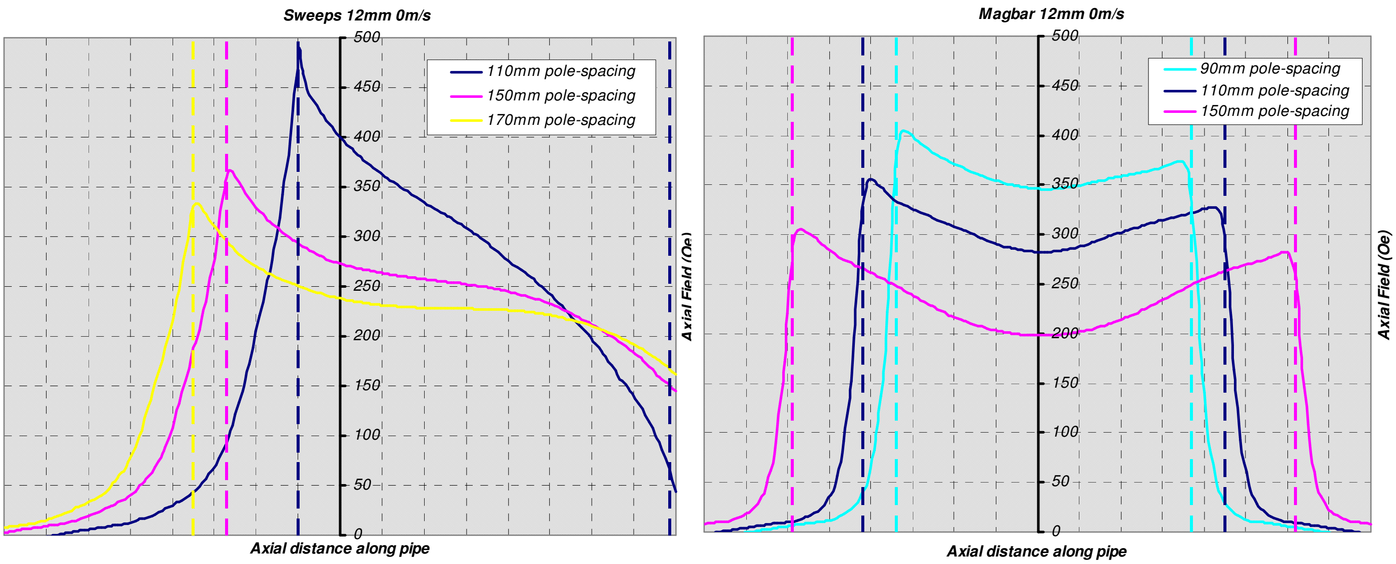

***Figure 8** – Axial field profiles on outer wall comparing sweep's brush and magbar designs with matching pole spacing at 0m/s, 12mm wall thickness. Sweep's brush (left), Magbar (right)*

In the static case the original models (Sweep's: 150mm, Magbar: 110mm) demonstrate that the sweep's brush magnetiser is producing a more uniform field across the estimated sensor position (figure 8). The magbar profile exhibits the characteristic 'M' shape with a relatively large field gradient from the poles to the centre. Any movement of the sensor in the axial direction will sweep it across a field gradient, introducing variability into any defect signal, risking an impact to sizing accuracy and precision. Although, by geometry, the axial movement of a sensor on a magbar *is* more restricted than for a sweep's brush. The field gradient is very similar across the pole-spacing range for the magbar design. There is some observable improvement at the centre of the profile but this is also where field levels are at a minimum. Since this design can produce a higher field with a shorter pole-spacing and gains no real advantage (at least in the static case) from having a long pole spacing vs. an equivalent sweep's brush pole spacing then it would indicate that magbar designs generally preclude and favour a short pole-spacing. A sweep's brush design with long pole spacing shows significant improvements in field uniformity even if it results in a drop in peak field.

Now let us consider the same designs at the top of the velocity range in figure 9.

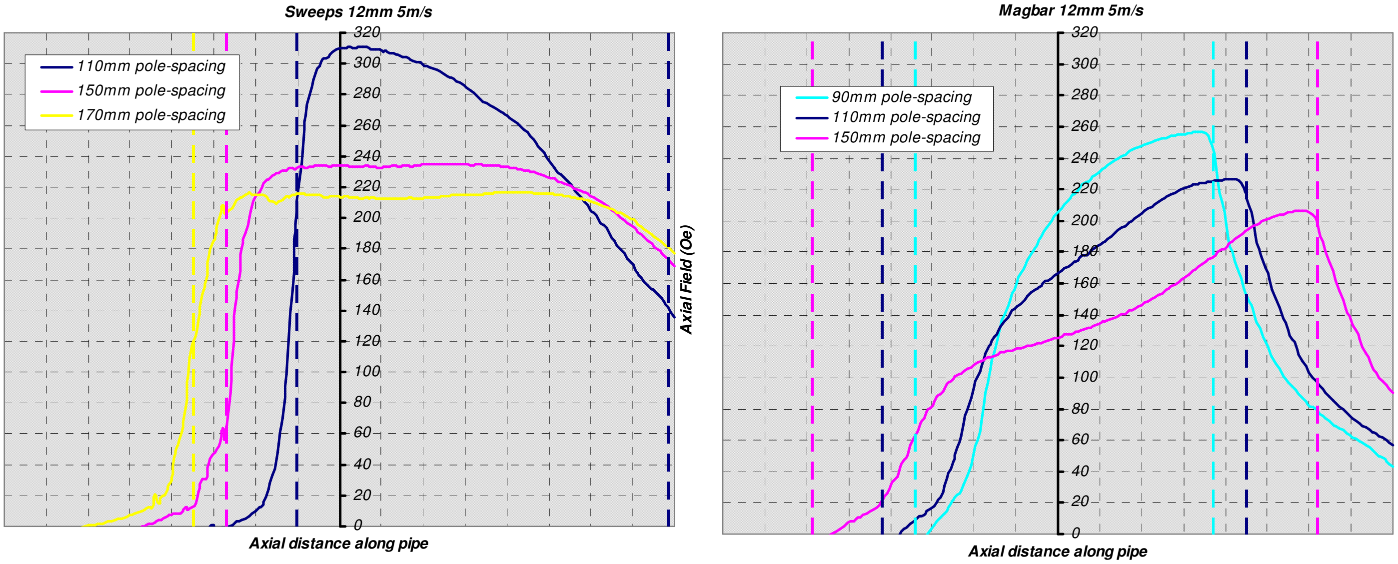

Figure 9 *– Axial field profiles on outer wall comparing sweep's brush and magbar designs with matching pole spacing at 5m/s, 12mm wall thickness. Sweep's brush (left), Magbar (right)*

Even at 5m/s the sweep's brush is maintaining a very uniform distribution with exception to the shortest model, which is beginning to show large field gradients. The magbar design shows very narrow field profiles, again with high field gradients between the poles. However, at high velocity there is some linearity gained from having a long magnetiser at the sacrifice of field level.

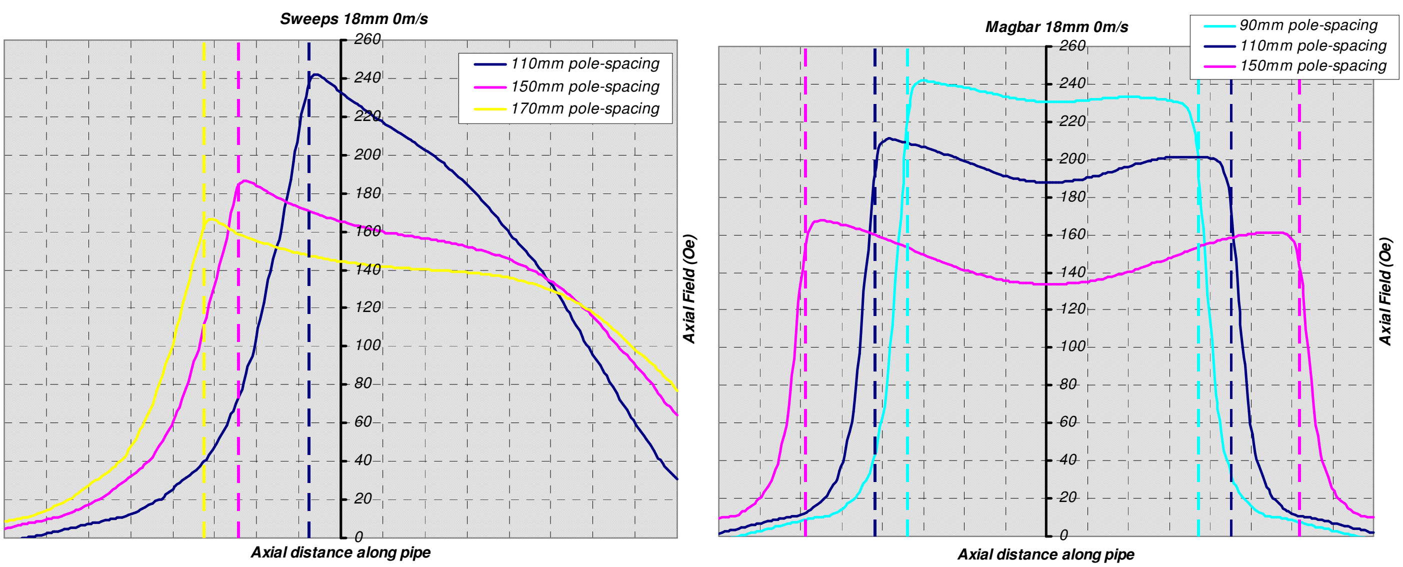

Figure 10 *– Axial field profiles on outer wall comparing sweep's brush and magbar designs with matching pole spacing at 0m/s, 18mm wall thickness. Sweep's brush (left), Magbar (right)*

In 18mm wall (static) the situation is similar (figure 10), however the magbar field profile appears more uniform than in thin wall. Notably, the expected drop in field is observable and the peaks of the profiles have been reduced. Velocity effects are more severe in thick-wall where peak field levels have dropped and the profiles have narrowed and shifted considerably (figure 11). Even the sweep's brush design has lost the uniformity seen in thinner wall but maintains a higher field than the magbar equivalent. Short pole spacing designs are still achieving the highest peak fields for the sweep's brush but the magbar no longer shows adequate field levels at the outer wall at 5m/s.

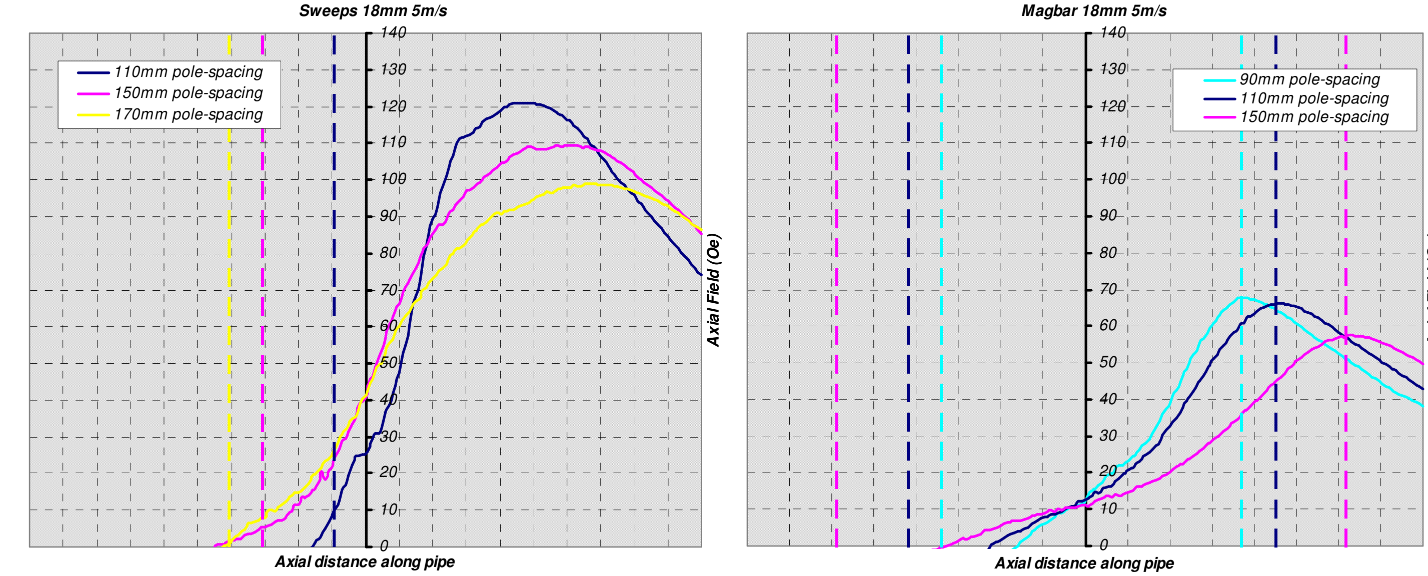

Figure 11 *- Axial field profiles on outer wall comparing sweep's brush and magbar designs with matching pole spacing at 5m/s, 18mm wall thickness. Sweep's brush (left), Magbar (right)*

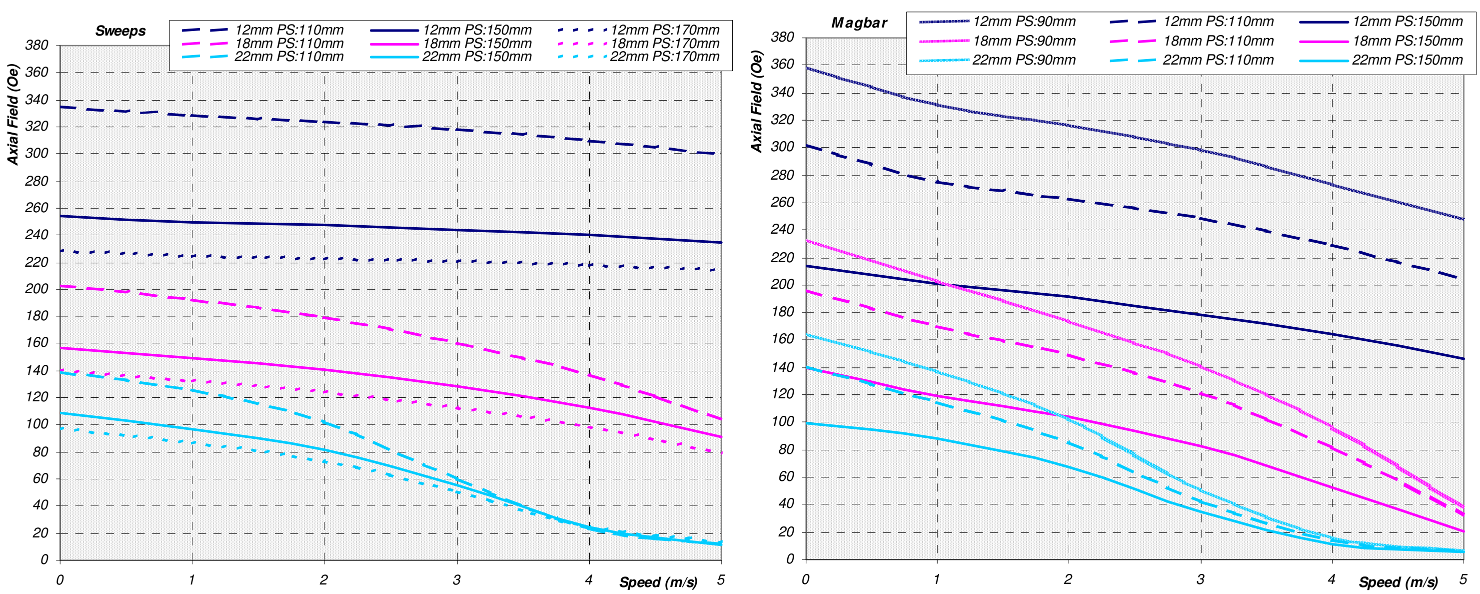

Figure 12 *– Axial field on outer wall at estimated sensor positions across velocity range 0-5m/s and wall thickness range 12-22mm. Sweep's brush (left), Magbar (right)*

The complete picture at the sensor positions is shown in figure 12. Overall the sweep's brush design is the more robust of the two in coping with speed effects and producing a uniform pipe-wall field profile whilst still delivering good field strength across the range. This produces the most stable environment, which is a pre-requisite for obtaining the best inspection specification.

In summary, the data shows that the design decision for both magnetiser styles essentially comes down to a compromise between speed capability and peak fields. Long return paths improve speed capability predominantly for sweep's brush designs, the effect is reduced for magbars. It is not possible to get the best of both designs by choosing a long magbar or a short sweep's brush. In doing this, the advantages gained through the use of a specific design are lost. The initial choice between magbar and sweep's brush will be the overriding decision in the properties of the pig (i.e. dynamic performance, geometry requirements). Optimisation after this initial decision will not deliver all of the desired capabilities without novel magnetiser design unlike the standard models analysed in this paper.

MAGNETISER AND SENSOR LIFT OFF

Most magnetiser designs endeavour to maintain a good coupling to the pipe-wall at all times in order to transmit the flux effectively. Sweep's-brush magnetisers ensure good contact through the use of long flexible bristle stacks, which follow the profile of the pipe extremely well. Magbars generally accomplish contact through a spring loading from a central body combined with the inherent magnetic attraction between the pipe-wall and the magnetiser. In order to ensure good magnetic contact with the pipe in a bend it is preferable to have a short return path with magbar designs. Sometimes magbar designs are fitted with short bristles or foils to help maintain magnetic contact in the bend. However, loss of contact with the pipe-wall is unavoidable in some circumstances. The magbar design in this investigation was modelled with a very short and dense bristle stack.

Magnetiser lift-off is defined as the distance between the magnetiser's contact poles and the pipe-wall. The scenario modelled here is of a magnetiser losing contact with a straight section of pipe-wall by various degrees of lift-off.

It is generally accepted that increasing *magnetiser lift-off* will increase the air-coupled field and hence decrease the sensitivity of the sensors. The effect of *sensor lift-off*, which is characterised by the distance of a sensor's standoff from the inner pipe-wall, is a decrease in amplitude and loss of the high frequency signal components. Sensor lift-off can occur due to geometric features, debris or even self-vibration. Hence, the combined lift off will produce an underestimate of defect depth, an overestimate of defect length and a possibility of missing small defects entirely. Some of these effects, if well understood, can be compensated later in the analysis of the data. Figure 13 compares the susceptibility of magbar and sweep's brush designs to lift off in respect to pipe-wall fields.

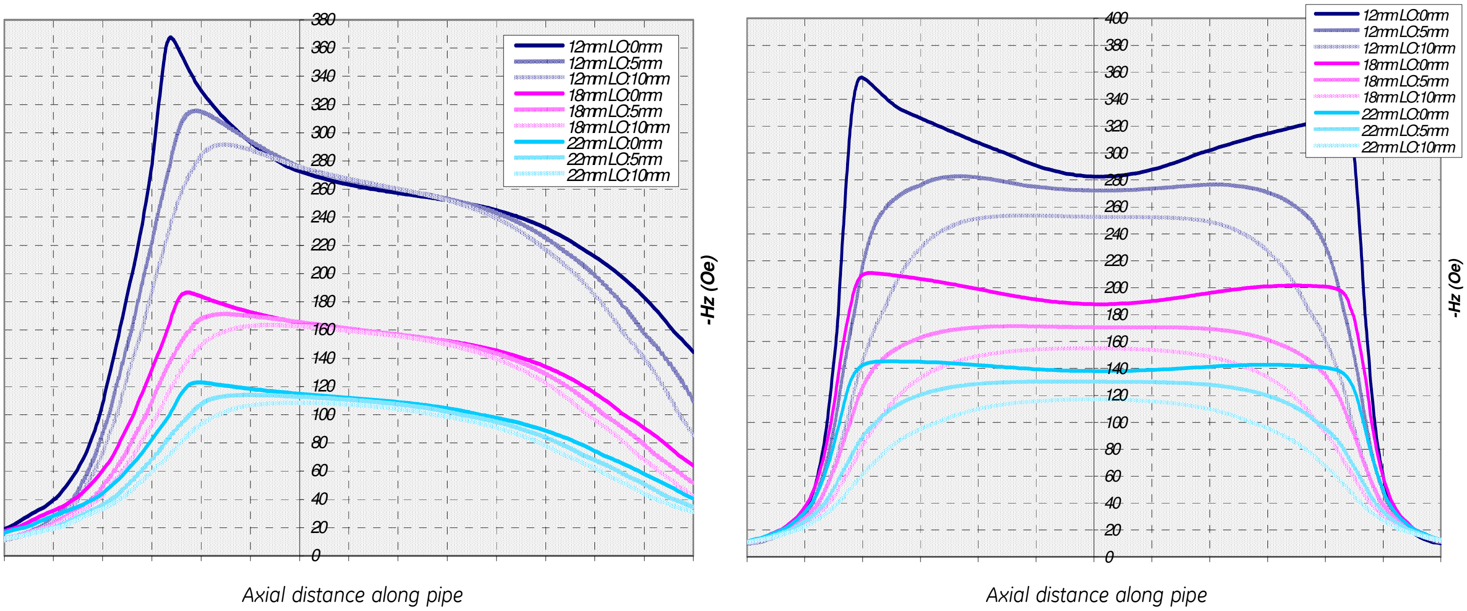

Figure 13 *- Static axial outer pipe-wall field profiles for various degrees of lift-off in 12-22mm wall thickness. Sweep's brush (left), Magbar (right)*

The smoothing and narrowing of the distributions shown in figure 13 is a result of flux leakage due to the modelled air-gap, as discussed above. The magnetic flux is no longer transmitted into the pipe-wall as efficiently; instead it is jumping the gap and spreading into the inter-pole region. As a result the peak axial fields in proximity to the poles are reduced with larger lift-off in both designs.

However, the effects are negligible across the centre of the sweep's brush field profiles. This is crucial since this is the region where the sensors will be located. Hence, the static effects of lift-off would not have a significant affect on the flux leakage due to a defect in this region of the distribution. However, the magbar design shows a drop in field across the entire profile, and hence, sensor position. A decrease in pipe-wall field will result in a decrease in flux leakage experienced at a defect. Both designs will suffer from the effects of sensor lift off in a similar way.

Figure 14 confirms these principal findings; lift-off does not affect pipe-wall axial field levels at the sensor position for the sweep's brush example (stationary case here). However, as predicted, the air-coupled axial field within the pipeline *does* increase with increased magnetiser lift-off but only by a minor degree. The greater the lift-off of the sensor the higher the field levels it will experience within the measured range. Also, the greater the lift-off of the magnetiser the larger the air-coupled field within the pipe and therefore the higher the axial field levels across the sensor. The combination of these effects will mean that a sensor and magnetiser experiencing extreme lift-off will overestimate the axial field in the pipe-wall by less than 9%. However, 10mm lift-off is extremely unlikely especially around the entire circumference of the pipe.

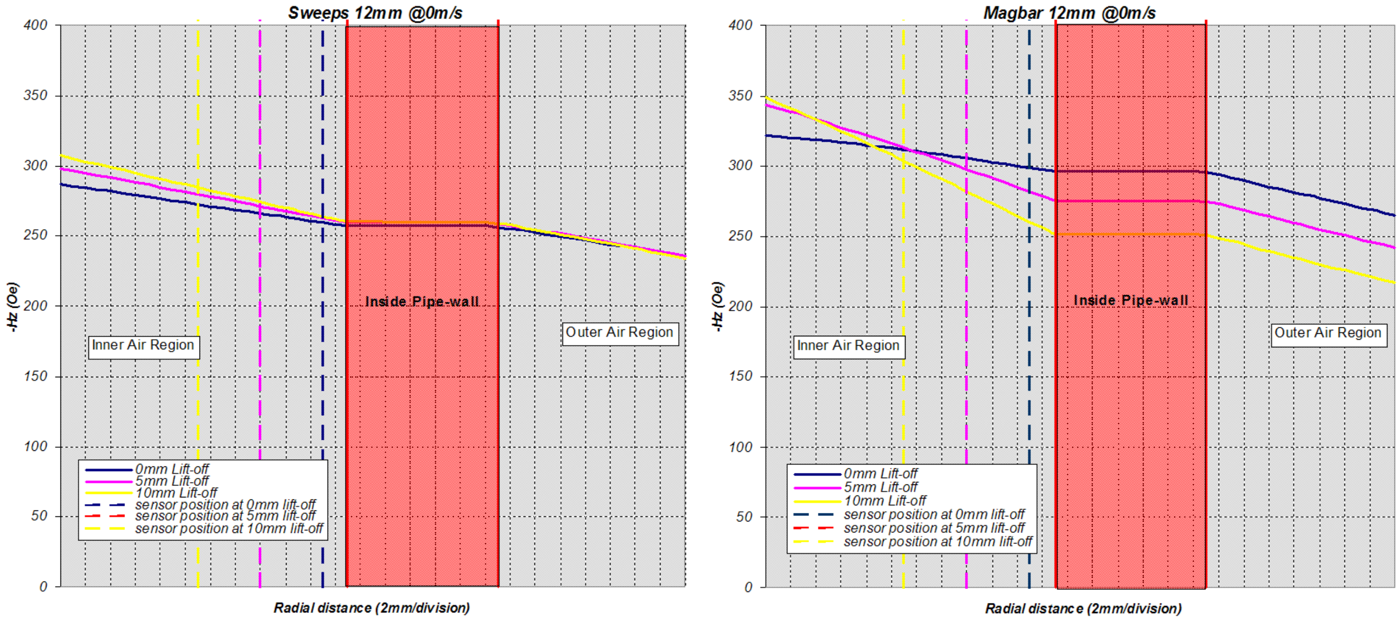

Figure 14 *- Axial field levels at the estimated axial position of the sensor on a radial line from within the pipeline to the outer air region for 0mm/5mm/10mm magnetiser lift-off. 12mm wall thickness with static analysis (pig speed = 0m/s). Sweep's brush (left), Magbar (right)*

Unlike the sweep's brush, the magbar design experiences a drop in pipe-wall field due to magnetiser lift-off at the axial sensor position. The magbar design relies on low reluctance poles contacting the pipe-wall in order to achieve high field levels, hence when an air gap is introduced the change in the magnetic circuit is significant. As a result of this, axial field levels in close proximity to the inner and outer surface of the pipe-wall are also affected. Whilst it is obvious that the axial field gradient is higher with increased magnetiser lift off, the field levels close to the inner surface of the pipe are actually lower for increasing lift-off. This is a direct result of the offset introduced by the drop in pipe-wall field levels, which cancels out the affect of lift-off at the sensor. Hence, the sensor will not detect a change in pipe-wall axial field with lift-off up to 10mm. In other words the collected data will be inconsistent with actual pipe-wall field levels. The combination of magnetiser and sensor lift-off will result in an overestimate of the pipe-wall field of up to 21%. This is more than twice the error experienced by the sweep's brush design. Again it must be said that 10mm lift-off is highly unlikely, yet the comparison between sweep's brush and magbar designs remains relevant.

Lift off data was also analysed across a range of speeds from 0 to 5m/s but the findings indicated that this effect is independent of speed. Any reduction in pipe-wall field due to lift off will be exhibited across the entire speed range.

CONCLUSIONS

There are a wide array of conflicting considerations that must be made in the design of a high specification MFL inspection tool. This paper has shown that designs should be chosen and optimised to meet specific targets. A magnetiser with short pole spacing can easily generate high peak pipe-wall fields at low velocity but in order to reduce the effect of eddy currents and maintain a healthy field level across the entire cross section of pipe, at a wide range of speeds (0-5m/s), a long return path by far the preferred choice.

The mechanical implications of choosing either a magbar or solid body sweep's brush design will determine the upper limit on return path length. Solid body sweep's brush designs are suited to a long return path (and pole-spacing) whilst still maintaining bend-passing ability. Magbar designs will be limited by the radial degree each bar is able to compress when encountering tight bends. A short magbar will be able to apply high pipe-wall fields at low velocity but will lose detection sensitivity at speeds in thick wall pipe. Long return path sweep's brush magnetisers are more capable of maintaining this detection across the entire speed range. This ability to inspect reliably at high velocity is of great value to pipeline operators since slowing product flow will result in significant throughput losses. For gas pipelines, it is possible to utilise a bypass system in order to reduce tool speed, but it is better to start with a tool with a higher native inspection speed capability and reserve the bypass system for even faster flow speeds.

Also, long pole spacing designs produce more uniform field profiles, which ultimately reduce noise, increase defect-sizing repeatability and allow for greater freedom in sensor positioning. PII Pipeline Solutions have designed novel sweep's brush magnetisers which deliver higher fields than standard brush designs, across the full speed range of 0 to 5m/s

Mechanically, the solid body sweep's brush provides a simpler and more robust design using the inherent length of bristles to provide additional suspension for the vehicle. It is also capable of reliably maintaining contact with the pipe-wall while reducing vehicular vibration noise and the likelihood of damage. A magbar design is required to take all of the impact from an in-pipe obstacle or weld, increasing the chances of damage, lift-off and noise on the collected data.

It is important to remember that whilst high pipe-wall fields are preferable in general, it has been shown that they are certainly not the only consideration to be made. Attempting to achieve high field levels using a short magnetiser results in severe drawbacks, which can compromise inspection ability.

Field levels have been shown to vary across a pipe thickness at speed, being lower on the outer wall where internal sensors are not able to measure. Specifically, it is important to be aware that a tool producing high field levels on the internal wall can be deficient in field across outer wall defects due to eddy current effects. Where field level is concerned, the value measured at the outside wall is much more relevant.

Ultimately, the real challenge is the ability to detect and accurately size defects anywhere in the pipe wall over a wide range of product speeds. To deliver this capability we need to take account of many complex issues as outlined in this paper. Concentration on any single parameter at the expense of others will lead to a sub-optimal design.

REFERENCES:

[1] American Society for Testing and Materials, "Standard Terminology of Symbols and Definitions Relating to Magnetic Testing," Volume 03.04, designation: A340-89a

[2] Pipeline Operators Forum (POF) document "Specifications and Requirements for Intelligent Pig Inspection of Pipelines"