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ESTIMATION OF PERMEABILITY FOR MAGNETIC FLUX LEAKAGE MODELLING

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Abstract − Non-destructive testing techniques are generally used for the evaluation of material properties and the detection of defects in pipelines. Especially, the measurement of magnetic flux leakage (MFL) is one of the most used methods for in-service monitoring of corrosion in buried oil and gas pipelines. However, for the geometrical reconstruction of defects in a pipeline from measured signals (the inverse problem), the magnetic properties of the material need to be known accurately. Due to the pipe geometry and wall thickness measurement of the bulk properties is complicated. In particular, the permeability of ferromagnetic steels shows a non-linear and hysteretic behaviour.

Current research is focussed on the measurement and simulation of the permeability of pipeline material. The magnetic properties of a small ferromagnetic test sample is first investigated using a transformer set up in order to find a correct fitting equation for the non-linear permeability as a function of the magnetic flux density. This equation is then used for model simulations of a MFL test set up. Refitting the parameters of the permeability equation to the permeability of the pipeline material in the MFL set up proved that flux leakage signals could be predicted accurately for several defects by model simulation.

Keywords permeability, magnetic flux leakage (MFL), finite element modelling

1. INTRODUCTION

Proper risk management applied to the management of gas or oil pipelines has become of immense value. Worldwide there are thousands of kilometres of pipelines of which many are at the end of their design lifetime due to stress (fatigue) and/or corrosion. Therefore, it has become very important to monitor the condition of components or structures both for the appearance of material degradation and material loss as well as to ascertain that the material properties of the structure still meet the functional requirements. Early detection of material degradation and accurate prediction of system reliability reduce maintenance costs and prevent, possibly, catastrophic, failures.

1.1. Non-destructive testing

Non-destructive testing methods include any form of testing or inspection that can verify the structural integrity of a component while the method is non-damaging and non-invasive. Measuring magnetic flux leakage (MFL) is one of the most economical methods that can be used for in-service monitoring of corrosion in buried oil and gas pipelines [1]. MFL tools use permanent magnets to magnetize the pipe's wall to near saturation flux density. If the wall's thickness is reduced by the presence of a defect, a higher fraction of magnetic flux will leak from the wall into the surrounding medium inside and outside the pipe. A Hall probe or an induction coil is generally used for the detection of this 'leakage flux'.

1.2. Inverse problem

Most research on electromagnetic non-destructive testing methods is based on the reliable detection of defects and their characterization. However, even though electromagnetic testing techniques have been developed to considerable levels of sophistication, successful application of these testing methods is still very limited. Fast and precise numerical methods are needed to post-process the magnetic measurements in order to attain an accurate evaluation of the geometric characteristics of the defects in a component. The electromagnetic inverse problem is however non-linear and ill-posed and it has been solved only for 2D problems or a simple 3D-geometry of the sample [2, 3]. Any effective inversion needs, as a first step, a complete understanding of the interaction between a defect and the field due to the probing source, i.e., the direct problem. Initial electromagnetic properties of the material need to be known in order to discern defects from non-defects. The capability to numerically model the materials' magnetic behaviour is complicated by non-linear and hysteretic effects [4]. Furthermore, accurate measurement of these properties is a complex task due to the pipe geometry and considerable wall thickness. Therefore, current research is focussed on the measurement and simulation of the permeability of pipeline material using measurements on a small ferromagnetic test plate.

1.3. Modelling permeability

Several models of magnetic hysteresis have already been presented in literature [5, 6]. Hysteresis can be caused by three types of phenomena: interaction between domains, anisotropy, and internal frictional pinning forces caused by dislocations, impurities etc. The dominant cause varies with the material.

Each model uses different theoretical assumptions relating to these phenomena that limit their performance and applicability. For example, the Jiles-Atherton model was developed as an attempt to create a quantitative model of hysteresis based on a macromagnetic fomulation [5]. The model describes isotropic polycrystalline materials (multidomain grains) in which the hysteresis phenomenon is represented as the consequence of a frictional force, which opposes to domain-wall motion. In the Preisach model, which is the most used hysteresis model in electrical engineering, the magnetic material is subdivided into many small independent magnetic particles [5]. Such an elementary particle switches abruptly from a magnetization (-*m*) to (+*m*), or vice versa, when the external magnetic field is increasing and reaches a certain value ($H=a$), or when the field is decreasing and reaches $H=b$, respectively ($a \geq b$; $a=b$ corresponds to a reversible process).

It must be noted that the scaling up of microscopic theories to account for macroscopic properties is a complex problem. Furthermore, many of the model parameters can only be interpreted as an average over all hysteretic mechanisms occurring in the material. In general, the parameters of the hysteresis models are calculated from the various intercepts and slopes taken from experimental hysteresis loops. Thus, at present, it is still necessary to obtain model parameters from curve-fitting procedures, even though a considerable number of models are based on a physical description.

In addition, for isotropic materials, one single *B-H* curve is used to describe the behaviour of material with the assumption that *B* is in the same direction with magnetic field *H*. When magnetic field *H* is applied in any direction, flux density *B* will follow this *B-H* curve. For anisotropic materials, the *B-H* relationship varies according to the direction of the applied magnetic field *H*, and the behaviour of material in each direction is different, so a single curve is not sufficient to express the material properties.

In this study no physics of the hysteresis phenomenon are considered. The material is assumed to be isotropic and material properties are investigated in only one direction. Using the permeability as an input parameter into a finite element model means that the hysteresis curve ($B=f(H)$) must be transformed ($\mu=f(H)$ or $\mu=f(B)$). The parameters of an analytical equation describing the permeability as a function of the applied magnetic field is fitted based on experimental data.

2. EXPERIMENTS AND MODEL SIMULATIONS

2.1. Transformer measurements and simulations

Measurement of the permeability as a bulk property of a material requires magnetization of this material homogeneously. Different levels of magnetization are needed for a complete hysteresis loop. Homogeneous magnetization of large samples up to saturation levels requires high magnetizing fields and thus permanent magnets of high strength or electromagnets that consist of coils with a large number of windings and/or application of high currents. Assuming that the behaviour of a small sample of ferromagnetic material is comparable to that of large samples a test set up is designed that allows the measurement of hysteresis curves of only a small sample.

The magnetic properties of a test plate can be estimated by using this material as the yoke of a transformer according to Fig. 1. The reluctance of the different parts of the transformer is calculated according to

$$R = \frac{\ell}{\mu S} \tag{1}$$

where ℓ is the length of the segment, μ the permeability of the segment material, and S the cross sectional area of the segment. The total reluctance of the transformer when excluding the air reluctance is given by

$$R_{tot} = \frac{1}{2}\left(R_{plate} + R_{core1}\right) + R_{core2} \tag{2}$$

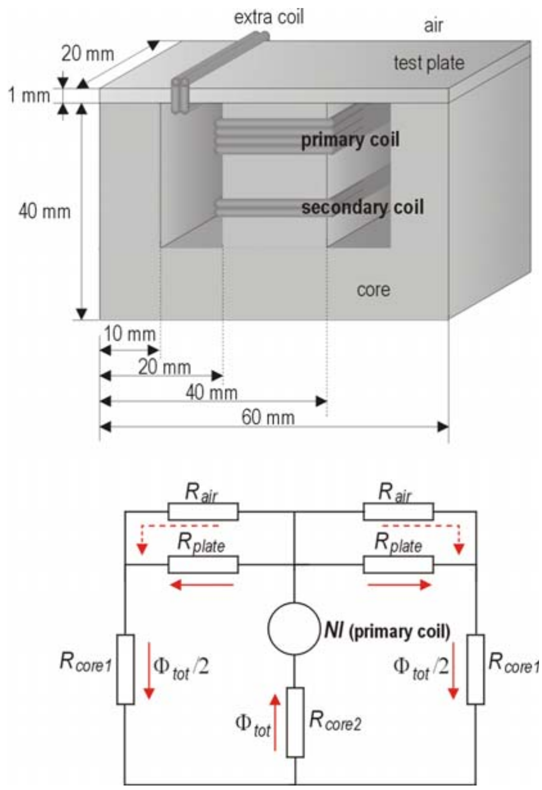

Fig. 1. A sketch of the transformer used for the estimation of the permeability of a test plate, and its corresponding magnetic circuit with reluctances R_{plate}, R_{core1}, R_{core2} and R_{air} representing the reluctance of the test plate, the core material and air, respectively. The magnetic field source *NI* is determined by *N*, the number of turns of the primary coil and *I* the applied current.

For the calculation of the reluctances the core is divided into three parts; the middle section is termed R_{core2}, and the two side sections, which are equally sized, are termed R_{core1}. The plate is divided into two parts ($R_{plate\_tot}=2*R_{plate}$).

Since the test plate has a small cross sectional area compared to that of the core, the test plate mainly determines the total reluctance. Initially, length ℓ of the test plate is assumed to be 25 mm. Driving the primary coil (N_1=2000) with a triangular input signal using different amplitudes resulting in values for NI ranging from 10 to 140 the hysteresis curves can be determined by measuring the induced voltage in the secondary coil (N_2=130). The flux density is determined according to Faraday's law

$$V_{ind}(t) = -N_2 \frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{3}$$

with Φ the flux through the secondary coil, and N_2 the number of turns of this coil.

The hysteresis curve is obtained by plotting the integral of the induced voltage ($\int V_{ind}(t)\mathrm{d}t$) as a function of the applied magnetic field (NI). The magnetic flux density B is calculated, according to

$$B = \frac{-\int V_{ind}(t)\mathrm{d}t}{NS} \tag{4}$$

by making use of Maxwell's equation, $\Phi = \int_S \vec{B}\cdot \mathrm{d}\vec{s}$, with S the area enclosed by the secondary coil, and $\mathrm{d}\vec{s}$ the differential surface area normal to the direction of the surface area S.

The permeability estimated from the measurement results in combination with circuit calculations are fitted according to an analytical equation describing the increase in permeability with flux density at low flux densities and a decaying permeability at saturation:

$$\mu_r = c + d \times (B^e) \times \exp(-\frac{B^f}{g}) \tag{5}$$

where c, d, e, f and g are fitting parameters and B is the flux density. The parameters are fitted using a least squares algorithm. As an example the permeability of the core of the transformer as given by the manufacturer is fitted using the above equation, which is shown in Fig. 2.

A 2-dimensional model of the transformer set up using the Finite Element Method (FEM) is developed in order to validate the method described above; i.e., assumptions made concerning the homogeneity of the flux through the test plate and its effective length are verified.

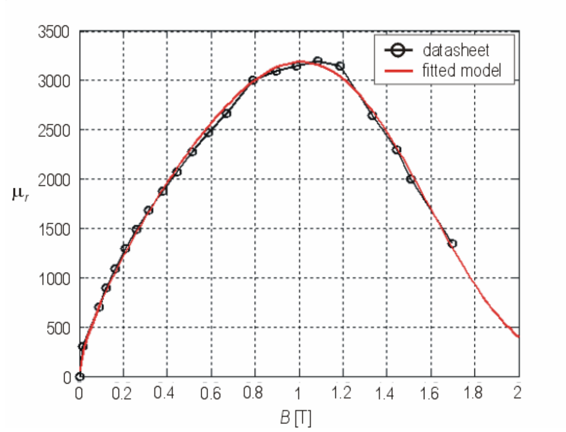

Fig. 2. Relative permeability of the transformer core according to the datasheet and (5) fitted to this curve, with c=46, d=3719, e=0.76, f=4.076, and g=5.9.

2.2. MFL measurements and simulations

An MFL test set up is developed in order to test the concept of measuring flux leakage from defects in a pipe wall. The set up consists of two permanent magnets with a backing yoke placed on a rectangular sample representing the pipe wall (see fig. 3). The test pipe wall is magnetized to a near saturation magnetization so that flux is forced to leak outside the pipe wall. Sensors (Allegro A3516UA for B_z, Sentron 2SA-10 for B_x and B_y) positioned near the inside of the pipe wall are used to measure the magnetic field adjacent to the pipe wall. When there is a defect in the pipe, more flux will leak due to a local increase in the magnetic reluctance. Measurement results are used to evaluate a 2-dimensional FEM-model of the MFL set up in which (5) is used to describe the non-linear magnetic behaviour of the pipe wall. Initially the parameters of this equation are obtained from the previous step. These need to be refitted by experimental data since both test materials do not have exact identical properties. Several defects in the pipe wall are simulated and evaluated.

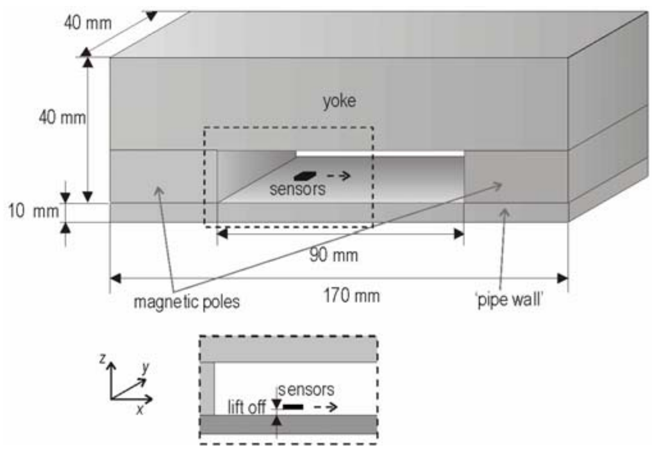

Fig. 3. Schematic presentation of the MFL set up. The box indicated by the dashed line is shown below in 2 dimensions indicating the lift off of the sensors.

3. RESULTS

3.1. Transformer measurements and simulations

Fig. 4 shows the hysteresis loops measured by the transformer and the anhysteretic loop obtained from these curves. For the calculation of the reluctance of the test plate a homogeneous flux density is assumed. Model simulations, however, show non-homogeneity within the test plate at the corners of the transformer (Fig.5).

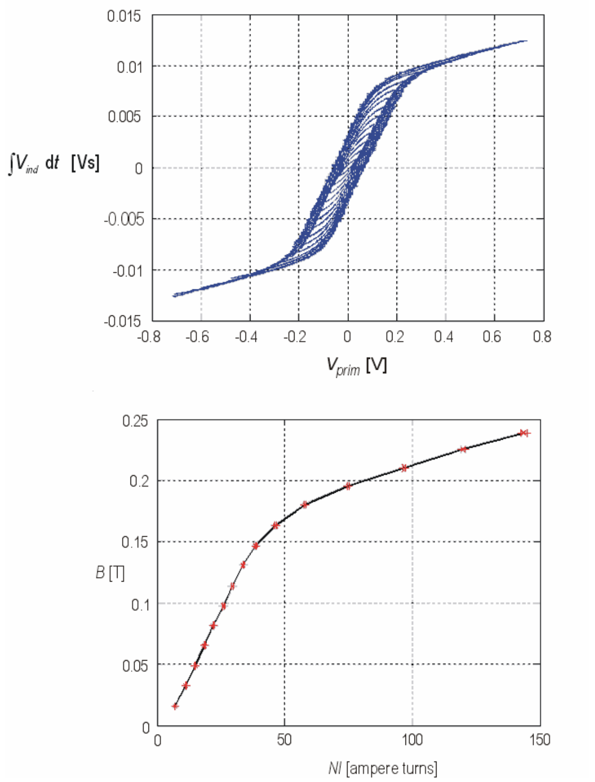

Fig. 4. upper graph: Measured hysteresis curves: the integral of the induced voltage in the secondary coil as a function of the voltage applied to the primary coil. lower graph: The anhysteretic curve obtained from the measured hysteresis loops.

The effective length of the test plate is therefore 11 mm instead of 25 mm as was used initially. Furthermore, when zooming in on the air above the test plate it is seen that at saturation flux leaks from this plate. The reluctance of the air just above the test plate must be included in the circuit model of Fig. 1 and the assumption that the measured induced voltage at the secondary coil is equal to the flux density through the test plate is therefore incorrect.

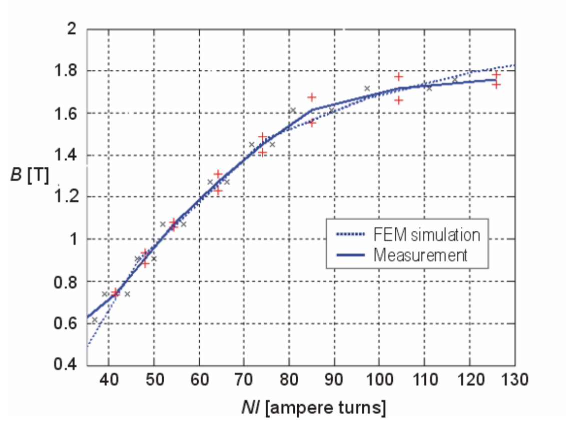

Fig. 6. The anhysteretic curve as obtained by measuring the flux through the test plate by the extra coil and model simulation in which the fitted curve is used (*c*=87.5, *d*=3777, *e*=0.7597, *f*=3.8152, *g*=4.9871).

The exact value of the air reluctance is difficult to determine, and therefore, an extra coil is wrapped around the test plate in order to measure the flux density through the plate directly (see Fig. 1). The permeability of the test plate according to this flux is shown in Fig. 6 together with the model simulation using a refitted curve.

3.2. MFL measurements and simulations

Defects of different shapes and dimensions were tested: slits across the width of the plate; round defects in the middle of the plate, and a slit along the length of the plate. Fig 7 shows some of the measurement results for two different defects. Fig. 8 shows the measured and simulated flux density above the test plate

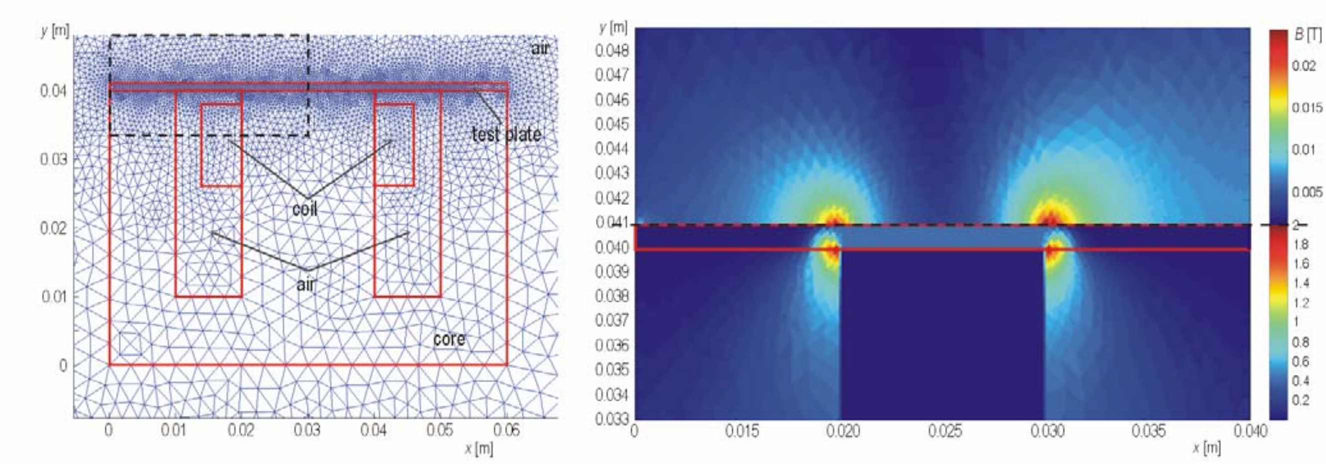

Fig. 5. Mesh of the 2D FEM-model of the transformer. The box indicated by the dashed line denotes the segment of which the flux density is shown on the right. Different scaling is used for the air above the test plate and the test plate-transformer segment to indicate the non-homogeneous flux leakage in air.

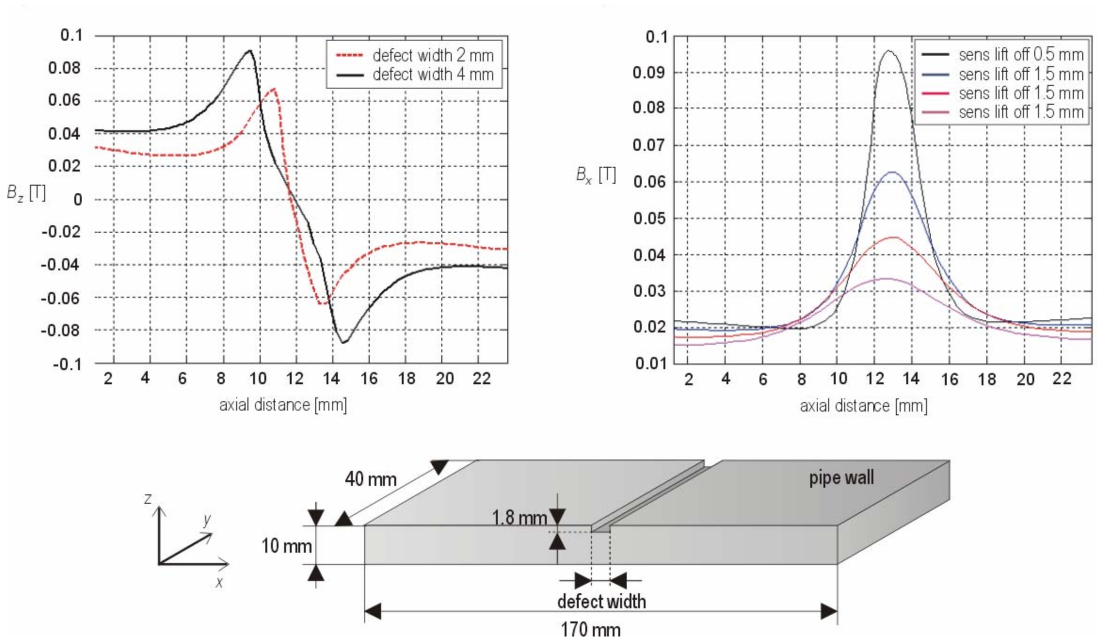

Fig 7. Measured flux leakage in x- and z-direction above the 'pipe wall'; left: B_z for two defects of different width (2 and 4 mm), right: B_x for a defect of width 2 mm at different sensor lift off distances.

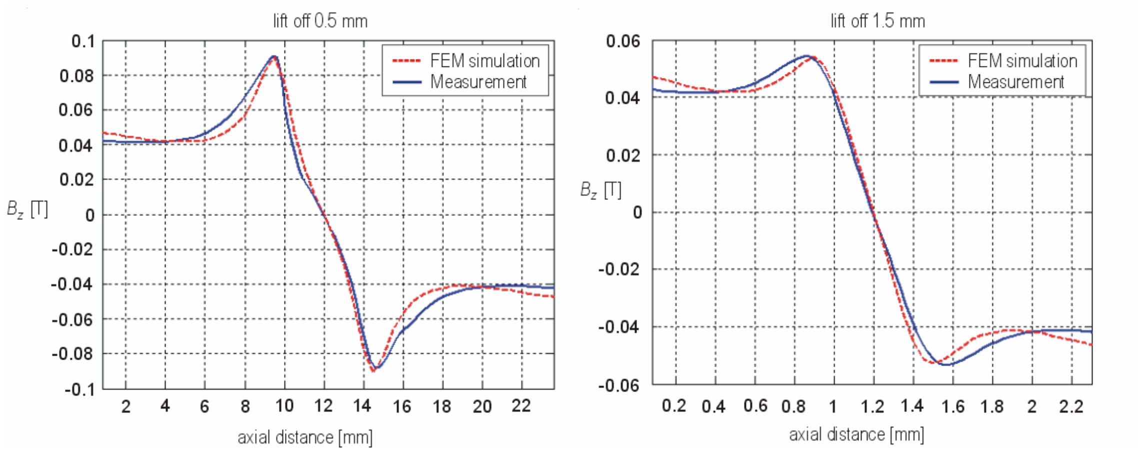

Fig 8. Measured and simulated flux leakage above the 'pipe wall' at two different sensor lift off distances; left: 0.5 mm, right: 1.5 mm (c=10, d=1276, e=1.05, f=1.8, g=4.8)

for a defect across the width of the test sample as indicated in this figure. Since the permeability of the material representing the pipe wall was not completely comparable to that of the test plate (5) was refitted to the measurement results. Once refitted, the leakage flux density of several defects could be predicted quite accurately in vertical as well as horizontal direction and for different lift off distances of the sensor.

4. DISCUSSION AND CONCLUSIONS

The akward boundary geometries and material characteristics hampered early progress in the detailed theory of MFL defect signals. Therefore, in the absence of adequate calculations, experimental measurements are the best help for understanding and using MFL signals obtained in the field.

Estimation of the permeability of the test plate via the calculation of the reluctance in the transformer set up gives reliable results. However, non-homogeneity of the flux through the test plate requires correction of the effective length. The analytical equation used for fitting the estimated permeability resulted in FEM-model simulations showing results comparable to the measurements. Furthermore, refitting this equation to the permeability of the pipeline material in the MFL set up proved that flux leakage signals could be predicted accurately for several defects by model simulation.

All experiments, however, were performed under laboratory conditions with artificial defects simulated by mechanically drilling pits in an unstressed pipe wall. This is not a true representation of the corrosion pits occurring in pipelines. Oil and gas pipelines are operated at pressures that can be as high as 70% of their yield strengths. This line pressure generates circumferential hoop stress in the pipe's wall, and it has been observed previously that stresses change the permeability, coercivity and other magnetic properties of the steel and hence may alter MFL signals by more than 40% [7]. The movement of the inspection tool also changes the measured MFL signals due to eddy-current effects. Therefore, when estimating the size of defects from MFL signals, all these effects should be incorporated and need to be included in future research.

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