Flaw detection and quantification for ferromagnetic steels using pulsed eddy current techniques and magnetization

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Abstract

Steel is an important industrial material and is used in various structures. Non-destructive testing (NDT) is required to make sure that these structures meet the safety requirements and function as intended. Eddy current technique (ECT) is one of NDT techniques used for steel inspection. The use of ECT in steel inspection is generally, however, limited due to skin effect and magnetic property variations, particularly in sub-surface defect detection and quantification. This paper shows how DC magnetic saturation improves the sensitivity of pulsed eddy current (PEC) sensors in steel inspection and the theory behind it. Based on a modelling, a practical study has illustrated the advantages of the approach. A wavelet-based feature extraction developed from our previous work has been extended for defect classification of steel targets. Conclusions and further work are provided at the end of the paper.

1 Introduction

Steel inspection is industrially important. Various steel structures require inspection during manufacturing and applications. Different NDT techniques used in the inspection, the selection of which depends on the structure of the specimen and the nature of the anticipated defects. Electromagnetic techniques including eddy currents are generally fast and non-contact, hence no or minimum surface preparation is required. This is why whenever technically possible, these techniques will be of preference. The use of these techniques however has limitation due to the magnetic properties of ferromagnetic steel \cite{1}. Firstly, steels have high magnetic permeability that forces low penetration of eddy current due
to the skin effect. Secondly, steels are known to possess varying permeability. The variations affect the distribution of the induced eddy current and the resulting noise in turn increases the difficulty in detecting flaws in the specimen.

One of the most economical NDT in steel inspection is magnetic flux leakage (MFL) [2]. It has been intensively used in monitoring corrosion in buried pipelines. This technique requires magnetization that generates magnetic flux flowing in the specimen in a certain direction. The presence of flaws will implement as an abrupt change of magnetic permeability to the flux in the specimen. This permeability is lower than that of flawless parts and provides high resistance to the flux and forces it to take a different route. In cases where the other routes are magnetically saturated, some flux has to leave the specimen causing flux ‘leakage’ before re-entering. This leakage is readily detected by magnetic sensors located in the proximity of the specimen surface. The parameters of defect that affect the distribution of leakage flux are ratio of depth of the defect to the thickness of the pipe wall, length, width, sharpness at the edges and sharpness at the maximum depth [3]. In practice, a permanent DC magnet or an AC electromagnet [2, 4, 5] is used for magnetization. For DC inspection, hall device, magnetoresistive and SQUID [6] can be used to measure the leakage field. For AC measurement a coil is another alternative.

Another reported technique is Pulsed Magnetic Saturation [7], that is useful when space is at premium, e.g. for pipe inspection that has to be carried out from the interior. Permanent magnets will not fit into the bore, and electromagnets will generate extensive heat rapidly. Using the pulsed magnetic technique, the saturating magnetic field is only generated for short periods of time. Tube walls of up to 5mm thick have been tested, and the power required was 500kW. Using a technique called multiple-property technique, the defect characteristics are derived. In the technique a number of values at particular times along the base signal are used. The relations between the defect characteristics and the reading functions are derived using linear least-square fits of the polynomial.

AC field measurement (ACFM) is a relatively new technique in NDT although it has developed into one of the established NDT techniques. This technique is particularly suited for crack sizing [8] and can also be used for crack detection. Some of the advantages of this techniques is that in many situations it requires no calibration and that it is relatively insensitive to permeability changes and lift-off [9]. On carbon steels, its use is limited to the detection of surface-breaking flaws [9]. The technique induces a uniform electric current into the specimen. The magnetic component that is parallel to the current and perpendicular to the surface, $B_x$, and the component that is normal to the specimen’s surface, $B_z$, are measured. The length and depth of a surface breaking defect are derived from a set of $B_x$ and $B_z$ readings. A butterfly plot of the readings is used to give some visualized indication to the user [10, 11].

Alternating Current Potential Drop (ACPD) is the only established magnetic technique for measuring crack depth in welds, and it is not used for crack detection [12]. It is generally only applicable for surface breaking cracks and requires electrical contact with the specimen. The use of AC, in oppose to DC, allows low current and thin layer inspection due to skin effect. The specimen
must be homogeneous and isotropic ($\sigma$, $\mu$ and $k$ are constant) to allow accurate results. An AC field is applied to the specimen so that the current is perpendicular to the crack. A pair of contacts with fixed distance are used to measure the potential difference between two points. When crack is existing the reading will vary, and this is used to estimate the crack depth. The technique requires no calibration [8].

Conventional eddy current techniques with AC or DC magnetic saturation are commonly practiced in steel inspection. The magnetization helps reduce magnetic property variations [13-16]. In this paper, the technique is extended to pulsed eddy current sensors. After introducing the PEC and magnetization simulation, a feature extraction for magnetization-based PEC sensors is reported.

2 PEC and magnetic saturation

Because of low cost and high sensitivity, eddy current based techniques have wide applications such as displacement/position measurement [17, 18] and crack detection [19-22] for NDT, although they are only applicable to conductive structures [1]. A number of techniques with different characteristics and application fields have been successfully used for NDT [23]. In particular, pulsed eddy current technique has emerged to be one of potential techniques in quantitative NDT due to its potential richness of information without compromising the speed. The richness of information is a result of the wide frequency spectrum contained in pulsed magnetic field. However, the amount of information extracted largely depends on the features used in the analysis of the PEC signals. A number of features have been used by various researchers [24].

As discussed in [1], $Z$, $L$ or $Q = F(x, \sigma, \mu, f)$. The eddy current magnetic field intensity is a function of $x$ the gap between the sensor coil and the target, $\sigma$ the electrical conductivity of the target, $\mu$ the permeability of the target and $f$ the frequency of current in the excitation coil. To use the sensor for flaw detection and quantification of steel materials, it is important to simplify the function $F$ by controlling the variables $x$, $\sigma$, $\mu$ and $f$. In PEC, theoretically, $f$ will be of wide spectrum, ranging from DC to infinite AC. To control the permeability $\mu$ and keep it constant in the sensor signals, magnetization is applied to eliminate or reduce the variation of permeability over different parts of the specimen.

Magnetization is also required to reduce the effective relative magnetic permeability towards unity, and hence, the penetration improves significantly. Due to the skin effect, field penetration is dictated by the skin depth, that is defined as

$$\delta = \sqrt{\frac{2}{\sigma \mu \sigma}}$$

where $\delta$ is skin depth (m), $\mu$ is magnetic permeability (H/m), $\sigma$ is electrical conductivity (S/m) and $\omega$ is the field frequency (Hz). From the equation, it can be seen that one way of improving the penetration is by reducing the magnetic permeability $\mu$ of the sample.

Two magnetization approaches are available, namely AC and DC magnetization. It is known that AC magnetization is very much limited to
surface or near surface flaws detection. The field is confined to the area close to the surface due to the skin effect. On the other hand, DC magnetization can penetrate deeper into the sample [14, 16, 25].

Magnetization of a sample could be accomplished by different ways, among others [16]: using permanent magnets, passing a heavy current through the component (locally or overall), placing a coil around or close the component under test and making the component part of a magnetic circuit (e.g. by means of a hand yoke). The selection of magnetization technique depends on various factors, among others are the working space and the geometry of the sample.

There are no universal rules regarding magnetization levels for MFL inspection [14]. In general practice, the strength of field required to magnetize industrial steel is about three times the value of the coercion $H_c$. At this level, the steels will be magnetically saturated.

Figure 1 shows how the magnetic flux distribution will appear around the sample and particularly the slot as simulated using a finite element software called FEMM [26]. The simulation is a simplified model for the experimental setup illustrated in Figure 4. The simulation shows how flux leakage occurs above the sub-surface slot. Figure 2 shows the normal magnetic flux density just above the surface of the specimen. It demonstrates that the magnitude of the...
magnetic density peaks above the edges of the opening, and both edges have the opposite polarity of magnetic field density. Based on the simulation as illustrated in Figure 2, the magnetic field distribution across defects is enhanced. In other words, DC magnetization could improve the detection depth of subsurface flaws and detection sensitivity. This DC magnetic flux density is readily detectable by the PEC sensor, and the leakage phenomena can be used to detect an existing crack.

Figure 3 The Wavelet-based PEC Feature Extraction

An advanced feature extraction technique for PEC has been developed and reported in our previous work [24, 27]. The technique involves two stages, i.e. off-line and on-line processes, as illustrated in Figure 3. In the off-line process, a database of PEC responses from defects of various types and sizes is used to generate a set of eigenvectors by Principal Component Analysis (PCA). Wavelet decomposition is applied on the PEC responses to extract relevant spectral and temporal information before eigenvectors are computed. These eigenvectors become the new coordinate axes of the PEC signal space. During testing, the on-line process is performed. Each wavelet-decomposed PEC signal is projected onto the eigenvectors and will then be represented by the coefficients. The projection produces a set of PCA coefficients, which are used for identifying the type and size of defect.

3 Experimental setup

A steel sample was manufactured for experimental purposes. The layout is as shown in Figure 5. Four slots with different depths were manufactured in the sample and the slots depths were chosen to accommodate that the sub-surface slots are more difficult to detect. A strong DC magnet is used to saturate the sample when required, as shown in Figure 4. The position of the permanent
magnet was supposed to be on the same side as the probe, however due to no magnetic yokes with suitable dimensions available during the experiment, the positioning of the yoke is as illustrated by Figure 4. The magnetic flux flows perpendicularly to the slot’s main axis.

![Figure 4 The Experimental Setup](image)

**Figure 4** The Experimental Setup

![Figure 5 The Steel Sample](image)

**Figure 5** The Steel Sample

**Stage 1**

```
  Probe
  Steel Sample
```

**Stage 2**

```
  Probe
  Steel Sample
```

```
  Aluminum
```

![Figure 6 Penetration Depth Test](image)

**Figure 6** Penetration Depth Test

In the experiment, the effects of magnetization will be investigated by comparing results obtained using magnetization and without magnetization. Both surface and sub-surface slots detection will be investigated. Another experiment will investigate the improvement of the penetration depth of the PEC when the specimen is magnetically saturated. A step steel block is used in this experiment. The step thickness ranges from 2mm to 10mm with a 2mm increment. In the experiment the probe will be fixed on the surface of a step with thickness d. The base response signal is then recorded as a reference signal. Then a written software works out the differential signal \( y_d \) by finding the difference between the reference signal \( y_{ref} \) and the current base response signal \( y_r \). When there is no change in the configuration of the experimental setup, the differential signal \( y_d \) should be relatively flat and small, or ideally zero. Then an aluminium block is brought to the proximity underneath the sample. When change is present in the differential signal \( y_d \) in terms of both shape and magnitude, a conclusion can be drawn that the system’s field can penetrate through the depth of \( d \), and the experiment is repeated with larger \( d \)'s until no change is detected in the
differential signal $y_d$. The experiment will be carried out both with and without magnetization for comparison. Figure 6 shows the two stages where the response signals, $y_{ref}$ and $y$, are measured. The illustration only shows the experiment without magnetization. For the one with magnetization, a magnetic yoke is used and located under the steel sample similarly as shown in Figure 4.

4 Experimental results

Figures 7 and 8 show the experimental results for measurement of surface and sub-surface slots respectively without magnetization applied. It can be seen that there is no apparent pattern of magnitudes or anything that correlate with the slot depths. As discussed in section 2, Figures 9 and 10 show that now the magnitude levels are amplified, especially the sub-surface slots measurements. This will increase the signal-to-noise ratio of the system. Some correlation between the signals magnitudes and the corresponding slots depths is also shown by the differential signals in these figures.

To improve the discrimination further, normalization of signals is carried out before differential signals are derived. It is thought that this would also help reduce magnetic property and magnetization level variations. The results are shown in Figures 11 and 12. The arrival times and magnitudes of the peaks and the troughs clearly have some correlation with the corresponding slots depths, especially the sub-surface signals. The discrimination of depth of the surface
slots is not very good. It is suspected that the slot depths are beyond the sensitive range of the sensor used in the experiment. Different shapes between the surface and sub-surface signals can be used to discriminate location of the detected slot.

Figures 13 and 14 show how defect classification is achieved by using the newly proposed PCA-based feature extraction. The figures also show that the magnetization has improved the measurement resolution with larger ranges of PCA scores. This suggests that the signal-to-noise ratio has been improved.

The results of the penetration depth are shown in Table 1. Standard deviation (STD) is used to measure the level of differential signals. The STD should be around 0.3 when there is no change in the measurement condition, and this indicates the signal noise. When a change is present, the STD will also vary. The figures in the table shows that without magnetization, at depth of 6mm there is hardly any change in the signal. However, with magnetization, significant changes are evident even at depth of 10mm. Hence, it is concluded that the magnetic saturation has improved the penetration depth of the PEC technique.

5 Conclusions

The results show that the magnetization has improved the signals strengths and has made deeper penetration into steel possible. It has also been shown that the magnetization based PEC technique is able to quantitatively characterize sub-
surface defects with good resolution. The discrimination between surface and sub-surface defects is also shown by the shape of the differential signals, mainly the differential of normalized. The technique can be expected to gain similar benefits when applied on other conductive ferromagnetic materials. The results also show the robustness of the developed feature extraction technique that can be applied in both diamagnetic and ferromagnetic material inspection. In future work, the technique will be tested on industrial samples and the application of advanced signal processing techniques for defect sizing will be investigated.

Table 1 Penetration Depth Test Results

<table>
<thead>
<tr>
<th>Steel Thickness (mm)</th>
<th>Mean STD of Differential Signal</th>
<th>Change (%)</th>
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<tbody>
<tr>
<td></td>
<td>No Aluminum</td>
<td>Aluminum Present</td>
</tr>
<tr>
<td>Without Magnetization</td>
<td>2.0</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>0.35</td>
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<tr>
<td></td>
<td>6.0</td>
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<tr>
<td>With Magnetization</td>
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<td></td>
<td>10.0</td>
<td>0.35</td>
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References


