A Review of Magnetic Methods in NDE

1 Introduction

That the magnetic field and the stress in ferromagnetic materials are coupled has been known for a while. Magnetostriction is the phenomenon of a change in the dimension due to the application of a magnetic field. Conversely, application of a stress could alter the magnetization in a ferromagnetic material. When an external load is applied to a ferromagnetic sample, tension orients the domains in the direction of this applied load, while compression orients the domains perpendicular to the loading direction. This is of course, known as the piezomagnetic effect. A number of magnetic non destructive methods are in common use today, like the Magnetic Flux Leakage method, the magnetic Barkhausen noise, and the metal magnetic memory.

2 Magnetic NDT Technology

A number of magnetic Non destructive techniques exist, and this section will attempt to review a few of them. This section majorly follows the review article by Wang et al [1]

2.1 Magnetic Flux Leakage

Magnetic Flux leakage is among the oldest magnetic NDT methods that exist, and is still widely used in practice. When a strong magnetic field is applied to a ferromagnetic object, any geometrical discontinuity will lead to a flux leakage. This leaked flux can then be measured using a magnetic field sensor and the signal inverse mapped to estimate the dimensions of the defect.
There are a number of challenges in implementing MFL, including:

1. The level of magnetic excitation should be large and homogenous to allow the magnetic variation to occur at the location of the defect
2. The sensors should be close to the position where the changes in the magnetic flux are distinct from the background noise

3. Effective and accurate inversion methods are yet to be found. There are a number of analytical models that attempt to provide this inversion method but they typically fail when it comes to irregularly shaped defects, which are more commonly observed in the industry. The Zatsipin-Schcherbinin model considered a dipole modelling approach [2] by modelling the defect as a magnetic dipole and investigating the field intensity due to the dipole at any point in the surroundings. While this worked for simpler defects like cylindrical defects, some models were later developed for ellipsoidal and slightly more complex defects. There have been attempts to use wavelet neural networks in this regard. Other new and interesting methods are being applied to this problem, that have not yet bore fruit due to the complex nature of the problem. Another issue is the elastic plastic region near the cracks. The localized plastic zone makes modelling relatively difficult.

In the following section, a case study is presented, of a tubing thread inspection using magnetic field leakage techniques

2.1.1 Tubing Thread Inspection - A report by Ding Jengfeng et al

This sub section follows from the research article by Ding Jengfeng and others [3] Oil well tubings, which are important components in oil fields, can fail by a variety of defects, including rupture, thread abrasion, cracks in the thread root, variations in the taper angle in the thread area. Identifying such defects could lead to prevention of oil field accidents. Magnetic flux Leakage technique offers a higher efficiency and reliability than the oft used magnetic particle testing technique. The authors identify a few inconveniences in the traditional manner of performing MFL tests. It is stated that traditional MFL testing avoids inspecting the ends of the rods. To address this deficiency, the authors propose that a magnetizing unit be attached to the end of the tubing anfd the thread area be scanned with Hall components.

The inspection equipment would contain the following systems - magnetizing assembly, sensor array, data acquisition and recording modules. The MFL signals are amplified by an amplifier and filtered by a high pass filter, to filter out the low frequency components produced by the background magnetic field. Also a spring is used to press the sensors against the tubing to ensure that the sensor is indeed close to the inspected surface, and to reduce the effect of the liftoff.

The results of the study were promising. The method developed by the authors succeeded in capturing the flux variations due to defects. For the purpose of the study, of course, artificial defects were produced on the components, and the leakage field could be verified against the known defects. Variations were captured, and while deeper cracks could be distinguished from shallow cracks, and defects could be distinguished from each other in the presence of a reference, there was no mention of defect sizing, or identifying a single defect based on the measured signal alone.

It must also be noted that, the direct problem in MFL testing is to predict the magnetic field based on the defects. The inverse problem, and the more complicated one, is to predict the defect based on the measured leakage field. This problem has largely been defined as an incomplete problem [4], and this, in a manner, explains the third difficulty stated above. The estimation of the defect dimensions and the shapes is important in the non destructive testing field. There have, however, been significant attempts to solve the direct problem. The dipole model by Zatsipin and Schcherbinin was among the first to be developed , and a number of improvements followed. Yuhua Cheng et al proposed a solenoid model [5] to address complex defects. Snarskii et al proposed an integral model [4]. Usage of neural networks has been on the rise and Minnhuy Le et al proposed a Deep Neural Network based model [6] for simulation of magnetic flux leakage.

2.2 Magnetic Barkhausen Noise

Unlike MFL, Magnetic Barkhausen Noise is a method typically used to determine the magnetic easy axis, which is the axis that encourages spontaneous magnetization in ferromagnetic materials, grain size and residual stress. When a ferromagnetic material is magnetized by an increasing field, noise is generated in the form of voltage pulsed in a coil near the material. Typical material anomalies llike precipitates, inclusions, defects, dislocations, micro strains typically translate into microstructural impediments or pinning sites [7]. Over a magnetization or a demagnetization process, the domain size fluctuations result in energy expenditure in overcoming the pinning sites as a consequence of the impulsive motion. Thus, by analysing the Barkhausen noise, precise information on the microstructural content of the materials can be obtained. MBN$_{energy}$ is commonly used to analyse the detected MBN voltage, and is defined as:

$$MBN_{energy} = A \sum_{events} \int V^2 dt \tag{1}$$

Loading has a clear effect on the MBN signal that is recorded. It is recorded that tensile stresses increase the number of 180° domain walls, modifying the pinning barriers, but compressive stresses decrease the number of 180° domain walls. The effect of plastic deformation is much more complicated than the effect of elastic deformation, and is disputed. While certain studies have reported that an increase in the plastic strain led to a continuous decrease in the Barkhausen noise, others have stated that there was an increase in the beginning, followed by a phase where there were not many changes, and this continued until failure. There is clear contradiction in the results of the studies and the conclusions. This is likely to be due to the very sensitive nature of the MBN signals.

2.2.1 Case Study - Cracks in Steel

This section follows the research article by Thomas W Krause et al [8] Stress Corrosion Cracking is a common cracking manner in steels and refers to crack formation in a corrosive environment. Detecting and quantifying these cracks is important in testing and inspection. Fracture mechanics calculations need axial profiles of the crack, especially if the dominant stress is circumferential. Common application of the MBN method in crack detection is limited because it requires extensive surface preparation, and due to the numerous parameters affecting the MBN signal. The MBN energy, which is commonly used in the analysis of the MBN voltage shows a decrease in the vicinity of the crack. This is typically attributed to the non uniform magnetization of the material near the cracks. The reduction increases with the depth of the crack. This is attributed to the interaction of the eddy current field with the crack, which is greater in the deeper portions of the crack.

The authors performed experiments to determine the location and dimensions of cracks. This was further verified using Magnetic Particle Inspection. The MBN energy reduced more near the middle section of the crack, confirming that the crack depth is indeed highest at the middle. The results were found to be quite close to the results from the MPI test, and the dimensions could be mapped with an accuracy of 1.5 mm. However, the shallow depth of the crack near the tip meant that it could not be distinguished from a defect free region. The authors concluded that MBN may only be useful where external cracks have previously been identified by the MPI methods.

2.3 Metal Magnetic Memory

Both the MFL and the MBN methods for magnetic testing are active methods requiring an external magnetic field and are quite complicated to perform. Metal magnetic memory, on the other hand, is a passive method that uses the earth's magnetic field as the stimulus source. It is a relatively newer method, and is quite effective in assessing early damage, while being easy and time saving

Under the effect of the earths magnetic field and a load, self magnetic flux leakage signals are generated in the stress concentration zones, where the tangential component of the SMFL signal reaches a maximum and the normal component changes sign and reaches zero. The magnetic state is still retained after the load is removed, and the zones of stress concentration can be detected by measuring the SMFL signals on the surface of the component. Thus in this method, magnetic sensors are used to measure the magnetic fields in both the tangential and the normal directions. An Abrupt change in these fields is taken to indicate the presence of a stress concentration zone. The MMM method is a simple method as it does not need a couplant, an external source for a magnetic field or special surface treatment [9]. It can be used to detect both micro and macro defects. However, while the SMFL method has been largely succesful in capturing significant attention, it still needs further study due to lack of physical models quantifying the relations between the SMFL signal and the plastic deformation, and the lack of quantitative criteria in capturing the defect features. A few models do exist, like the dipole model, that attempt to quantify this relationship as a prediction but these only consider the effect of the crack itself and ignore the stress aspects.

3 The Dipole Model for Magnetic Field Leakage

The following is presented from the paper by X Zhao et al [9] They follow a similar treatment by Aharoni et al.

$$B = \mu_0(H + M) = \mu_0\mu_r H \tag{2}$$

This implies

$$M = \frac{B}{\mu_0}\left(1 - \frac{1}{\mu}\right) \tag{3}$$

From Maxwells equations we may write:

$$\nabla.B = 0 \tag{4}$$

$$\nabla \times H = 0 \tag{5}$$

(4) and (5) give that

$$\nabla.M = 0 \tag{6}$$

Magnetic field intensity H can be expressed as:

$$H = \frac{1}{4\pi}\int_{\forall}\frac{-\nabla.M}{|r^3|}\vec{r}d\forall + \frac{1}{4\pi}\int_S \frac{n.M}{|r^3|}\vec{r}dS \tag{7}$$

From (6), (7) can be rewritten as:

$$H = \frac{1}{4\pi}\int_S \frac{n.M}{|r^3|}\vec{r}dS \tag{8}$$

This is only valid for constant permeability If $\sigma = n.M$, then it can be considered to be a surface charge density. F.Förster, in his study [10], formulated the following equations for σ and H

$$\sigma = \frac{2.65}{2\pi} \frac{\frac{h}{2a} + 1}{\frac{1}{\mu}\frac{h}{2a} + 1} H_a \tag{9}$$

$$dH = \frac{2\sigma\vec{r}}{|r^3|} dA \implies H = \int_A \frac{2\sigma\vec{r}}{|r^3|} dA \tag{10}$$

The magnetic field can then be split into two components in the two directions (tangential and normal), and written as a superposition of the types of magnetic charges (magnetic monopoles do not exist. This is simply a representation)
Then, if the crack were triangular,

$$H_{1x} = 2\sigma \int_0^b \int_{-a}^0 \frac{x_0 - x}{[(x_0-x)^2 + (y_0-y)^2 + (z_0-z)^2]^{3/2}} \sqrt{1 + \left(\frac{h}{a}\right)^2} dxdz \tag{11}$$

$$H_{2x} = 2\sigma \int_0^b \int_0^a \frac{x - x_0}{[(x_0-x)^2 + (y_0-y)^2 + (z_0-z)^2]^{3/2}} \sqrt{1 + \left(\frac{h}{a}\right)^2} dxdz \tag{12}$$

$$H_{1z} = 2\sigma \int_0^b \int_{-a}^0 \frac{z_0 - z}{[(x_0-x)^2 + (y_0-y)^2 + (z_0-z)^2]^{3/2}} \sqrt{1 + \left(\frac{h}{a}\right)^2} dxdz \tag{13}$$

$$H_{2z} = 2\sigma \int_0^b \int_0^a \frac{z - z_0}{[(x_0-x)^2 + (y_0-y)^2 + (z_0-z)^2]^{3/2}} \sqrt{1 + \left(\frac{h}{a}\right)^2} dxdz \tag{14}$$

$$H_x = H_{1x} + H_{2x} \tag{15}$$

$$H_z = H_{1z} + H_{2z} \tag{16}$$

In the above set of equations, H_1 represents the magnetic field due to the positive part and H_2 the field due to a negative part. Refer to Figure 1

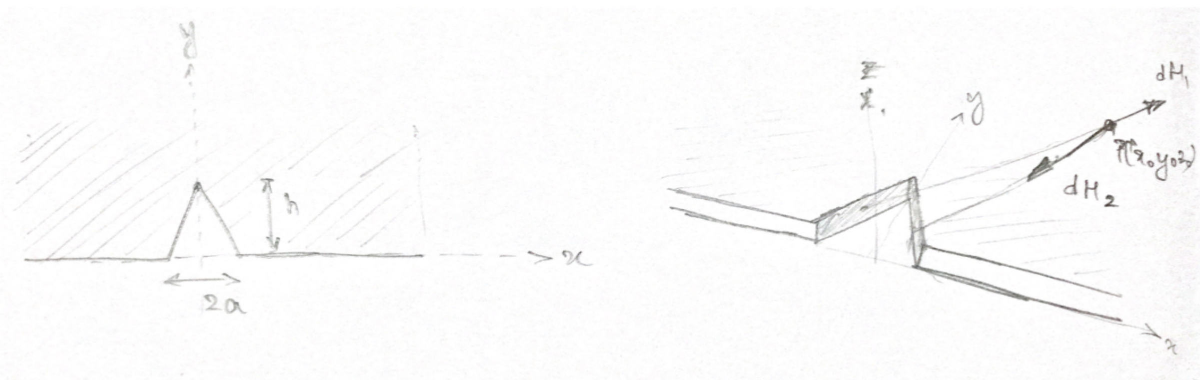

Figure 1: Triangular Crack on a plate

Indeed, nowhere in this method was the effect of the stress taken into consideration. The geometry of the defect should ideally not be sufficient to predict the magnetic fields.

This is a clear drawback of this method. However, it can be used, not only in MMM techniques, but also in MFL.

4 An Implementation of the Dipole Model

A plausible dipole model was discussed in the previous section that enumerated the relations that could be used to model the leakage field due to a defect in a component. Despite being a fairly simplistic treatment, and far from accurate, it does provide one with a tentative intuition about the leakage field and the challenges to be had. In this section, the results are presented from a dipole model that was simulated using Python

4.1 Method

The equations used are enumerated in the previous section, and majorly follow the work of Förster. The relevant equations are (11), (12), (13), (14), (15), (16). The python libraries used were numpy, sympy and matplotlib. The usage of the symbolic library greatly simplified the equations but increased time consumed

The code is not interactive but can be changed to produce the graphs for the required purposes. The half crack width, crack height, and crack depth are inputs. Also alterable is the location of the measurement axis. The code works with the assumption that all cracks can be considered triangular with a deepest point and linear fits for the rest of the profile. The equations were integrated numerically using the Ito integration scheme. The numerical integration steps could be altered, but at the expense of time taken to complete the iteration. The results are shown below:

4.2 Results

The relative magnetic fields were plotted for the following measurement cases.

4.2.1 Case 1

The crack was taken to be 2mm wide, 0.5 mm high, and 5 mm deep in the lateral direction (along the y axis in figure 1). The measurement axis was taken directly above the origin (y=0) at a height of 1mm

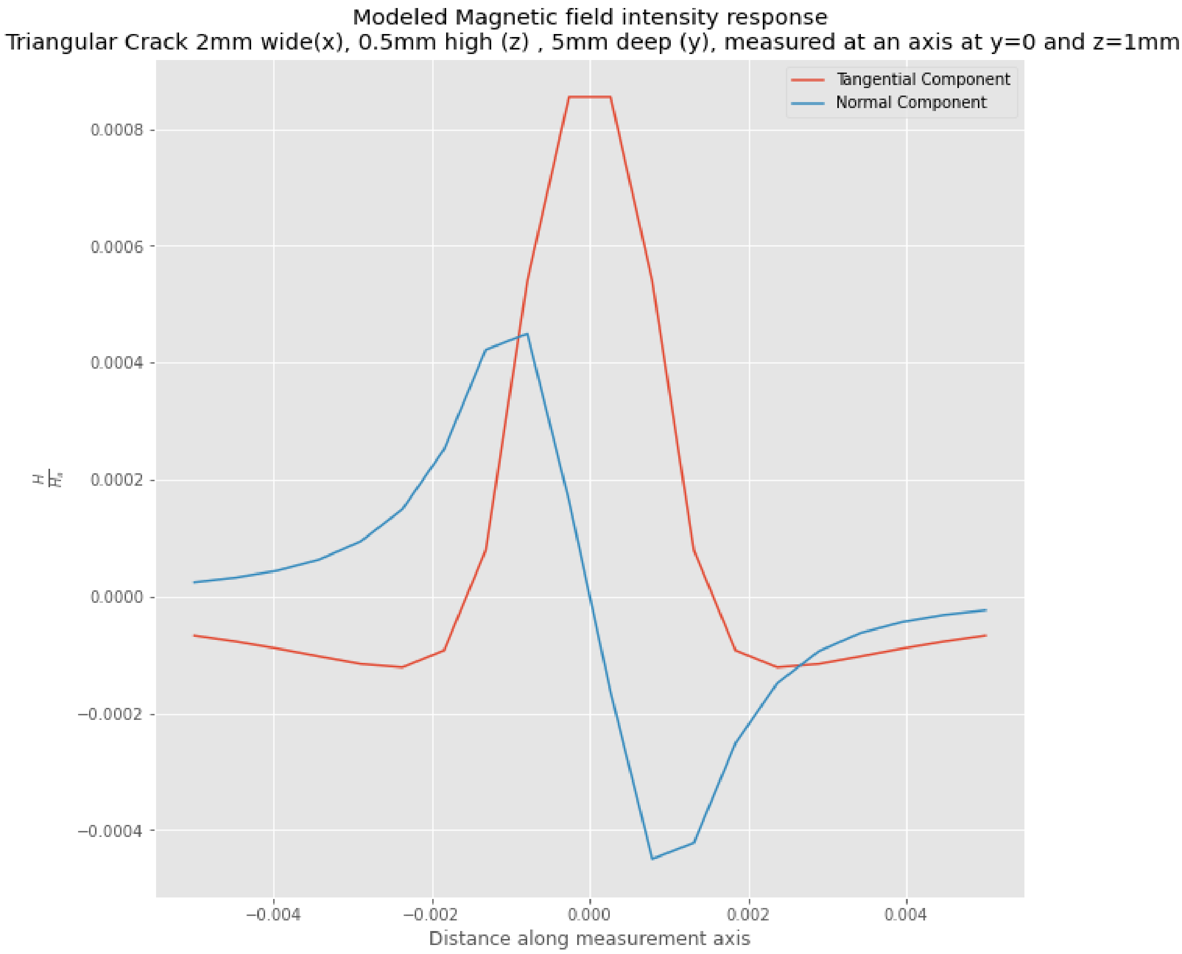

Figure 2: The relative magnetic field intensity for case 1

Figure 2 shows the variation in the leakage field along the measurement axis. It is known that the measurement axis is exactly above the widest part of the triangular crack. It is interesting to note that even then, the magnitude of $\frac{H}{H_a}$ is small and at most is only a fraction above 0.0008. This says that the applied magnetic field needs to be such that the leakage fields are detectable. Also significant indicators are clearly seen in the vicninity of the crack. The normal component changes sign at the crack and the tangential component reaches the maximum.

4.2.2 Case 2

The crack was unchanged. The measurement axis was changed to y=1mm and z=5mm. The drastic change in the results are shown below

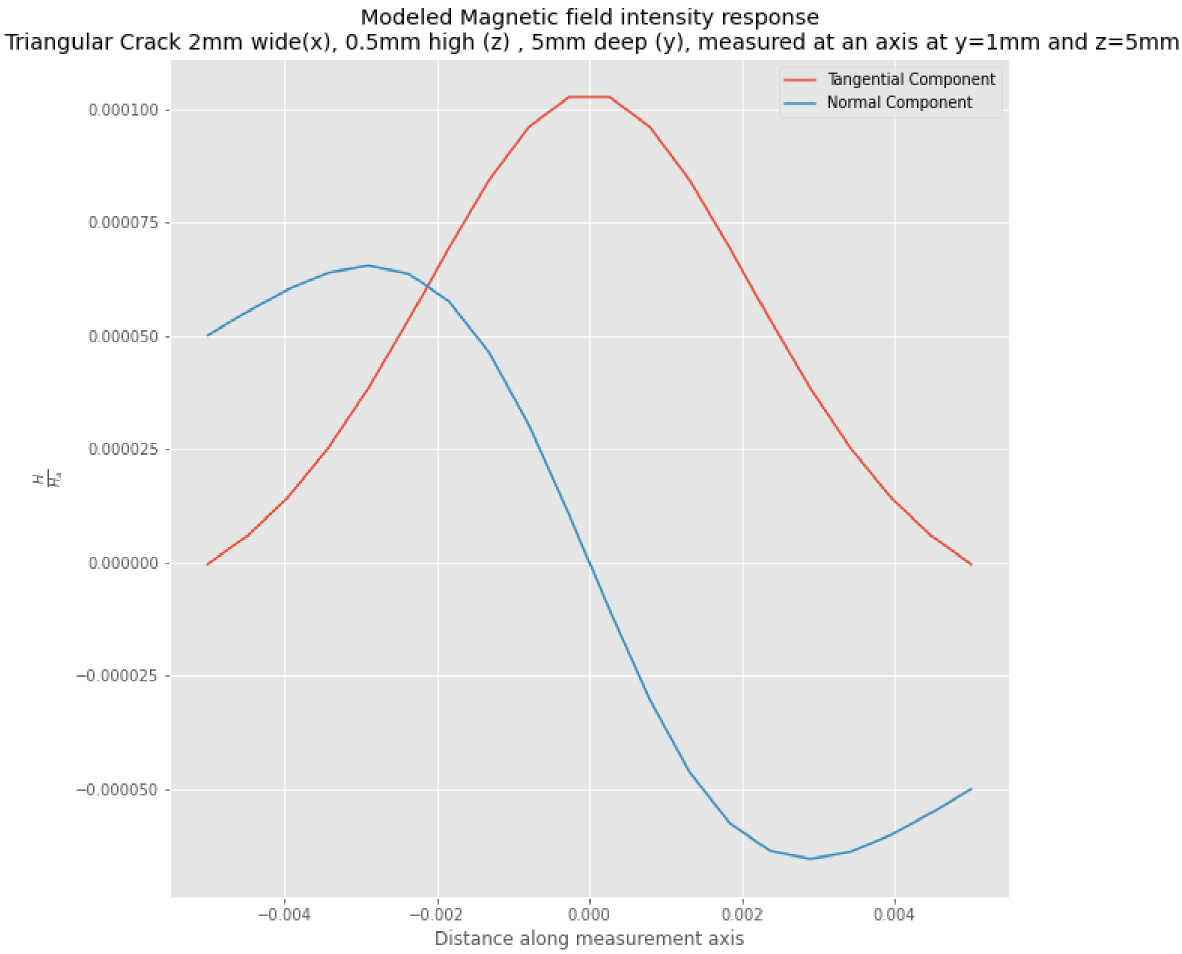

Figure 3: The relative magnetic field intensity for case 2

Figure 3 shows the variation in the leakage field along the measurement axis, which has been shifted laterally by 1mm and vertically by 4mm. The trends are still clear in that the normal component reaches its maximum at the widest part of the crack and the tangential component changes sign. However, the magnitude has dicreased drastically, by about 8 times, only for a shift of the order of milli meters. This is significant because of the lift off in detectors. Any slight variation in the measurement axis could lead to a drastic change in the measured value.

The code used in this report can be found here

5 Conclusion

The magnetic stress coupling effect being one of the basic characters of the ferromagnetic materials and there are various magnetic NDT methods developed based on it. Here, a few of them are summarised. A few case studies are presented to show their practical applications. A dipole model is presented for analytical defect modeling, and plots are presented for an intuition of the trends.

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