Giant Magneto-Resistive (GMR) Sensors for Non-Destructive Detection of Magnetic Flux Leakage from Sub-Surface Defects in Steels

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Abstract

There is an increasing demand for using high sensitive sensors which can detect very low levels of magnetic flux leakage from hidden defects or far-side wall loss due to pitting or local corrosion in ferromagnetic steels. This paper discusses the use of highly sensitive tiny GMR sensors for detection of sub-surface defects in carbon steel plates. Notches located at different depths below surface are machined in 12 mm thick carbon steel plates and the tangential component of the leakage magnetic field is measured. The sensor output is amplified selectively for reliable detection of feeble leakage magnetic fields from sub-surface notches. MFL images of notches are obtained by raster scan imaging of surfaces using GMR sensor. Application of GMR sensor to detect natural and artificial defects in steel wire ropes is also discussed.

Introduction

Magnetic flux leakage (MFL) technique is an electromagnetic non-destructive evaluation (NDE) technique which is widely used in industry for assessing the structural integrity of ferromagnetic steels like underground pipelines, oil-storage tank floors, etc. [1-2]. In this technique, on the magnetization of the ferromagnetic steel having defects the magnetic flux leaks out and takes a longer path around the defect. Measurement of this leakage flux using magnetic sensors is the basic principle of MFL technique. The normal and tangential components of leakage field due to a defect in the material are detected using coils or solid state sensors and correlated with the defect dimensions [3]. Four steps are needed to carry out MFL testing successfully viz. (i) proper magnetisation of component, (ii) detection of leakage flux using a suitable magnetic flux sensitive device, (iii) processing data to get good signal-to-noise ratio and (iv) interpretation of test results. The magnetisation of the test object can be done using one of three possible ways: (a) permanent magnets, (b) electromagnets and (c) electric current passing through the material. Permanent magnet is seldom preferred as magnetisation can not be turned off when desired [4]. This problem is absent with electromagnets and electric currents. Generally, the test object is magnetised close to the saturation region of B–H curve to get better sensitivity and repeatability. To get maximum amplitude signal for a defect, it is necessary to ensure that the magnetic flux is perpendicular to the expected orientation of the defect.

Use of sensors in MFL enables automated testing of components and this is especially attractive in engineering industry for inspection of symmetric components. The most widely used sensors for MFL applications are Hall sensors (for measurement of normal component) and Giant magneto-resistive (GMR) sensors (for measurement of tangential component). In this paper, results of application of GMR sensor for detection of tangential component of leakage fields from sub-surface notches in carbon steel plates are presented. MFL images of sub-surface notches are obtained by raster scanning of surfaces using GMR sensor. Feasibility of using GMR sensor for detection of hidden defects in steel wire ropes is also discussed.

GMR Sensor Characteristics

GMR sensor consists of magnetic metallic multilayer such as Fe/Cr, Co/Cu, Co/Ag, NiFe/Cu and NiCo/Cu in which ferromagnetic layers are separated by non-magnetic layers of a few nm thick. It works based on GMR effect in which there is large change in electrical resistance of multilayer when exposed to an applied magnetic field. This reduction in electrical resistance is due to the spin dependent scattering of electrons at interfaces between ferromagnetic films and nonmagnetic interlayers [5]. The GMR sensors are characterized by high sensitivity at low
magnetic field, high signal-to-noise ratio and high spatial resolution. Besides, they are inexpensive, consume less power and easy to use. They can also be integrated as array of sensors to facilitate rapid scanning of surfaces [6]. These attractive features make them very good candidate sensors for MFL testing, especially for detection of sub-surface (hidden) defects which produce very weak leakage magnetic fields.

For this study, GMR sensor (AA003-02) manufactured by NVE Associate is used. Because of the bridge configuration (Figure 1a), GMR sensor measures the differential output voltage and ensures high stability with low noise. This sensor can be operated from room temperature to 125°C and has a maximum hysteresis of 4% unit [7]. The output characteristic of the GMR sensor for calibrated magnetic fields is shown in Figure 1b. The sensitivity of the GMR sensor (260 VT at 5V biasing voltage) is 26 times larger than that of Hall sensor (10VT). The linear response of GMR sensor is found to be within the range of 0.2 mT to 1.3 mT.

Experimental Set-up for MFL Measurements

The experimental set-up made for MFL measurements using GMR sensor is shown in Figure 2. This consists of a C-core electromagnetic yoke (length 120 mm, cross-sectional area, 55x75 mm² and leg spacing, 70 mm), GMR sensor, ferromagnetic plate with defects, X-Y scanner, amplifier and personal computer. Keeping the electromagnetic yoke centered over the defects, the tangential component (along the scan direction) of the leakage magnetic flux is measured by scanning the GMR sensor across the defects with a physical lift of 0.3 mm. The sensor output is amplified by a low noise DC amplifier for enhancing the defect signals. This output is digitized using a data acquisition (DAQ) system and then, stored in the computer for removal of background noise and for subsequent analysis.

A steel wire rope of 820 mm length and 64 mm diameter consisting of some natural defects is examined by magnetizing longitudinally with a coil consisting 4 layers of 16 SWG copper wire, each of 25 turns. To

![Figure 2](image2.png)

Figure 2. Experimental set-up for MFL studies.

The specimens used in this study are four carbon steel plates (thickness, 12 mm) each having two 15 mm long EDM notches of widths of 0.5 mm and 1 mm and of different depths. The depths of the EDM notches are measured by ultrasonic technique with an accuracy of ± 0.03 mm using 10 MHz transducer, as given in Table 1. With the notches on the opposite of sensor side (plate inverted) surface notches are examined (Figure 3). The sub-surface notches have a definite location h below the scanning surface.

![Figure 3](image3.png)

Figure 3. Nomenclature for subsurface (far-side) notch in Carbon steel plates.

Table 1. Dimensions of subsurface notches in steel plates.

<table>
<thead>
<tr>
<th>Plate</th>
<th>Length (mm)</th>
<th>Width, w (mm)</th>
<th>Depth, d (mm)</th>
<th>Location, h (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate 1</td>
<td>15</td>
<td>0.5</td>
<td>1.74</td>
<td>10.26</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.72</td>
<td>10.28</td>
<td></td>
</tr>
<tr>
<td>Plate 2</td>
<td>15</td>
<td>0.5</td>
<td>3.38</td>
<td>8.62</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3.32</td>
<td>8.68</td>
<td></td>
</tr>
<tr>
<td>Plate 3</td>
<td>15</td>
<td>0.5</td>
<td>5.84</td>
<td>6.16</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>5.76</td>
<td>6.24</td>
<td></td>
</tr>
<tr>
<td>Plate 4</td>
<td>15</td>
<td>0.5</td>
<td>8.84</td>
<td>3.16</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>8.90</td>
<td>3.10</td>
<td></td>
</tr>
</tbody>
</table>
measure the leakage flux in wire rope, the GMR sensor is kept at optimum position of 18 mm from one end of magnetizing coil.

Optimization of Magnetizing Current

The magnetising current in the yoke coil is optimised by studying the MFL signal peak amplitudes for sub-surface notch located at 6.24 mm below surface. As shown in Figure 4, the signal amplitude is found to be maximum at 5 A. This current is chosen as the optimum current for detection of sub-surface notches in plates. In the case of wire rope, the optimum magnetizing current is found to be 6A. After acquiring the MFL data, background noise from yoke poles is removed by polynomial fitting.

![Figure 4](image1.png)

Figure 4. Optimization of magnetizing current for detection of sub-surface notches in 12 mm thick steel plate.

Results and Discussion

The GMR sensor signals for sub-surface notches located at different depths, as obtained by linear scans are shown in Figure 5. As can be seen, GMR sensor detected sub-surface notch located at 10.28 mm (depth 1.72 mm) below the surface with signal amplitude 4.75 times the background signal from notch-free regions. The GMR sensor signal amplitude as a function of notch location below the surface is compared in Figure 6 for two different notch widths. As can be observed, with increase in notch location below the surface, the leakage field strength decreased and hence, the MFL signal amplitude. The amplitudes of GMR sensor signal are found to be higher for wider notches. With increase in location below surface, the MFL signals are seen broader due to divergence of magnetic field in the material. Hence, use of signal parameters such as peak amplitude, full width at half maximum (FWHM) is beneficial for quantification of defect dimensions and its locations.

![Figure 5](image2.png)

Figure 5. GMR sensor signal response for various sub-surface notches of a) 0.5 mm width and b) 1 mm width.

![Figure 6](image3.png)

Figure 6. GMR sensor signal amplitude for sub-surface notches as a function of notch location below the surface.
signals and gives a global perspective of imaged region. Figure 7 shows the MFL images of the sub-surface notches located at 6.24 mm and 8.68 mm below surface. As can be seen, the MFL images show the spatial information of notches. The SNR of MFL images for sub-surface notches located at 6.24 mm and 8.68 mm are 11.13 and 5.64 respectively.

The GMR sensors signal from a hidden defect present in the steel wire rope as obtained by scanning the sensor along the axial and circumferential directions are shown in figures 8(a) and 8(b) respectively. As there is no evidence of damage on the surface of wire ropes, these signals are attributed to the broken strands and localized fretting of wire the rope, identified other NDE techniques [8].

![GMR Signal](image)

**Figure 7.** MFL images of sub-surface notches located at 6.24 and 8.68 mm below surface in 12 mm thick carbon steel plates.

**Figure 8.** GMR signal from a hidden defect in a 64 mm dia wire rope for a) axial and b) circumferential directions.

**Conclusion**

GMR sensor has been used for detection of tangential component of leakage magnetic flux from sub-surface notches in 12 mm thick carbon steel plates. Using optimized measurement system with magnetic yoke, GMR sensor and selective amplifier; it is possible to detect a sub-surface notch located 10.28 mm below the measurement surface. The GMR response for sub-surface notches is found to decrease with notch location below the measurement surface. MFL images of sub-surface notches located at depths 6.24 mm and 8.68 mm below surface show the spatial extent of notches. GMR sensor could detect hidden defects in steel wire rope. Development of inverse algorithms for characterization of defects is in progress.

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