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MFL field. Recently, Siebert and Sutherland [7] and Li et al. [9] were the first to discuss 3-component MFL measurement and the tangential component.

3. The literature also lacks a systematic study of lift-off. Lift-off is the radial distance between the surface of the pipe specimen and the sensor which measures MFL. It is widely known that increasing the lift-off decreases the MFL signal amplitudes drastically. However, the influence of lift-off on defect characterization is not documented in the literature.

The objective of any MFL sensing technique is to provide as accurate and comprehensive MFL data as possible. The data so collected is then referred to an expert who forms inferences about the existence, location, and topology of defects in the specimen, based on prior experience. The next section discusses the contributions of this work in light of the above discussion.

Figure 1.4: The InspectorBot (courtesy itRobotics, Inc.)

Figure 1.5: 3-dimensional pipe coordinate system
simulation for the cylindrical defect at the $x - y$ plane above the surface of the specimen.

**Figure 2.7:** Solution of FEM simulation. Cylindrical defect

This chapter briefly discussed the theory of magnetostatics using Maxwell's equations applied to defects in ferromagnetic specimens, and presented a simple framework for modeling the MFL field by solving Maxwell's magnetostatic equations using the finite element method. The MFL fields thus obtained can be used to augment experimental MFL data from real defects. As discussed in Chapter 1, experimental surface scanning MFL data is rare in the literature. Therefore, in this work, MFL data from the finite element method will be used in lieu of experimental MFL data.
3.3 Simulation Results and Discussion

Figure 3.3 shows the MFL streamlines (magnetic lines of flux) in the vicinity of a cylindrical surface-breaking defect with parameters given by Table 3.1 and with the applied field along \( y \)-axis. The flux lines originate from the sample in the negative half-space \( (y < 0) \) and end at corresponding points on the sample in the positive half-space \( (y > 0) \). The slice color contours at \( z = 0.5 \text{ mm} \) and \( z = 10 \text{ mm} \) show the magnitude of normalized overall MFL flux density. They are obtained by normalizing the overall MFL flux density magnitude at each elevation (\( z \) position) by the peak magnitude at that elevation. Red color indicates a high magnitude, while blue color denotes low magnitude. It can be seen that at low lift-off \( (z = 0.5 \text{ mm}) \), the peaks in the overall MFL signal coincide with the periphery of the defect. However, at high lift-offs (characterized here by \( z = 10 \text{ mm} \)), the overall MFL signal peaks are more diffused and displaced from the periphery of the defect.

![Figure 3.3: MFL streamlines due to a cylindrical hole defect](image)

Figure 3.4(a) shows the orthogonal projection of the MFL streamlines on the \( x-z \) plane, and the slopes denote the ratio of the radial component to the tangential component. Infinite slope at \( x = 0 \) implies that the tangential component is zero at \( x = 0 \). This forms one explanation as to why the tangential component has largely
Figure 3.5: Normalized MFL components. (a)–(c) Surface mesh plots; (d)–(f) contour colormap plots
Figure 3.7: Normalized MFL components at $h = 1 \text{ mm}$. (a)–(c) FEM model; (d)–(f) Proposed model
Figure 3.8: Normalized MFL components at $h = 10$ mm. (a)–(c) FEM model; (d)–(f) Proposed model.
Figure 3.9: Normalized MFL components. Cylindrical defect. (a)–(c) $h = 0.5$ mm; (d)–(f) $h = 10$ mm
Figure 3.10: Normalized MFL components. Cuboidal defect. (a)–(c) $h = 0.5$ mm; (d)–(f) $h = 10$ mm
Figure 3.12: MFL components along line-scan at $x = 0$ mm

Figure 3.13: MFL components along line-scan at $x = 6.5$ mm

Figure 3.14: MFL components along line-scan at $x = -6.5$ mm
Similarly, the fractional sensitivity of the radial MFL component to defect radius $R$, and that to defect depth $b$ are given, respectively, by

\[
S^R_z = \frac{R \ dB_z}{B_z \ dR} \quad (3.30)
\]
\[
S^b_z = \frac{b \ dB_z}{B_z \ db} \quad (3.31)
\]

It should be noted that the above expressions for fractional sensitivity with respect to defect parameters $R$ and $b$ are meaningful, even though the magnitude of magnetization $M$ is a function of these parameters. This is because $M$ from the numerator and denominator cancels out and hence does not explicitly appear in the fractional sensitivity expressions.

Figure 3.15 shows a plot of the fractional sensitivity $S^b_z$ of the radial MFL component to lift-off for parameter values given in Table 3.6. Several conclusions can be drawn from Figure 3.15:

1. Negative fractional sensitivity throughout implies that the radial component decreases everywhere, as lift-off is increased.

2. In general, the fractional sensitivity of the radial component to lift-off increases with lift-off.

3. At very small lift-off, the radial component is most sensitive to lift-off closest to

![Figure 3.15: Fractional sensitivity of radial MFL component to lift-off](image-url)
Figure 4.5: Measured line-scan data set 1

Figure 4.6: Estimated magnetic charge

Figure 4.7: Reconstructed defect
Figure 4.8: Measured line-scan data set 2

Figure 4.9: Estimated magnetic charge

Figure 4.10: Reconstructed defect
Figure 4.11: Measured line–scan data (only axial and radial components)

Figure 4.12: Estimated magnetic charge

Figure 4.13: Reconstructed defect
throughout the circumference of the pipe for more comprehensive measurement. These sensors pick up the magnetic flux density generated by the magnetizer and the MFL field of the pipe wall.

The internal device is supposed to traverse inside the pipe and negotiate different regions of the pipe which might have non-uniform dimensions. Splitting the annular cylindrical structure into three different wedges enables the device to traverse through a range of cross section areas. Once inside the pipe, these wedges tend to stick to the inner surface of the pipe due to magnetic attractive forces, thus ensuring consistently uniform lift-off. Figure 5.4 shows the simplified axisymmetric geometry of the internal device as it is situated inside a pipe. Table 5.1 shows the geometric
the magnetic circuit flows in a counter-clockwise manner. The magnetic flux density in the core is negative, and that in the thin region of the pipe is positive. The flux density in free space is of the order of $\sim 10$ mT. Furthermore, the region of the pipe closest to the center of the magnetizing device is saturated, as indicated by the dark red color. The Hall-effect sensor reading can be simulated by simply recording the flux density at the point where the sensor is situated.

Similar simulations are performed for a range of characteristic wall thinning defects, from 0% to 60%. From each simulation, the simulated Hall-effect sensor axial reading is recorded and plotted against % wall thinning. Note that $(\% \text{ wall thinning}) = 100 - (\% \text{ wall thickness})$. The resulting plot of axial MFL signal vs. % wall thinning can be called the \textit{wall thinning reference curve}. Since the wall thinning defects are on the outside wall of the pipe, the positions of the magnetizing device and the Hall-effect sensor are constant with respect to the inner pipe wall. In other words, lift-off is constant.

For validation of the simulations, as well as to tune the magnetization scaling factor $\gamma$, experiments are conducted with the magnetizing device inside actual pipe samples with a range of external wall thinning defects. The result of such an ex-
the flux in the magnetic circuit flows in a clockwise manner. The flux density in the magnet is negative, and that in the thin region of the pipe is positive. The flux density in free space is of the order of $\sim 10$ mT. Furthermore, the thinned region of the pipe is saturated, as indicated by the dark red color. The Hall-effect sensor reading can be simulated by simply recording the flux density at the point where the sensor is situated.

Similar simulations are performed for a range of characteristic wall thinning defects, from 0% to 60%. From each simulation, the simulated Hall-effect sensor axial reading is recorded and plotted against % wall thinning. Since the wall thinning defects are on the outside wall of the pipe, and since the magnetizing device is stationary and rigid, lift-off is variable. A single validation experiment is conducted to tune the magnetization scaling factor $\gamma$. Since the structure of the magnetizing device is fixed, the scaling factor remains constant irrespective of the pipe geometry being tested. Figure 5.13 shows the axial MFL profile obtained from a validation experiment conducted at speeds in the range $0 - 0.5$ m/s. From this profile, the characteristic axial MFL signal for each wall thickness is extracted. The axial MFL signal is plotted against % wall thinning, to obtain experimental wall thinning reference curves. The results are shown in Figure 5.14(a). As a result of variable lift-off,
with this apparatus are also presented.

The mechanical design of the ultrasonic NDE apparatus is based on the following considerations:

1. C-scan capability: A C-scan (or area scan) is a sequence of echo signals obtained at discrete points on a two dimensional grid overlaid on the surface of a sample [88]. If the grid points are sufficiently close together, the discrete grid is a good approximation to the surface of the sample. Figure A.6 shows an example of a C-scan image [89]. C-scan capability is an important requirement for the apparatus because it provides a complete 2-dimensional mapping of the flaw, provided the resolution is high enough. Issues related to resolution are discussed later in this section.

![Figure A.6: A quarter and its C-scan image](image)

2. 100% surface area coverage: The tubular sample can have simulated defects distributed all over its surface. Thus, the ultrasonic illumination needs to cover the entire surface area of the sample.

3. 2-dimensional relative motion: The preceding two requirements imply that either (1) there should be a large number of transducers over the entire surface area of the sample so that every point on the sample is illuminated by a transducer, or (2) there should be one transducer and there is 2-dimensional relative motion between the sample and the transducer. The latter option is selected for its practicality and low cost.

4. Acoustic couplant: The choice of acoustic couplant should be such that it allows relative motion between the sample and the transducer, and also covers the entire surface area of the sample.

Based on the above design considerations, a schematic of the ultrasonic test apparatus is shown in Figure A.7. The apparatus allows 2 degrees of freedom (DOF): the linear displacement of the transducer $x$, and the angular displacement of the sample $\theta$. The sample is immersed in a mixture of water and propylene glycol,
Figure A.8: Mechanical drawing of coiled tubing sample

Figure A.9: Photographs of the ultrasonic NDE apparatus

(a) View from drain end  (b) View from drive end

A.4 Ultrasonic Testing Experiments

Experiments were conducted with the ultrasonic NDE apparatus on the coiled tubing sample shown in Figure A.8. The Krautkramer 241-270-PWCCS straight-beam transducer was used in pulse–echo mode to record the echo signals from the undeformed pipe surface as well as from simulated defects A–G, N–Q (see Figure A.8). Figure A.10 shows a detailed photograph of the transducer at a distance $z = 32.385$ mm from the sample surface. The transducer sits on a platform between the ball screw and a parallel shaft with linear bearing. This configuration is used for pulse–
echo testing of the sample. A 50 % V/V mixture of water and ethylene glycol was used as acoustic couplant in some of the experiments.

![Figure A.10: Pulse–Echo testing of tubular sample using straight-beam transducer](Image)

The mass density and acoustic velocity in this couplant are calculated as follows. Let mass density be denoted by \( \rho \) and acoustic velocity by \( c \). Let the couplant occupy a volume \( 2V \). Let the subscripts 1 and 2 denote water and ethylene glycol, respectively. A simple model is assumed whereby the couplant can be considered to comprise of equivolume and parallel layers of water and ethylene glycol. Let ultrasound take time \( \Delta t \) to travel a distance \( 2z \) in the couplant. Then,

\[
\Delta t = \frac{2z}{c} = \frac{z}{c_1} + \frac{z}{c_2}
\]

\[
\Rightarrow c = \frac{2c_1c_2}{c_1 + c_2}.
\]

Also,

\[
2\rho V = \rho_1 V + \rho_2 V
\]

\[
\Rightarrow \rho = \frac{\rho_1 + \rho_2}{2}.
\]

The parameters are: \( \rho_1 = 1000 \text{ kg/m}^3 \) and \( \rho_2 = 1113 \text{ kg/m}^3 \), and \( c_1 = 1480 \text{ m/s} \) and \( c_2 = 1660 \text{ m/s} \). Hence, we obtain \( c = 1564.8 \text{ m/s} \) and \( \rho = 1056.5 \text{ kg/m}^3 \). Water was used as acoustic couplant in some other experiments. These choices of acoustic couplant were based on easy availability. In future, pure propylene glycol will be used as acoustic couplant.

Figure A.11 shows a typical pulse–echo time profile obtained from the experiments. The oscillations in region A at the left constitute the pulse emitted by the transducer. The oscillations in region B at the center constitute the echo from the top outer surface of the sample. The oscillations in region C following this echo are
Figure A.21: Feature level data $f_{13}$ and $f_{23}$. Defect E

Figure A.22: Feature level data (features 1 and 2). Defect E

(a) $f_{1i}, i = 1, ..., 1435$

(b) $f_{2i}, i = 1, ..., 1435$

A.5.2 Symbol Level Data

Finally, actual qualitative and quantitative characteristics of the defect are interpreted from the symbol level and feature level data.

Figure A.22(a) yields that the defect perimeter is rectangular in shape and also yields the rough dimensions of the rectangle. Figure A.22(b) yields the defect depth (since a higher echo arrival time indicates a higher distance of the reflecting surface from the transducer). The defect depth is uniform along the axial direction, while it is the greatest at the tangential coordinate of 32 degrees, and decreases both ways in the tangential direction.

Figure A.23(a) shows a plot of normalized, time-shifted echo signal at defect E against normalized, time-shifted echo signal at a location near defect E. Such a plot