

An Improved Estimation of Length and Depth of Defects Using Magnetic Flux Leakage with Eddy Current Signals

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In this paper, an improved method for accurately estimating the length and depth of defects using magnetic flux leakage (MFL) and eddy current (EC) signals is proposed. Although detailed defect shapes affect the MFL signals, their blunt response limits accurate sizing. Magnetization-based eddy current testing (MB-ECT) can detect local permeability perturbation caused by defects, allowing characterization of the detailed features of defects. By combining the MFL and EC signals, length and depth estimation performance can be improved. The parameters of defect such as defect opening, sharpness, and the position of maximum depth can be estimated. The defect shapes are represented in the function of these parameters and improved algorithm for sizing depth is proposed. In 2-page digest, MFL and EC signals are analyzed using three defect shapes using 3-D FEA simulation, and ideas for estimating the detailed features of defects are deduced. Detailed algorithm will be presented in full paper with further simulations and experimental results.

Index Terms—Defect characterization, Eddy current testing (ECT), Magnetic flux leakage (MFL), Magnetic permeability.

I. INTRODUCTION

NON-DESTRUCTIVE TESTING (NDT) techniques for in-service inspection of oil and gas pipelines have been extensively researched and implemented since the 1960s [1]. To assess pipeline integrity, a pipeline inspection gauge (PIG) travels inside the pipeline and detects defects using integrated sensors. The sensor techniques for defect detection include magnetic flux leakage (MFL), and eddy current (EC) testing.

MFL is one of the most widely adopted techniques for detecting metal loss caused by corrosion. Detected defects by the leakage flux are evaluated as equivalent cylindrical shapes by three geometric parameters: length, width, and depth [2]. However, real corrosion defects usually have irregular shapes with complex features such as defect opening and depth profile [3]. Despite these features affecting the position and magnitude of signal, the MFL signal appears blunt shape, making it difficult to estimate characteristics of defect. These limitations in MFL signals result in errors in length and depth estimation. There have been many studies to improve the accuracy of defect estimation using MFL signal. However, these methods require significant computational costs [4], or do not consider the detailed geometric factors of defects [2], [5].

Defects under the magnetic field cause not only leakage flux but also local permeability perturbations around the defect. Since the permeability changes significantly at the defect opening and groove, it reflects the shape and depth profile of the defect well. By sensing the response of local permeability perturbation, the detailed features of the defect can be estimated.

Permeability perturbations can be detected using magnetization-based eddy current testing (MB-ECT). An eddy current probe, placed between the magnetizer, can detect buried defects by sensing the response due to the permeability changes. In [6]-[7], the principles of MB-ECT were introduced, and the relationship between defect depth and signal of MB-ECT in various operation conditions was analyzed.

In this paper, an improved defect estimation algorithm using MFL and EC signal is proposed. By combining the local permeability signal from EC probe and leakage signal from Hall sensor, detailed shape of defect is estimated, improving length and depth estimation accuracy. In the 2-page digest, the signals are analyzed in three defects that represent the characteristics of defects using finite-element simulation. Ideas for estimating defect opening, and depth profile are. An overall algorithm for improving accuracy of defect length and depth, and experimental verification will be presented in the full paper.

II. DEFECT CHARACTERIZATION USING MFL AND EC SIGNALS

A schematic diagram of the sensor module and the defect is shown in Fig. 1(a). The magnetizer induces a DC magnetic field into the ferromagnetic steel plate, and the Hall sensor detects the leakage field, and the EC probe measures the permeability of the surface layer of the plate. Typical corrosion defects usually have an arbitrary shape as shown [3].

To simulate the MFL and EC signals when the sensor module scans defects, 3D finite-element analysis was conducted using COMSOL Multiphysics 6.2. The simulations were performed for three defect types depicted in Fig. 1(b), all having the same volume and depth. The leakage field was computed through

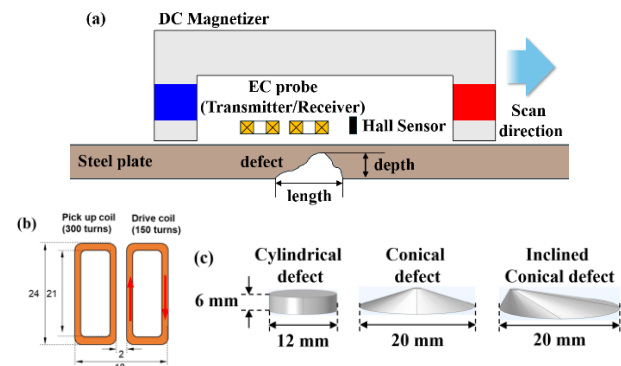


Fig. 1. (a) A schematic diagram of MFL-EC sensor module. (b) structure of EC sensor module (c) Three defects that represent the corrosion defects.

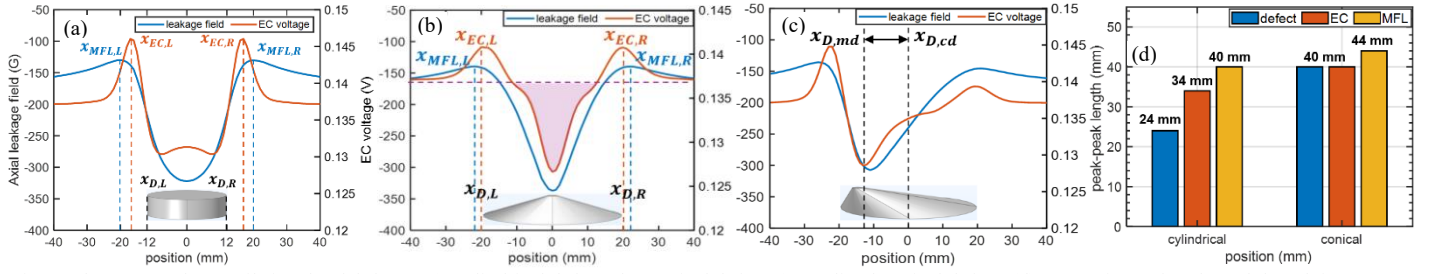


Fig. 2. The MFL and EC coil signals of defects. (a) Cylindrical defect, (b) Conical defect, (c) Inclined conical defect, (d) comparison of peak-peak length in MFL and EC signals.

a static analysis. The plate material was API 5L X42, a nonlinear B-H curve and an electrical conductivity of 6.85×10^6 S/m. A external magnetic field was applied to the edge of the test plate by imposing Neumann boundary conditions in the model, then the leakage field due to the defect was calculated. The resulting B-field distribution was stored and used to derive the incremental permeability of the test plate, which was subsequently employed as an input for the time-harmonic analysis. The voltage of the EC probe was obtained, where the probe current was set to approximately 5 mA and the frequency was 20 kHz. Since the magnitude of the AC field induced by EC probe was much smaller than the applied DC magnetic field, and the material was operating near the saturated region of the B-H curve, the minor loop could be approximated as linear.

The simulation results are presented in Fig. 2. By comparing signals, the idea for estimating the defect opening, sharpness, and position of the maximum depth is proposed.

A. Defect opening

In Fig. 2(a) and (b), the position of the peak signals x_{MFL} , x_{EC} , and the defect opening x_D were compared. The distance between the EC signal peaks and the actual defect edges decreases significantly as the defect slope decreases, while the change in MFL peak distance is relatively small as shown in Fig. 4(d). This indicates that the EC signal is more sensitive to variation in defect sharpness. Based on the difference in trends between the two signals, defect length can be effectively estimated. In both cases, x_D is located outside the x_{MFL} and x_{EC} . So, the position of the defect opening and defect length can be estimated as

$$x_{D,L} = x_{EC,L} + \alpha(x_{EC,L} - x_{MFL,L}) \quad (1)$$

$$x_{D,R} = x_{EC,R} + \beta(x_{MFL,R} - x_{EC,R}) \quad (2)$$

$$length = x_{D,R} - x_{D,L} \quad (3)$$

where α and β are a function of the distance between the signals x_{MFL} and x_{EC} . Since defect length, depth, and signal magnitude are not independent of each other, accurate estimation of defect length is crucial, as it directly contributes to improving the accuracy of depth estimation.

B. Sharpness of the defect

The magnitude of the MFL signal is affected by the slope of the defect. Although the defects in Fig. 2(a) and (b) have the same volume and depth, the MFL signal magnitude for the conical defect is approximately 10% higher. Therefore, it is important to determine the sharpness of the defect measured. Sharpness can be quantified by calculating the area of the EC

signal beneath the baseline (purple region) and comparing it to that of cylindrical defects. This sharpness parameter, denoted as S , is incorporated to compensate for the estimated depth.

C. Position of the maximum depth

The position of the maximum depth in defect $x_{D,md}$ also affects the MFL signal magnitude. Comparing Fig. 2(b) and (c), the magnitude in (b) was 18% higher than in (c). By estimating the distance between $x_{D,md}$ and center position of defect $x_{D,cd}$ and serving the parameter C , depth can be estimated more accurately. This C is dimensionless, so expressed as

$$C = \left| \frac{x_{D,md} - x_{D,cd}}{length} \right| \quad (4)$$

As a result, the estimated length, sharpness, and maximum depth position are incorporated into the depth estimation process through functional correction. The estimated depth is expressed as

$$depth = kf(length) \cdot g(S, C) \cdot MFL, \quad (5)$$

where f is a function that estimates the defect depth based on the length for cylindrical defects, and g is a correction function that adjusts the estimated depth by accounting for the sharpness S and asymmetry C of the defect. The detailed definitions of the parameter S and C , the functions f and g and the coefficient k require further simulations and experimental validation. A complete description of these components and overall algorithm will be provided in the full paper.

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