Numerical Simulation of Electromagnetic Flux Leakage in Application of Internal Defects Prediction of Metal Parts

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Abstract—Metal products were widely used at a variety of industry, so it is essential to predict the security and the usability without the destructive testing for the desired production efficiency under the different their working conditions. Recently, the plasma deposition dieless manufacturing process (PDM) is an innovative and promising application of plasma heat source with extensive industrial potential for refractory and intractable material part or prototype, rebuilding of worn components and especially the direct rapid fabrication of functionally graded materials (FGMs). However, Residual stress and distortion induced by the highly localized transient heat and strongly nonlinear temperature distributions would likely promote undesired and unpredictable warps and cracks in this process. Thus, to distinguish the internal defect from the significant discontinuities during the nondestructive testing of the metal parts, in this paper, the finite-element method (FEM) was applied to predict the electromagnetic distribution. According to the difference the magnetic flux leakage analysis, distinction threshold was built by the ratio of the peak-to-peak amplitudes of the raw inspecting signal anomaly. Computational results show that it is potential to decrease the testing period and improve the security of metal parts, in particular, the micro-raw and hole in the metal parts can be predicted, thus the possibly-intended breakage would be improved.

1. INTRODUCTION

Tubular products are widely used at a variety of industry. Considering their working condition, nondestructive testing (NDT) stands essential for both the desired production efficiency and security [1–3]. As a popular testing method used for the steel pipes’ testing, MFL was supposed intuitively to provide more health information sufficiently. During the real-time inspection, other factors, such as shape and orientation could contribute significantly for the defect’s location characteristics, leading the location identification disorder. This problem has been attached more and more importance during the evaluation system of the steel pipes’ health information in their supply-and in their service. To assess the severity of the flaw in the tubular product, Perazzo et al. have improved the signal processing and extracted more features. They also suggested some additional threshold for the reliable inspection [4]. The desired differentiation has yet been achieved in our experimental inspections to the artificial defects’ designed with different shape and machined at the same surface of the reference materials with regular wall-thicknesses, respectively. With the help of the noise-decreasing process, J. Etcheverry et al. threw some light on the signal-processing to the raw MFL signal. Harmonic functions were used to eliminate the disturbance from the noise, and transformation was carried out from the inspected vector series into the normalized scalars, which the latter could function as the index, presenting more information about the flaws. In fact, signal procession is popular in the defect identification, such as wavelet analysis and neural-network algorithm. Although some promising progress has been taken to identify the artificial discontinuities’ shape characterization, further work needs carrying to achieve the desired inspection, especially to their application on the natural flaws’ evaluation. Any biased evaluation desperately leads either the danger in its service or the un-expected production cost after the inspection. As a kind of signal processing method, the differentiating index provided in this paper focuses on the ratio between the peak-to-peak amplitudes of the original-signal anomaly and its difference component at second order, instead of some single index inspected or some component originating from some transformation in conventional MFL techniques. Verified by the experimental inspections on the transverse notches and pits artificially machined on the drill pipe with 9.35 mm in wall-thickness and 88.7 mm in outer diameter, this method presents the advantage, which is irrespective of the
defects’ critical physical size and shapes, comparing with the currently applied methods. This alternative discrimination index could be used in the conventional MFL testing system, providing more information about the inspection result with the minimum cost.

2. CHARACTERISTIC ANALYSIS OF THE FLUX LEAKAGE

MFL testing probe is designed to scan along the outer surface of the pipe, with some desired lift-off distance. Any discontinuity in the specimen under magnetic saturation could be taken as a kind of magnet-dipole. As illustrated in Figure 1, \(M_1-M_{11}\) was used for the magnetic dipole simulation, which configures the magnetic flux anomaly in the vicinity of the defects. As a kind of nonlinear and micro-spatial sector, specific flux strength distribution is decomposed to normal and tangential components i.e., \(H_X\) and \(H_Y\) at the \(A\) and \(A_p\) points, which are raised by the external discontinuity and the internal one respectively and denoted through the formulas below:

\[
H_X = \int_0^h dH_{M_1} + \int_0^h dH_{M_{11}} = 2\sigma_s \cdot \left[ \arctg \frac{h \cdot (x + b)}{(x + b)^2 + y \cdot (y + h)} - \arctg \frac{h \cdot (x - b)}{(x - b)^2 + y \cdot (y + h)} \right] \\
H_Y = \int_0^h dH_{M_1} + \int_0^h dH_{M_{11}} = \sigma_s \cdot \ln \left[ \frac{(x + b)^2 + (y + h)^2}{(x + b)^2 + y^2} \cdot \frac{(x - b)^2 + (y + h)^2}{(x - b)^2 + y^2} \right]
\]

(1)

\[
(2)
\]

3. RESULTS AND DISCUSS

As the conventional MFL inspection illustrating, the peak-to-peak amplitude was always used as the index to calibrate against to build the threshold. Induced by the discontinuity at the opposite surface, the flux anomaly is ferrous influenced, and presents being smoothed and weakened, comparing to those at the scanning surface. As illustrated in Figure 1. With the help of FEA (Finite Element Analysis) simulation to the 2-dimensional axis-symmetric model, we could find the relation quantitatively about the amplitudes of the signal anomalies, arising from the simulated defects with comparable physical size but different location. According to the wall thickness of the

<table>
<thead>
<tr>
<th>Wall-thickness (mm)</th>
<th>N5 (5%)</th>
<th>N10 (10%)</th>
<th>N15 (16%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{ED}/V_{ID}</td>
<td></td>
<td></td>
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<tr>
<td>5.50</td>
<td>2.30</td>
<td>2.13</td>
<td>2.50</td>
</tr>
<tr>
<td>9.35</td>
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<td>2.06</td>
<td>2.23</td>
</tr>
<tr>
<td>12.00</td>
<td>2.06</td>
<td>2.04</td>
<td>2.08</td>
</tr>
</tbody>
</table>
5.50 mm, 9.35 mm, and 12.00 mm, the discontinuities were designed with the depths varying with 5%, 10% and 15% of the wall-thickness. The analyzing results were listed in Table 1, and it could be obviously found that the amplitude index, induced by the discontinuities at the outer surface, approximately twice the counterpart of the discontinuities at the inner surface.

The external notches are commonly set as the reference signal source in the most MFL equipments’ calibration, and some characteristic components were used to assess the severity of the imperfection in the specimen during the real time production inspection, such as peak-to-peak amplitude and other indexes corresponding to the anomaly single. But is it available to identify the flaws’ location? As shown in the formula (1) and (2) and illustrated in the Figure 1, the lift-off distance could not be ignored for the defects’ location identification. In fact, the permeability change happening at the media, which separates the material with high permeability (steel wall) and the far lower one (air), conventional proportion-approximating procedure and the linear simulation will definitely distort the inspecting subject with biased inspection result.

![Figure 2: Dissimilar characteristics between the signal anomalies.](image)

![Figure 3: Tangential flux density induced by defects with the same physical size but at different surface.](image)
As the signal anomaly illustrating at the calibration and real-time inspection, the external flaw corresponds to some relative sharper flux anomaly than that from the internal one. Based on this, ad hoc triggering thresholds shall be set independent of each other corresponding to the external and internal defects during the calibration. As the essential index, width between the crests of signal anomaly was discussed below. With the help of 2-dimensional axis-symmetric model FEA (Finite Element Analysis) model, some flaws were designed at the inner surface, subsurface and the outer surface, showing the variation of the signal anomaly due to its location. Obviously the width between the adjacent crests in vicinity of the designed flaws shows their inherent characteristic in the Figure 3.

4. CONCLUSIONS
Based on the analysis on the original inspected signals belong to the spatial domain and the spectral domain, the ratio index was formulated by the peak-to-peak amplitudes of raw signal and its second difference component, supplying an alterative accessing index. To be exempt of the disturbance from the defects' physical size and shape during the MFL inspection in field, some procedures were built and fabricated into the defects' location identification in this paper, by resort of the further difference process, the first process, i.e., feature extracting capability could be assessed.

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