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Experiment and simulation study of 3D magnetic field sensing for magnetic flux leakage defect characterisation

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Abstract

Magnetic flux leakage (MFL) testing is widely used to detect and characterise defects in pipelines, rail tracks and other structures. The measurement of the two field components perpendicular to the test surface and parallel to the applied field in MFL systems is well established. However, it is rarely effective when the shapes of the specimens and defects with respect to the applied field are arbitrary. In order to overcome the pitfalls of traditional MFL measurement, measurement of the three-dimensional (3D) magnetic field is proposed. The study is undertaken using extensive finite element analysis (FEA) focussing on the 3D distribution of magnetic fields for defect characterisation and employing a high sensitivity 3-axis magnetic field sensor in experimental study. Several MFL tests were undertaken on steel samples, including a section of rail track. The experimental and FEA test results show that data from not only the *x*- and *z*-axes but also *y*-axis can give comprehensive positional information about defects in terms of shape and orientation, being especially advantageous where the defect is aligned close to parallel to the applied field. The work concludes that 3D magnetic field sensing could be used to improve the defect characterisation capabilities of existing MFL systems, especially where defects have irregular geometries.

Keywords: Nondestructive testing; Magnetic flux leakage; Finite element analysis; 3D magnetic field measurement

1. Introduction

Magnetic flux leakage (MFL) is one of the most widely used electromagnetic NDT techniques and has been used in pipeline inspection gauges (PIGs) for gas pipeline inspection since the 1960s [1–5]. MFL testing relies on the fact that when a magnetic field is applied to a ferromagnetic material, any geometrical discontinuity and local gradients in magnetic permeability in the test material will cause the field to leak out of the material, into the air. This flux leakage is measured by a magnetic field sensor and used to estimate the dimensions of the defect. Recent advances in the field include the development of residual field measurement techniques [6–8]; where the magnetic field remaining in the sample from magnetisation applied during previous testing or generated by stresses in the sample is measured, reflecting both geometrical discontinuities and variations in material properties of the sample due to applied stresses, etc.

The concept of 2-axis measurement of the field components perpendicular to the surface of the material under test (B_z) and parallel to the applied field (B_x) has been investigated via experiment and finite element analysis (FEA) in previous MFL research, concentrating on the MFL signal response to regularly shaped defects [9,10]. The two-dimensional (2D) magnetic field over defects has given sufficient information for defect characterisation, as a result of which the third field component (B_y) and its utilisation have not caught much attention in industry [11]. However, in in-situ conductive specimens, defects with irregular shapes are more frequently found than regularly shaped defects. Therefore, the traditional measurement of 2D magnetic field cannot accurately characterise natural defects, e.g. stress corrosion cracks [12–14]. In this work, following the FEA investigation, measurement of the 3D magnetic field was conducted and its contribution to defect characterisation, focussing on location and orientation was investigated. The residual magnetisation technique has

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been used along with a low field range, high-resolution magneto-resistive sensor designed for compassing applications to investigate the possible advantages of using 3-axis field measurement to provide extra information for defect characterisation in terms of shape and orientation.

The paper is organised as follows: Section 2 presents FEA of MFL with an irregular-shaped defect and discusses the advantage of 3D magnetic field sensing in the characterisation of irregular defects; Section 3 elaborates on the experimental study for MFL inspection of a slotted plate and a section of rail track with a naturally occurring, irregularly shaped crack. The experimental results show good correlation with the simulation and indicate that 3D magnetic field measurement has a lot of potential for the characterisation of irregularly shaped defects using MFL.

2. FEA simulations of MFL with irregular defects

As the electromagnetic (EM) field in MFL systems complies with the well-established Maxwell's equations which govern electromagnetism in physics, FEA has been employed in solving the Maxwell equations that apply to MFL magnetic fields in a bid to unveil the electromagnetic phenomena underlying MFL, and characterise the magnetic field variations due to the occurrence of surface defects within the specimens under investigation. So FEA is beneficial not only to verify experimental study but to provide models for defect characterisation in MFL systems.

2.1. Theoretical background

Because the electromagnetic phenomena underlying the MFL systems still comply with the well-established electromagnetism, the Maxwell's equations are applicable to the analysis of electric as well as magnetic field within MFL systems.

Generally, Maxwell's equations governing MFL are written in time-dependent form as [15]

$$\nabla \times \bar{H} = \bar{J}; \quad \nabla \times \bar{E} = -\partial \bar{B}/\partial t, \tag{1}$$

where $\bar{B}, \bar{H}, \bar{E}$ and $\bar{J}$, respectively, represent magnetic flux density, magnetic field intensity, electric field intensity and source current density.

The EM field can be investigated on a macroscopic level by solving Eq. (1) in conjunction with constitutive relationships, which depict the interaction of the EM field with linear, homogenous and isotropic materials whilst the hysteresis effects is not taken into account for simplification:

$$\bar{B} = \mu_0 \mu_r \bar{H}; \quad \bar{J} = \sigma \bar{E}, \tag{2}$$

where μ_0 and μ_r denote the permeability of air and relative permeability of materials with respect to air and σ is material conductivity.

Since, in our work, permanent magnets are used for generation of the magnetic field, the electric field has not been taken into account and accordingly the magnetostatic analysis applies to our simulation study. Therefore, EM phenomena in MFL are governed by the simplified Maxwell's equation along with one constitutive relationship, as follows [15]:

$$\nabla \times \bar{H} = 0; \quad \bar{B} = \mu_0 \mu_r \bar{H}; \quad \bar{H} = -\nabla v_m, \tag{3}$$

where v_m is magnetic scalar potential.

The magnetic quantities can be computed out as long as the unknown, i.e. v_m in Eq. (3) is worked out. To fulfil that, numerical and analytical approaches for getting the solution to Eq. (3) are to be chosen.

With consideration of the establishment and definition of MFL models, FEA was eventually adopted for analysis into MFL for characterisation of an irregular defect. FEMLAB, one of the commercial FEA packages for electromagnetism, was selected to implement modelling and simulation of MFL in 3D.

2.2. Simulation setup

As shown in Fig. 1(a), a surface defect (SF) was introduced in an arbitrary-shaped magnetic specimen to be interrogated. The shape of SF is irregular and like 'Γ', which is exhibited in Fig. 1(b). The width of the slot is 2 mm while the depth is 5 mm. The angle between the horizontal section (HORS) and perpendicular section (PERS) of the SF is 90°. There is also a diagonal section (DIAS) between VERS and PERS with a 135° angle. The SF is located at the edge of the specimen, and in particular PERS is positioned in the localised area with a curved surface, which brings about a formidable challenge in identifying the shape and orientation of SFs. The information on dimensions and material of the specimens are listed in Table 1.

The simulation model of the magnetic specimen with the SF was built in FEMLAB with 3D coordinates in order to implement a better description of the problem. The 3D magnetostatic linear solver was employed to calculate v_m, following which the distribution of the magnetic field over the SF in three independent axes, namely B_x, B_y, B_z were obtained and investigated. Since the 3D simulation costs a lot of computing energy, some assumptions are made, as follows:

- the applied magnetic field generated by the permanent magnets which are not included in the models is uniform and homogenous within the specimens (simulation of traditional MFL);
- the characteristics of the residual magnetic field within the specimen after pre-magnetisation are assumed to be analogous to those of the applied magnetic field (simulation of MFL measuring residual field without applied field);
- The magnetisation of the permanent magnets or residual magnetisation of the specimen is 1 T and it is aligned with the length of the specimens.