Portable Lorentz Force Eddy Current Testing System with Rotational Motion

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In this study we investigate a new portable Lorentz force eddy current testing (PLET) system using a diametrically magnetized cylindrical magnet rotating around its axis of mass. In order to compare the Lorentz force and the electromagnetic torque used for defect detection, three different model approaches are considered - the weak reaction approach and the quasi-static approach as approximating approaches and the transient simulation as a reference one. The results are validated by measurements.

***Index Terms*—Eddy currents, finite element analysis, nondestructive testing, rotation of permament magnets, torque measurement**

I. Introduction

NONDESTRUCTIVE testing (NDT) prevents failure of safety components and is widely used in quality control in industry. In the recently developed Lorentz force eddy current testing (LET), a relative motion of a permanent magnet (PM) and an electrically conductive, non-ferromagnetic specimen induces eddy currents in the specimen [1]. Hence, the Lorentz force acts on the specimen and according to Newton's third law also on the magnet. In presence of a defect, eddy currents are perturbed leading to a perturbation of the measured Lorentz force. Previous LET systems used a translational motion of the specimen and a magnet fixed to a frame [2].

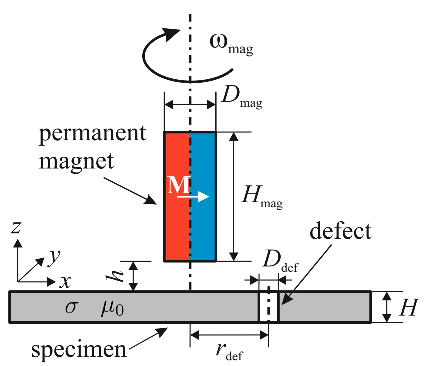

Fig. 1. Schematic of the portable LET system

In contrast to previous LET systems and the system described by Tan et al. [3], we investigate a new portable LET (PLET) system, in which a PM is rotating around its centroid axis of mass. In this study, we consider a diametrically magnetized cylinder magnet rotating perpendicular to the specimen under test.

II. Problem definition

We investigate a cylindrical PM of the diameter D_{mag} and the height H_{mag} diametrically magnetized with the magnetization $\mathbf{M}$. The PM rotates with an angular velocity ω_{mag} clockwise. It is located perpendicularly to the circular specimen of radius R and height H as shown in Fig 1. The lift-off distance between the specimen and the magnet equals h. A defect in form of a bore hole of diameter D_{def} is placed in the specimen at a distance r_{def} from the center of axis of rotation. The Aluminum specimen is described by an electrical conductivity σ. The distance of the center of the bore hole to the center of rotation r_{def} is varied in the study.

III. Methods

However, the PM is rotating in the PLET system, but not the specimen, in the calculation model using finite element method, the frame of reference is assigned to the magnet. Hence, the specimen below the PM is rotating counterclockwise with angular velocity $\mathbf{\Omega}_{\mathrm{spec}} = -\omega_{\mathrm{mag}}\mathbf{e}_z$. The velocity components of the specimen at a point P(x,y,z) in the fixed frame of reference can be calculated as

$$\mathbf{v} = \mathbf{\Omega}_{\mathrm{spec}} \times \mathbf{r} = \omega_{\mathrm{mag}}\, y\, \mathbf{e}_x - \omega_{\mathrm{mag}}\, x\, \mathbf{e}_y. \tag{1}$$

Ohm's law for moving conductors can be also applied for rotational motion [4]:

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}). \tag{2}$$

In this study, we compare two different numerical approaches, the weak reaction approach (WRA) and the quasi-static approach (QSA). In the weak reaction approach, the secondary magnetic field $\mathbf{B}^{(s)}$ generated by the eddy currents are neglected ($\mathbf{B}^{(s)} = 0$). For low products of velocity and conductivity this approach produces reasonable results [2]. In the QSA, the time-dependent derivative of the secondary magnetic field is neglected ($\partial\mathbf{B}^{(s)}/\partial t = 0$). In the WRA, the primary magnetic field $\mathbf{B}^{(p)}$ of the permanent magnet is calculated using the scalar magnetic potential ψ_{m} with $\mathbf{B}^{(p)} = -\mu_0\nabla\psi_{\mathrm{m}}^{(p)}$

$$\nabla \cdot (-\nabla\psi_{\mathrm{m}}^{(p)} + \mathbf{M}) = 0, \tag{3}$$

where $\mathbf{M}$ is the magnetization of the PM. Thus, all calculations in this step are performed without considering the presence of the moving specimen.

In the second step, the electrical potential ϕ, given by $\mathbf{E} = -\nabla\phi$, is determined using the continuity of the current density

$$\nabla \cdot \mathbf{J} = 0. \tag{4}$$

Using (2) and (3) the continuity equation (4) becomes

$$\nabla \cdot \mathbf{J} = \nabla \cdot \left[\sigma(-\nabla\phi - \mu_0 \mathbf{v} \times \nabla(\psi_{\mathrm{m}}^{(p)}) \right] = 0. \quad (5)$$

After separating ϕ and assuming a homogeneous conductivity σ in the specimen apart from the defect, (5) changes to

$$\sigma\nabla^2\phi = -\mu_0\sigma \left[\nabla\psi_{\mathrm{m}}^{(p)}(\nabla \times \mathbf{v}) - \mathbf{v}(\nabla \times (\nabla\psi_{\mathrm{m}}^{(p)})) \right]. \quad (6)$$

For the rotating specimen $\nabla \times \mathbf{v} = -2\omega_{\mathrm{mag}}\,\mathbf{e}_z$, which leads to the final governing WRA equation for the electrical potential ϕ

$$\nabla^2\phi = 2\mu_0\,\omega_{\mathrm{mag}}\,\partial\psi_{\mathrm{m}}^{(p)}/\partial z. \quad (7)$$

In case of QSA, the problem is described by the electrical potential ϕ and magnetic vector potential $\mathbf{A}$, and the following equation

$$\nabla \times (\frac{1}{\mu_0}\nabla \times \mathbf{A} - \mathbf{M}) = \sigma(-\nabla\phi + \mathbf{v} \times (\nabla \times \mathbf{A})). \quad (8)$$

Additionally, the continuity of the current density $\nabla \cdot \mathbf{J} = 0$ has to be taken into account. For both approaches, the boundary condition

$$\mathbf{n} \cdot \mathbf{J} = 0 \quad (9)$$

has to be fulfilled on the surface of the specimen in order to prevent current flowing out the specimen.

The resulting Lorentz force $\mathbf{F}$ acting on the magnet is calculated using Newton's third law by integrating the force density $\mathbf{f}_{\mathrm{spec}} = \mathbf{J} \times \mathbf{B}$ in the conductive specimen

$$\mathbf{F} = -\mathbf{F}_{\mathrm{spec}} = -\int_V \mathbf{J} \times \mathbf{B}\, dV. \quad (10)$$

The electromagnetic torque $\mathbf{T}$ acting on the permanent magnet is determined as

$$\mathbf{T} = -\mathbf{T}_{\mathrm{spec}} = -\int_V \mathbf{r} \times (\mathbf{J} \times \mathbf{B})\, dV. \quad (11)$$

IV. Results

In the simulation, the defect is rotating. The position of the defect can be described by time-varying angle $\varphi(t) = -\omega_{\mathrm{mag}}t$. As the magnet is fixed and its magnetization is assumed to be in x-direction, the angle φ describes the angular position of the defect with respect to the x-axis. The diametrical magnetization of the permanent magnet leads to a periodical signal with an angular period of 180°. As a consequence, the force components F_x and F_y and the torque T_z acting on the magnet can be expressed as a function of the angle φ for different positions r_{def} of the defect (Fig. 2). For angles φ up to 90° the solid lines represent the results calculated by the WRA and the circled points represent the QSA results in Fig. 2. First, it can be noticed that differences between the results of both methods are small. Furthermore, the change of Lorentz force components and the torque strongly depends on the position r_{def} of the bypassing defect, i.e. its relative position to the magnet. The perturbations of the torque T_z are the largest for the defect located at r_{def} = 10 mm.

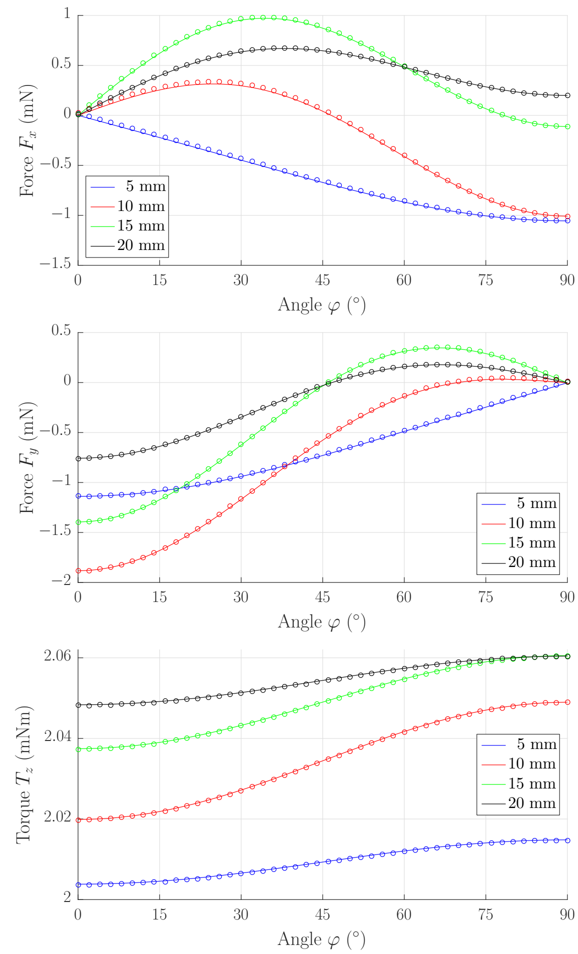

Fig. 2. Lorentz force components F_x and F_y and torque T_z acting on the permanent magnet for different defect radii r_{def} as a function of the angle φ. Solid lines denote WRA results and circles the results of QSA. Used setup: D_{mag} = 20 mm, H_{mag} = 40 mm, $\mu_0 M$ = 1.43 T, ω_{mag} = -5 s^{-1}, h = 1 mm, R = 60 mm, H = 10 mm, D_{def} = 4 mm, σ = 21 MS/m.

V. Conclusion and Outlook

We presented a new portable Lorentz force eddy current testing system using a diametrically magnetized magnet. The studied WRA and QSA methods show good agreement for the analyzed angular velocity. Furthermore, the resulting signals depend strongly on the defect's position r_{def}. It allows to find an optimal PM distance to the defect to maximize the signal perturbation due to the defect. In the full paper, the results of the WRA and QSA are compared with the transient solution and the numerical results will be validated by measurements.

References

[1] H. Brauer and M. Ziolkowski, "Eddy Current Testing of Metallic Sheets with Defects Using Force Measurements," *Serbian Journal of Electrical Engineering*, Vol. 5, No. 1, pp. 11-20, 2008.

[2] K. Weise, *"Advanced Modeling in Lorentz Force Eddy Current Testing"*, doctoral thesis, Technische Universität Ilmenau, Ilmenau, Germany, 2016.

[3] Y. Tan, X. Wang, and R. Moreau, "An innovative contactless method for detecting defects in electrical conductors by measuring a change in electromagnetic torque," *Measurement Science and Technology*, vol. 26, no.3, pp.1-8, 2015.

[4] T. Shiozawa, "Phenomenological and Electron-Theoretical Study of the Electrodynamics of Rotating Systems," *Proc. IEEE*, vol. 61, pp.1694-1702, 1973.