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PERFORMANCE DEGRADATION EVALUATION OF FERROMAGNETIC MATERIALS BASED ON MAGNETO-ACOUSTIC COMPOUNDING INSPECTION TECHNIQUE

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ABSTRACT

Existing nondestructive testing methods can be used separately to extract the acoustic parameters and the electromagnetic parameters. The number of the characterization parameters available for evaluating performance degradation of the ferromagnetic materials is limited. In this paper, a magneto-acoustic inspection technique was used to extract both ultrasonic and the pulsed eddy current signals. Multi-parameters can be obtained by a single magneto-acoustic combined inspection. The acoustic and electromagnetic parameters were used to comprehensively characterize the performance degradation of ferromagnetic materials. The results show that the magneto-acoustic combined inspection technique gives the advantages of both electromagnetic ultrasonic and eddy current testing. It can perform rapid and wide range testing, with improved sensitivity near-surface. Performance degradation of the ferromagnetic materials can be characterized through the multiple-parameters given by the magneto-acoustic compounding inspection technique, and both the sensitivity and robustness of electromagnetic ultrasonic testing can be improved.

Keywords: ferromagnetic materials, magneto-acoustic compounding inspection, multi-parameters, ultrasonic, eddy current

1. INTRODUCTION

The microstructure of ferromagnetic materials is changed when they have been used in a high temperature environment. Such changes will cause performance degradation in the materials, it is necessary to carry out nondestructive testing to ensure their safety.

Electromagnetic acoustic transducers (EMATs) are suitable for non-contact excitation and reception of ultrasonic waves in metal plate [1, 2]. EMATs have the advantage of using no couplant [3, 4]. When ferromagnetic materials are measured using an EMAT, the acoustic parameters of the signals are extracted to characterize the properties of the ferromagnetic materials, and the magnetic parameters of signals were usually ignored. In order to obtain both acoustic parameters and magnetic parameters, dual probes were developed to improve the testing efficiency and accuracy [5-8], for example ultrasonic testing (UT) / eddy current testing (ECT), EMAT/ECT probe. However, their inspection systems were independent. The UT/ECT probe needed to be used with a UT and a ECT system separately [6]. The EMAT/ECT probe still needed two independent EMAT and ECT systems [7, 8]. The dual probe increased the difficulty of operation and increased the cost of detection. The EMAT signal actually contained the pulsed eddy current and ultrasonic parts. The research results have shown how to decouple the ultrasonic eddy current and pulse eddy current signals when EMATs were applied on an aluminum plate [9]. The working principle of EMAT is based on the Lorentz force when the EMAT was applied to generate ultrasonic waves on the aluminum plate. However, when EMAT was used to generate ultrasonic waves on steel plates, the working principle of EMATs were different from that of the aluminum plate, and their working principle is based on the Lorentz and magnetostrictive forces. Therefore, it is more difficult to extract the acoustic parameters of ultrasonic waves generated by the Lorentz force and magnetostrictive effects and to decouple them from eddy current signals.

In this study, a 3D finite element model of an EMAT was established to simulate the ultrasonic wave generated by both the Lorentz and magnetostrictive forces. The combined magneto-acoustic inspection technique was used to extract both the ultrasonic and the pulsed eddy current signals. Multi-parameters can be obtained by a single magneto-acoustic combined inspection, including the acoustic and the electromagnetic parameters. The ultrasonic voltage and the pulsed eddy current voltage signals were decoupled with a filtering strategy. The acoustic and the electromagnetic parameters were used to comprehensively characterize the performance degradation of ferromagnetic materials.

2. MATERIALS AND METHODS

2.1 Theoretical analysis of the magneto-acoustic compounding inspection

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The input current to the coil induces the eddy currents J_e and a dynamic magnetic field H_d when a pulse current with a certain center frequency is supplied to the coil. The dynamic magnetic flux density B_d will lead to induced electric field E_k. According to Faraday's law of electromagnetic induction, the induced electromotive force ε_m will be generated in the coil, which is defined as the pulsed eddy current voltage signals.

$$\varepsilon_m = \oint_l E_k \bullet dl = -\frac{d\Phi_m}{dt} \tag{1}$$

$$\varepsilon_m = -\frac{d}{dt}\iint_s B_d \bullet dS \tag{2}$$

where Φ_m is the induced magnetic flux.

The Lorentz force F_L can be expressed as the interaction of the eddy currents J_e with the static magnetic flux density B_s and the dynamic magnetic flux density B_d:

$$F_L = B_s \times J_e + B_d \times J_e \tag{3}$$

The magnetostrictive force F_{Ms} can be expressed as the interaction of the reverse piezomagnetic stress coefficient e_{ik} with the dynamic magnetic field H_d :

$$F_{Ms,i} = -c_{ij}^H d_{jk} H_{dk} = -e_{ik} H_{dk}$$
$$i, j —— 1,2,3,4,5,6 \tag{4}$$
$$k —— 1,2,3$$

where c_{ij}^H is the stiffness coefficient, d_{jk} is the piezomagnetic strain coefficient.

The Lorenz and the magnetostrictive forces will cause the test piece to vibrate and ultrasonic waves will be generated in the conductor. The governing equation of ultrasonic wave propagation in a homogeneous isotropic medium can be written as

$$\mu\nabla^2 u + (\chi + \mu)\nabla(\nabla \bullet u) - \gamma\frac{\partial u}{\partial t} + F_L + F_{Ms} = \rho\frac{\partial^2 u}{\partial t^2} \tag{5}$$

where ρ is the density of the material, γ is the damping coefficient of the material, and u is the displacement vector. μ and χ are the material elastic constants,

The specimen vibration will cut the magnetic line of flux B_s and will produce the motional electromotive force ε_v, which we define as the ultrasonic voltage signals.

$$\varepsilon_v = -\frac{d\Phi_v}{dt} = -\frac{B_s \bullet dS}{dt} \tag{6}$$

$$\varepsilon_v = -\oint_l \frac{B_s \bullet (vdt \times dl)}{dt} = -\oint_l B_s \bullet (v \times dl) \tag{7}$$

$$\varepsilon_v = \oint_l (v \times B_s) \bullet dl \tag{8}$$

where Φ_v is the motion caused magnetic flux, $\boldsymbol{v}$ is the velocity of the particle

The total electromotive force can be divided into motional electromotive force and induced electromotive force because of the relativity of motion, electric field and magnetic field. The EMAT test signal ε_{total} itself actually contains the pulsed eddy current voltage signal and the ultrasonic voltage signal.

$$\varepsilon_{total} = \varepsilon_v + \varepsilon_m \tag{9}$$

2.2 Simulation analysis of the magneto-acoustic compounding inspection

A 3D finite element simulation of the EMAT was built using COMSOL software, as shown in Fig. 1. The dimension of the permanent magnet is 14 mm, and the thickness is 10 mm. The magnetic flux density of the permanent magnet is 0.5T in the z direction. The excitation coil is a single layer spiral coil 12 mm diameter and with 21 turns. The thickness of the steel plate is 10 mm and parameters of the steel plate are shown in Table 1. Lift-off was designed to be 0.05mm. A 3-cycle sine burst signal modulated by a Hanning window was used, the excitation frequency is 2 MHz. The time step of the simulation is 0.05 μs.

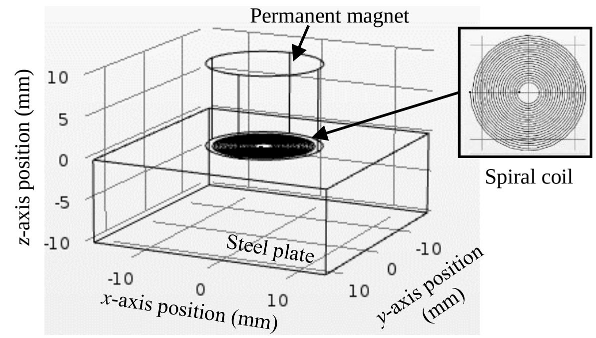

Fig. 1. 3D finite element simulation model based on COMSOL software.

Table 1: Parameters of the steel plate.

Parameters	value	Parameters	value
Conductivity (s/m)	7×10^6	Initial magnetic susceptibility	200
Relative magnetic permeability	500	Poisson's ratio	0.45
Relative dielectric constant	1	Young's modulus (GPa)	60
Saturation magnetostriction	2×10^{-4}	Density (kg/m^3)	7870
Saturation magnetization (A/m)	1.5×10^6	Number of elements	411319

3. RESULTS AND DISCUSSION

Simulation results included the ultrasonic voltage signal (Fig.2) and the pulsed eddy current voltage signal (Fig.3) of the point on the surface layer of the steel plate corresponding to the bottom center point of the spiral coil. The total voltage signal is shown in Fig.4. The longitudinal wave velocity of the steel plate is 5380 m/s, the arrival time of the first reflected echo is 3.72 μs, based on the time-of-flight method.

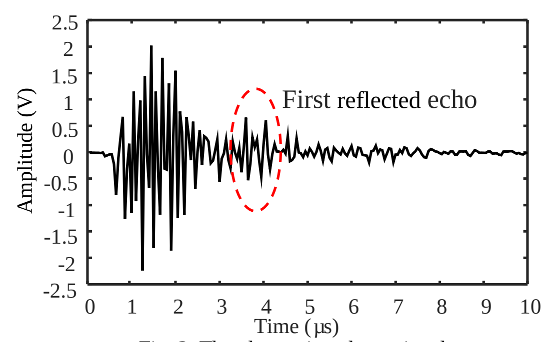

Fig. 2. The ultrasonic voltage signal

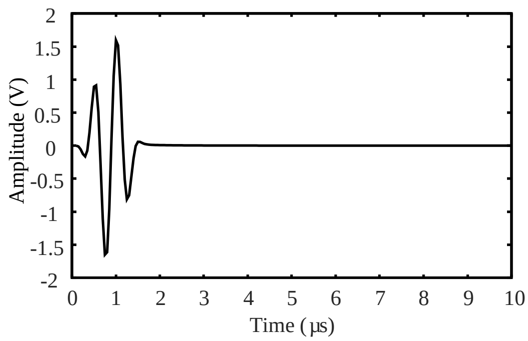

Fig. 3. The pulsed eddy current voltage signal

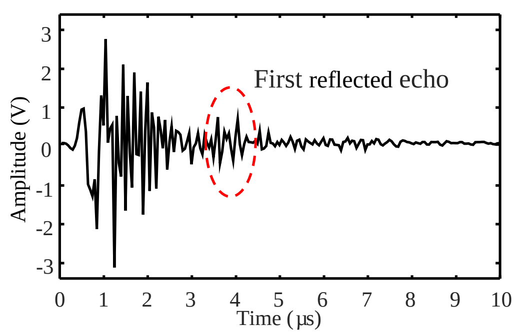

Fig. 4. The total voltage signal

The spectrum analysis results of the simulated voltage signals were obtained by Fourier transform. Fig. 5 shows the spectrum analysis result of the ultrasonic voltage signal, and Fig. 6 shows the spectrum analysis result of the pulsed eddy current voltage signal.

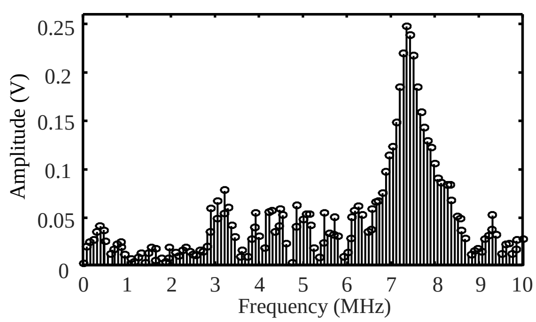

Fig. 5. Spectrum analysis of the ultrasonic voltage signal

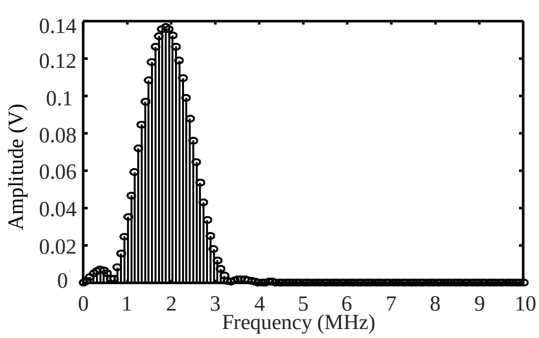

Fig. 6. Spectrum analysis of the pulsed eddy current voltage signal

According to the spectrum analysis results of the simulated voltage signals, the energy of the ultrasonic voltage signal is mainly concentrated in the range of 3-8MHz, the energy of the pulsed eddy current voltage signal is mainly concentrated in the range of 1-3MHz. The total voltage signal will be filtered, and the ultrasonic voltage signal and the pulsed eddy current voltage signal are respectively obtained, thereby extracting the acoustic parameters and the electromagnetic parameters to characterize the performance degradation of ferromagnetic materials.

4. CONCLUSIONS

The 3D finite element simulation modeled the EMAT working under the joint action of the Lorenz and the magnetostrictive forces. The voltage signals were detected by the coil of the EMAT. The voltage signal was consists of two parts, the ultrasonic voltage signal and the pulsed eddy current voltage signal. The spectrum analysis results were obtained by Fourier transform. The spectrum of the ultrasonic signal and the pulsed eddy current signal were in different frequency ranges. Therefore, the total voltage signal was separated by a filtering method, thereby obtaining the ultrasonic voltage signal and the pulsed eddy current voltage signal.

The compound magneto-acoustic compounding inspection technique is particularly well suited for the detection of ferromagnetic materials. It has the advantages of both electromagnetic ultrasonic testing and eddy current testing. It can rapidly test large areas and give improved sensitivity for near surface testing. Performance degradation of the ferromagnetic materials can be characterized through the multi-parameters of acoustic and electromagnetic, and the sensitivity and robustness of electromagnetic acoustic testing can be improved.

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REFERENCES

[1] Hirao M, Ogi H. Electromagnetic Acoustic Transducers: Noncontacting Ultrasonic Measurements using EMATs [M]. Springer press, 2017.

[2] Moran T J, Panos R M. Electromagnetic generation of electronically steered ultrasonic bulk waves [J]. Journal of Applied Physics, 1976, 47: 2225-2227.

[3] Liu Z, Hu Y, Xie M, et al. Development of omnidirectional A0 mode EMAT employing a concentric permanent magnet pairs with opposite polarity for plate inspection [J]. NDT & E International, 2018, 94:13-21.

[4] Liu Z, Fan J, Hu Y, , et al. Torsional mode magnetostrictive patch transducer array employing a modified planar solenoid array coil for pipe inspection [J]. NDT&E International, 2015, 69:9-15.

[5] Uchimto T, Takagi T, Ichihara T, et al. Evaluation of fatigue cracks by an angle beam EMAT-ET dual probe [J]. NDT&E International, 2015, 72:10-16.

[6] Zhang Q. Technique of complex NDT based on ultrasonic & eddy current testing [D]. China: South China University of Technology, 2010.

[7] Tang H. Research on composite non-destructive detection technology of ECT and EMAT [D]. China: Zhejiang University, 2014.

[8] Urayama R, Uchimoto T, Takagi T. Application of EMAT/EC dual probe to monitoring of wall thinning in high temperature environment[J].International journal of applied electromagnetics and mechanics, 2010,33:1317–1327.

[9] Xie S, Tian M, Xiao P, et al. A hybrid nondestructive testing method of pulsed eddy current testing and electromagnetic acoustic transducer techniques for simultaneous surface and volumetric defects inspection [J]. NDT&E International, 2017, (86): 153–163.