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An approach to reduce lift-off noise in pulsed eddy current nondestructive technology

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ABSTRACT

The pulsed eddy current (PEC) technique, as an emerging technique of the eddy current technique, has been used in engineering, such as aircrafts, oil/gas pipelines, nuclear steam pipes and high-speed rails, due to its richer information in time domain and frequency domain. However, the lift-off noise, introduced by varying coating thicknesses, irregular sample surface or movement of transducers, has a serious influence on the accuracy of the detection for the defects in these key structures. It greatly limits the application of PEC in quantitative nondestructive testing. In order to reduce the effect of the lift-off, the lift-off effect is analyzed theoretically and experimentally; based on the investigation of the relationship between the peak value of the difference signal and the lift-off, an approach to reduce the lift-off noise for detection the defect depth or width is proposed. In this approach, the defect depth and width are determined by the slope of the linear curve of the peak value of the difference signal and the lift-off. The proposed approach is verified by experiment and the results indicate that it can highly reduce the lift-off noise in the PEC technique. Therefore, it can be applied in characterization of the surface defects in sample with non-ferrous material.

1. Introduction

Eddy current nondestructive testing (NDT) techniques are widely used in monitoring the safety of the critical components in diverse industries due to its advantages, such as nondestructive testing, high sensitivity and robustness. The pulsed eddy current (PEC) technique, using pulsed excitation, generates responses over a wide range of frequencies, containing more information than traditional eddy current inspection in the frequency domain. The PEC technique has found applications in metal thickness measurement [1], defect detection in multi-layered structures [2–4], stress measurement [5] and corrosion detection [6,7], and so on. However, the PEC technique also has been hampered by some notorious problems, lift-off noise is one of them. The lift-off noise can be caused by varying coating thicknesses, irregular sample surface or movement of transducers.

Lift-off noise problem has been attracting the attention of many scholars [8]. Giguere et al. [9,10] exploit unique signal characteristics of the pick-up coil for overcoming problems with lift-off and interlayer gap variations. However, these features are not obtainable when Hall devices are used. As is well known that the magnetic sensor (e.g. hall sensor, GMR) can greatly improve the sensitivity of PEC [11]. In Tian′s study, a reference signal denoting the magnetic field of the coil in air is added in the traditional PEC system. This approach can efficiently reduce the lift-off noise in surface defect detection [12]. However, the improvement of the reducing lift-off noise is not described quantitatively and the feasibility of this approach in detecting the width of defects is not mentioned in this paper. Also, the lift-off intersection (LOI) was investigated by C. Mandache and J.H.V. Lefebvre [13], this finding can be used to eliminate the lift-off noise. To understand and reduce the lift-off noise, Giguere and Dubois conducted intensive investigations of lift-off and proposed the lift-off point of Intersection (LOI), representing a lift-off independent point in time-domain PEC signal to eliminate lift-off noises in multi-layer structures [11,14]. Lefebvre and Mandache investigated the characteristics of lift-off via theory and experiment [15] and proposed the use of the LOI slope to accurately measure the thickness of a non-conductive layer on a conductive substrate [16]. Generally, LOI depends on many factors, such as the coil structures, excitation frequency and detection condition, so it is difficult to be determined in engineering. As an extension to LOI, lift-off range (LOR) is improved in [17] and it is used to determine the sample conductivity.

In this paper, an approach has been presented to reduce the lift-off noise in detecting the depth and width of the defect by PEC, and the detection error due to the lift-off change in range from

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0.0 mm to 2.0 mm is smaller than 6% by comparison with the traditional method in PEC. The rest of the paper is arranged as following: the lift-off effect is analyzed via the theoretical and experimental methods in Section 2; in Section 3, the distribution of the peak value of the difference signal and the lift-off are investigated, in which the depth of the defect is taken into account; because the lift-off has little influence on the slope of the line relating the peak value of difference signal and lift-off when the depth of defect is fixed, an approach to reduce the lift-off noise is proposed for PEC nondestructive technique. In this approach, the depth of defect is determined by the slope of the relationship line of peak value of difference signal and lift-off; then, the diagram of the proposed approach is illustrated; finally, the results of the proposed approach are discussed; in Section 4, some discussions and conclusions are put forward.

2. Lift-off effect analysis by the theoretical and experimental methods

2.1. Lift-off effect analysis by the theoretical method

In a standard pulsed eddy current testing system, a coil carrying square wave current is placed in proximity to the test specimen (which must be electrically conductive). The alternating current/voltage in the coil generates changing magnetic field H_1, it interacts with test specimen and generates eddy current. The eddy current in specimen will adversely generate another magnetic field H_2. Variations in the electrical conductivity or magnetic permeability of the test specimen, or the presence of any flaws, will cause a change of eddy current in specimen; Variation in lift-off will cause change of the magnetic coupling coefficient between the magnetic field H_1 and the magnetic field H_2. The change of the eddy current in specimen and a corresponding change in the change of the magnetic coupling coefficient between the magnetic field H_1 and the magnetic field H_2 will directly cause the change of the resultant magnetic field of the magnetic field H_1 and the magnetic field H_2, which can be detected by the pick-up coil, excitation coil or the magnetic sensor (e.g. Hall sensor, GMR). Therefore, the PEC system can reflect the discontinuities (change of the magnetic permeability and electrical conductivity) in specimen and it is widely used in the discontinuities evaluation of the conductive specimens.

However, as mentioned before, the change of the lift-off can also cause the change of the resultant magnetic field; it affects the evaluation to discontinuities in specimen. Because the step excitation signal in PEC can be deemed as the resultant of a series of the odd harmonics components, the influence of the lift-off on the resultant magnetic field can be explained by the equivalent circuit of eddy current testing system excitation by a harmonic with the frequency f. The equivalent circuit is shown in Fig. 1 [18,19].

Where R_1, L_1 is the DC resistance and inductance of the transducer coil, respectively; R_2, L_2 is the resistance and inductance of the eddy current loop in the measured, respectively; U_{sr} is the excitation voltage, M is the mutual inductance between the coil and the specimen. Based on the Kirchhoff's voltage laws, we will obtain

$$\begin{cases} I_1R_1+I_1j2\pi fL_1-I_2j2\pi fM=U \\ -I_1j2\pi fM+I_2R_2+I_2j2\pi fL_2=0 \end{cases} \tag{1}$$

where, f is the excitation frequency of coil. Via Eq. (1), we will get

$$\begin{cases} I_1=\frac{U}{R_1+((2\pi f)^2M^2/(R_2{}^2+(2\pi fL_2)^2)R_2)+j[2\pi fL_1-((2\pi f)^2M^2/R_2{}^2+(2\pi fL_2)^2)2\pi fL_2]} \\ I_2=j2\pi f(MI_1/(R_2+j2\pi fL_2))=(M(2\pi f)^2L_2I_1+j2\pi fMR_2I_1/(R_2{}^2+(2\pi fL_2)^2)) \end{cases} \tag{2}$$

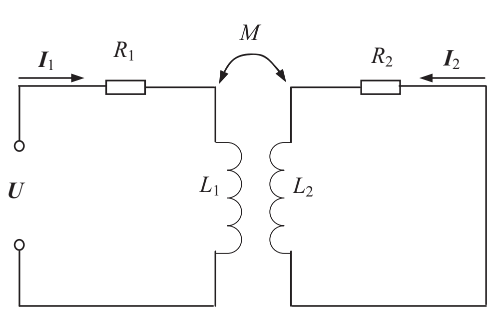

Fig. 1. The equivalent circuit of eddy current testing system.

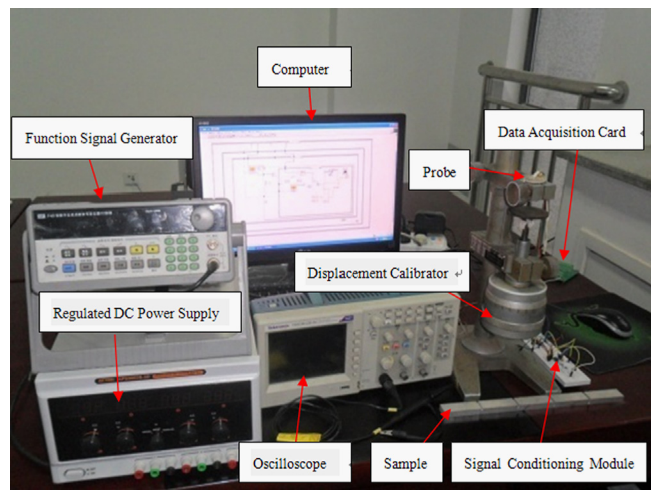

Fig. 2. The PEC experiment testing system.

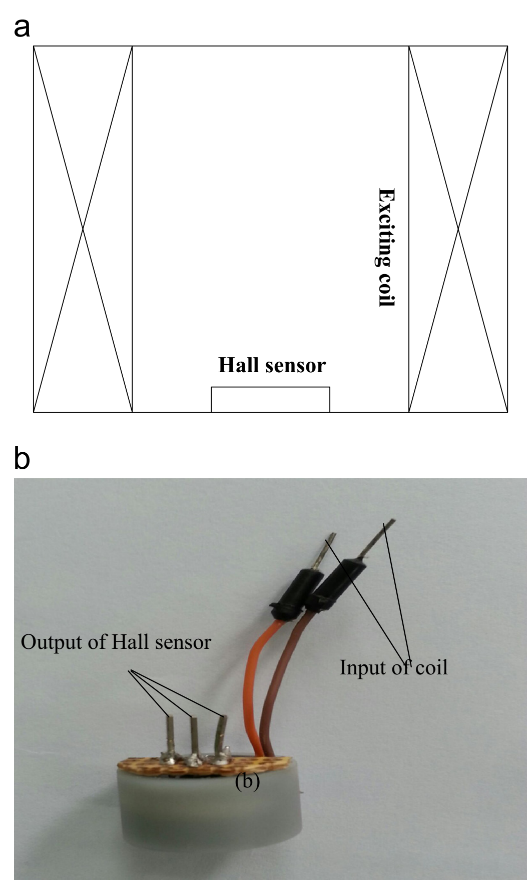

Fig. 3. (a) Probe's structure and (b) probe used in experiment.