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Sensor-tilt invariance analysis for eddy current signals

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ABSTRACT

In the application of electromagnetic nondestructive evaluation (NDE), the measured signals received by sensors are decided by the flaw associated with operational parameters during inspection. The techniques of invariant pattern recognition have been studied to render NDE signals insensitive to operational variations and preserve or recover crack information. The invariant scheme and algorithms have been addressed to facilitate magnetostatic flux leakage and eddy current NDE, which eliminated operational parameters and lift-off changes corrupt from signal measurements. A novel invariance analysis of eddy current (EC) signals in the inspection of deeply embedded cracks under layered fastener heads has been presented in this paper. A detection system based on uniform EC excitation and giant-magnetoresistive (GMR) pick-up sensors has been developed and shown improved detectability of 2nd and 3rd layer defects around fastener sites in multilayer structures. However, the sensor-tilt due to variation of probe lift-off can generate redundant response as noise effect and obscure the flaw inspection. The variations of GMR sensor-tilt with crack inspection are investigated using an efficient numerical model that simulates the used EC-GMR system. The scheme of invariance transformation is proposed to exclude the sensor-tilt noise and keep the defect inspection identical. The statistical features insensitive to tilt effects are extracted after the invariance processing, which has ensured the probability of flaw detection.

1. Introduction

Eddy current (EC) techniques are utilized extensively in the inspection of cracks and discontinuities associated with conducting parts and structures [1,2]. With the development of magnetoresistive sensing and the introduction to electromagnetic nondestructive evaluation (NDE), low frequency EC excitation in combination with magnetic sensor has found increasing applications in detecting sub-surface defects, particularly hidden cracks underneath layered aircraft structures [3–13]. The giant magnetoresistive (GMR) sensors and Hall sensors have been extensively studied in the field of EC NDE [7–13]. The magnetic sensors pick up the field magnitude directly instead of the ratio of field difference and produce the voltage output proportionally, which bring promising for the low frequency EC testing. Among the family of magnetoresistive sensors, GMR sensors have been overwhelmingly utilized because they offer high sensitivity over a wide range of frequencies ranging from DC to megahertz (MHz) and low signal–noise ratio prominently [8–13]. Previous work has presented the feasibilities of the low EC and transient pulsed EC detection using GMR sensors [11–13]. The electromagnetic GMR inspection system has been developed to detect embedded cracks under fastener heads (CUFs) in multilayer aircrafts. The GMR sensors are employed to measure the normal component of magnetic flux density associated with induced eddy currents in the structure under test. The measured GMR signals are exclusively defined by the cracks or discontinuous conditions of testing sample, which have successfully enhanced the detection of deeply buried flaws and small size cracks less than 1 mm [11–13].

In the designed inspection system, a multi-line EC coil is excited as the source to generate uniform fields along the samples. The asymmetry observed in the GMR measurements is typically adopted to distinguish crack and no crack conditions [11–13]. However, irregularities due to the poor drilling around fastener hole sites and variations in the experimental operation, the probe and sensor-tilt diversion particularly are able to produce asymmetric signals, because they disturb induced current patterns same as the crack behavior [17]. The invariant feature analysis using signal processing techniques and invariance transformations have been reported to remove the asymmetry noise and probe lift-off effects which hinder crack identifications and ascend false calls [14–17]. Since the GMR sensor is placed at the center of multi-line EC probe, the lift-off changes might yield tilt sensor. This paper presents the invariance

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analysis of GMR sensor-tilt for EC signals in hidden CUFs detection. A novel application of statistical method is investigated to conduct the invariance transformation of measured GMR signals under sensor-tilt variations, and maintain the measurements insensitive to tilt perturbation. In addition, the statistical features invariant to sensor-tilt are studied for detection classifications regarding different crack cases. The presented scheme has no requirement of signal trainings that are time-consuming and used by radial basis functions and neural network in [15,16].

An efficient finite element (FE) model without re-meshing the source coil is implemented to study the sensor-tilt scenario during scanning detection of CUFs structures, which results in the significant computational savings. The designed EC–GMR inspection system is introduced in Section 2. Simulation model based sensor-tilt study along with GMR detected results, are presented in Section 3. The sensor-tilt invariance analysis and invariance feature based crack detection are discussed in Sections 4 and 5. Conclusions are summarized in Section 6.

2. EC–GMR inspection

2.1. Inspection system

An EC–GMR sensing system using the uniform field coil and sensor receiver has been developed and shown effectiveness in detecting sub-surface cracks around multilayer riveted structures [11–13]. The system configuration is shown in Fig. 1, which uses a high-resolution *X*–*Y* scanner to control the probe motion and data acquisition at each scan position. A planar probe, with linear and multi-line currents and GMR sensor posed on the line of symmetry produces the measurements of line scan (B-scan) and two-dimensional scan (C-scan) around each fastener. The detection principle is sketched qualitatively in Fig. 2. The uniform distribution of the induced currents and zero magnetic field along the normal direction are observed, when the EC probe scans a plate area without any disturbances. In the presence of fasteners and/or cracks, a non-zero normal magnetic field (B_z) is produced and picked up by the GMR sensor at the center of the source coil. The existence of crack at a fastener hole site distorts the induced eddy currents and yields asymmetric information. These characteristics of GMR measurements are utilized to evaluate the presence of cracks.

2.2. GMR measurement

The GMR sensor is sensitive to the normal component of magnetic flux density B_z, associated with the induced eddy currents in the sample. The C-scan image of B_z magnitude has been employed as the assessment of local magnetic flux density interacting with the structural condition. A simple method that

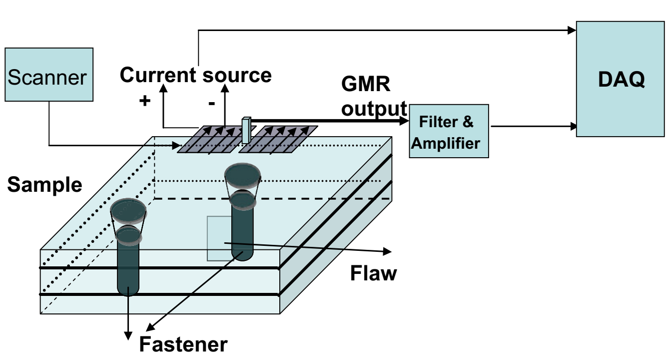

Fig. 1. Schematic of the EC–GMR inspection system.

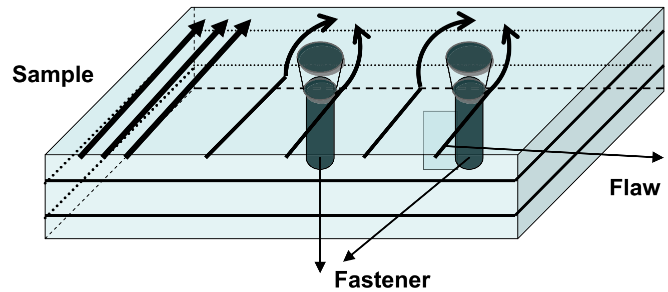

Fig. 2. Illustration of the induced eddy currents associated with geometry conditions.

examines the degree of asymmetry in the shape of each flux density image and signal peak values as well has been studied to decide a faster as the defective one or not [11–13,18].

However, the non-flat placement of the used planar probe causes lift-off variation and tilt sensor due to practical operations. This tilt effect is different from the general lift-off changes of the distance between the coil probe and test piece, as shown in Fig. 3(a) [17]. In the designed inspection system, the EC–GMR probe is fastened at the automatic scanner and distance variation between the probe and sample during scanning is not able to occur. The presence of sensor-tilt scenario keeps constant lift-off but alters the conventional GMR measurement in Eqs. (1) and (2). With the sensor-tilt effect, the GMR sensor measures the combination of flux density along normal and tangential both directions, illustrated in Fig. 3(b). The induced eddy currents associated with the magnetic field through the sample are no longer uniform distributions. Consequently, the asymmetry phenomenon occurs under sensor-tilt situation even when no crack is present.

$$B_{\mathrm{GMR}} = B_Z \tag{1}$$

$$B_{\mathrm{GMR}} = B_Z \times \cos(\theta) - B_X \times \sin(\theta) \tag{2}$$

3. Model based sensor-tilt study

A systematic study of the effect of GMR sensor-tilt concerning crack recognitions is performed using a fast numerical model. The previous work [13] has validated the application of an infinite current foil to simulate the multi-line excitation field. Without meshing the source coil and no need for modeling the scanning operation, it has reduced the computational time significantly. Whereas, the investigation of sensor-tilt effects needs to simulate the finite source coil that scans at each detection position along with the GMR sensor.

3.1. Efficient numerical model

A FE model using the reduced magnetic vector potential $\mathbf{A}_r$ and the electric scalar potential V (also named $\mathbf{A}_r - V - \mathbf{A}_r$) formulation has been developed for simulating the EC–GMR inspection of multilayer geometries [19,20]. The advantage of this formulation is that it models the multi-line coil motion along the sample without re-meshing the source coil. The mesh and system matrix remain unaltered at different coil positions. The execution of the system matrix pre-conditioner is executed only once during the simulation of a complete scan.

The proposed model introduces the reduced magnetic vector potential by decomposing the magnetic flux density B into two parts:

$$B = B_s + B_r = \mu_0 H_s + B_r \tag{3}$$