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A Novel Self-Compensating GMR-Based Eddy Current Probe for Hidden Crack Detection

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Abstract:

This paper is concerned with a novel self-compensating Giant Magneto-Resistance (GMR) based eddy current probe for hidden cracks inspection. Instead of a pickup coil commonly used, a GMR sensor is employed in the probe to work as the sensing element to detect magnetic field. In order to obtain the compensating signal, the system identification techniques are used to establish a transfer function model, which quantitatively describes the relationship between the excitation and response of the GMR-based probe. Subsequently the compensating signal is predicted by the developed transfer function model and reproduced by physical circuits via phase shifter and amplitude regulator. Inspection experiments on simulated hidden cracks in thick conductive specimen were carried out. The experimental results show that the newly developed self-compensating GMR-based probe has larger dynamic range as well as higher sensitivity and resolution. The presented new probe is promising for the in-service inspections in many fields such as aircrafts and pipelines evaluation using eddy current testing.

Keywords: Eddy Current Testing, Self-Compensation, GMR-Based Probe, System Identification, Hidden Crack Detection

1. Introduction

Aging aircraft poses many challenges to safety, readiness and maintenance. Detection and quantification of hidden cracks are essential for extending life of the aircraft. However, at present, one of the more challenging problems is to inspect the cracks hidden in interlayer or thick conductive structures. To detect deeply buried flaws, a low frequency excitation should be provided to increase the penetration depth. For traditional eddy current testing (ECT) based on driver-pickup coils, however, the sensitivity of the pickup coil is reduced proportionally with decreasing working frequency. The GMR-based probe, which employs GMR sensor as magnetic pickup, is considered as one of the promising measures to address this problem [1], because it has far higher sensitivity at low frequencies and resolution than conventional coil-based probe.

Other measures should also be taken to eliminate the effect of thick object under test on the output of ECT probe [2][3]. Compared to the signals due to hidden cracks, the signal change caused by thickness of the tested object is much larger, which occupies much of the dynamic range of ECT probe, thus reduces detectability of eddy current instrument for cracks.

To make ECT more quantitative to evaluate hidden cracks, a novel sell-compensating GMR-based probe is devised. Unlike common differential probes needing two or more sensors, the phase and amplitude of excitation signal are varied to make it identical to the output of GMR sensor, and processed excitation signal is used as the compensating signal. To work out the phase and amplitude change of excitation signal, the relationship between the excitation and response of GMR-based probe is seen as a linear system, and the system identification techniques are utilized to obtain the transfer function of GMR-based probe on a specimen free of cracks, which discloses its dynamic behaviors.

The rest of the paper is organized as follows: Section 2 describes system identification techniques. In section 3, the self-nulling probe is presented, including its design and operating principle. In section 4, the experiments on simulated hidden cracks in thick conductive specimen were made to demonstrate the performance of the self-compensating GMR-based probe proposed in this work. The last section concludes this work.

2. System Identification and Least-Squares Method

Typically in ECT, there is a probe placed above the conductive specimen in Fig.1 (a), and the object under test is coupled to the pickup coil by the excitation magnetic field, which is very similar to the operation of a transformer [4]. Therefore, a loaded transformer can be used to model probe-to-specimen coupling. The excitation coil acts like the primary winding, while the specimen with induced eddy current is modeled by a secondary winding. All the distributed capacitances are neglected. As a result, an equivalent circuit Fig.1 (b) is derived. Further, a more concise circuit is illustrated in Fig.1 (c).

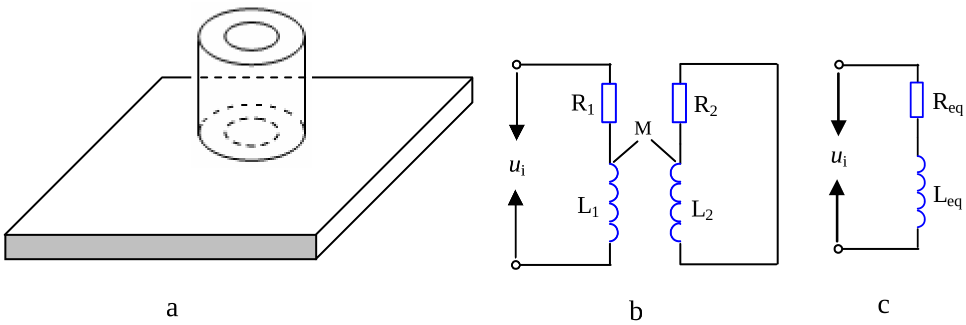


Fig.1. Probe-specimen setup and its equivalent circuit

The relationship between the excitation and response of GMR-based probe can be regarded as a linear system [5]. The proposed transformer model is intended to get the order of the system. The applied AC voltage source and the GMR sensor response are defined as the input and output of the system respectively. According to the Biot-Savart Law, the probe-specimen setup in Fig.1 can be considered as a first-order linear system and its transfer function is expressed as.

$$G(s) = \frac{K}{Ts+1} \tag{1}$$

Where coefficients K and T are the gain and time constant of the transfer function respectively. Once they are determined, both the amplitude and phase response are given by

$$A(\omega) = 20\log K - 10\log(T^2\omega^2 + 1) \quad (2)$$

$$\varphi(\omega) = -\arctan(T\omega) \quad (3)$$

Where $A(\omega)$ and $\varphi(\omega)$ denote the frequency and phase response respectively. ω is angular frequency. Once the transfer function of a linear system is established, its dynamic characteristics can be simulated and its output could also be predicted with a specified input.

From Eq. (1), the following difference equation is derived with sampling period T_s.

$$u_o(k) = a_1 u_o(k-1) + a_2 u_i(k) \quad (4)$$

Where, $u_o(k)$ and $u_o(k-1)$ are the *k*th and and (*k*-1)th output of the system respectively, $u_i(k)$ is the *k*th input of the system, $a_1 = \frac{T}{T+T_s}$, and $a_2 = \frac{KT_s}{T+T_s}$.

The least-squares technique provides us with a mathematical procedure, by which a best fit to experimental data can be achieved in the sense of minimum-error-squares. Estimates obtained by the least-squares method also have optimal statistical properties: they are consistent, unbiased and efficient.

Provided that a sequence of m (m >>2) observations on both u_o and u_i has been acquired, and Eq. (4) utilized to relate these data is written as

$$\boldsymbol{u}_o = \boldsymbol{x\theta} \quad (5)$$

Where,

$$\boldsymbol{u}_o = \begin{bmatrix} u_o(2) \\ u_o(3) \\ \cdots \\ u_o(m) \end{bmatrix}, \boldsymbol{x} = \begin{bmatrix} u_o(1) & u_i(2) \\ u_o(2) & u_i(3) \\ \cdots & \cdots \\ u_o(m-1) & u_i(m) \end{bmatrix}, \boldsymbol{\theta} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

Define $\boldsymbol{u}_o - \boldsymbol{x\theta}$ as an error vector $\boldsymbol{\varepsilon}$, and *J* is written as

$$J = \boldsymbol{\varepsilon}^T \boldsymbol{\varepsilon} = (\boldsymbol{u}_o - \boldsymbol{x\theta})^T (\boldsymbol{u}_o - \boldsymbol{x\theta}) \quad (6)$$

Differentiate *J* with respect to $\boldsymbol{\theta}$ and equate the result to zero. Thus

$$\hat{\boldsymbol{\theta}} = (\boldsymbol{x}^T \boldsymbol{x})^{-1} \boldsymbol{x}^T \boldsymbol{u}_o \quad (7)$$

From Eq. (7), parameters T and K can be worked out. Further, the amplitude- and phase-frequency expressions are also easy to obtain based on Eq. (2) and (3).

3. Design and Operation Principle of Self-Compensating GMR-Based Probe

Self-compensating GMR-based probe mainly consists of three parts, a GMR-based probe, system identification setup and compensating signal generation setup, schematic diagram of which is shown in Fig.2. The procedures are described as follows that GMR-based probe completes its output nulling operation.

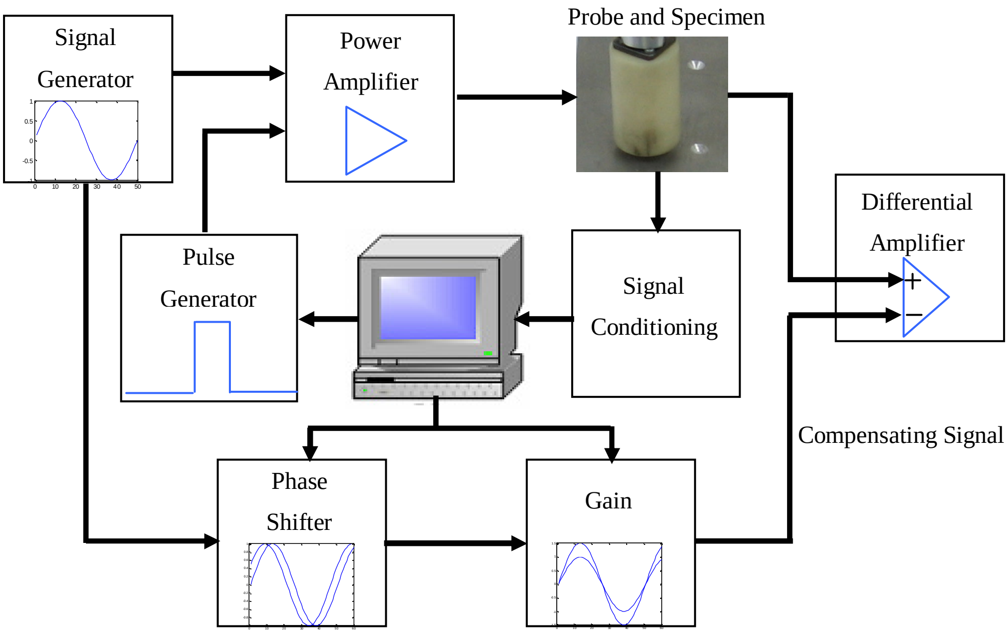


Fig.2 Schematic diagram of self-compensating GMR-based probe

1) The relationship between the excitation and response of GMR-based probe placed above a metal sample free of cracks is regarded as a linear system, and the system identification techniques used to obtain its transfer function. Firstly, the pulse generator and built-in high speed A/D, digitally controlled by PC, start to operate synchronously. The width of generated pulse is large enough to make the GMR-based probe go to steady. Subsequently, the collected data is filtered to improve SNR and the least-squares method is used to estimate the coefficients of the transfer function of the GMR-based probe, which reveals its dynamic characteristics.

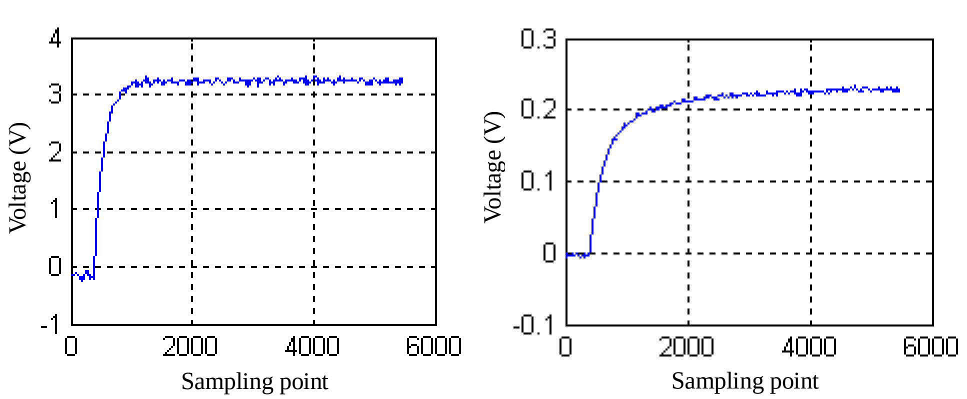
2) After the transfer function of the GMR-based probe has been identified, the amplitude and phase of the output of the GMR sensor are easily solved from Eq. (2)-(3) for the given excitation sinusoidal signal. Consequently, both the ratio of the amplitude of the GMR sensor to that of excitation signal and the phase difference between them can be easily figured out. According to them, the parameters of phase shifter and gain should be varied in order to make the processed excitation signal identical to output of the GMR sensor.

3) The excitation sinusoidal signal is generated by the signal generator with selected frequency. It is used to energize the excitation coil through the power amplifier. The magnetic field generated by the eddy current and the excitation coil is detected by the GMR sensor, the output of which is supplied to the non-inverting terminal of the differential amplifier. Meanwhile, the driving signal is conditioned by phase shifter and gain to become identical to the output of GMR sensor, and then is supplied to the inverting terminal of the differential amplifier. The output of the differential amplifier works as the output of the GMR-based probe on the tested specimen.

Therefore, if there is no crack inside the test piece, the GMR-based probe is in equilibrium. Its output can only be influenced due to the anomalies of the tested material such as cracks and corrosions, while removing noises and other unwanted signals such as fluxes generated by the excitation coil and eddy current induced in the tested sample without cracks.

4. Experimental Setup and Results

A set of experiments were executed in order to confirm the feasibility of applying system identification techniques to prediction of the compensating signal. Two aluminum samples, free of cracks, the thicknesses of which are 2mm and 5mm respectively, were manufactured. The excitation frequencies 0.5 kHz and 1 kHz were selected. Typical results of time-domain measurement, showing step driving voltage and GMR sensor response, are depicted in Fig3.



(a) excitation of GMR-based probe (b) response of GMR-based probe

Fig.3 Excitation and response of GMR-based probe on 2mm specimen

Tab.1 compares the predicted with experimental results. From Tab.1, it can be found that predicted results agree well with those of experiments, which demonstrates that the compensating technique used in this work is feasible. In addition, it can also be found that the output of GMR sensor including amplitude and phase varies significantly with working frequency, while it varies much smaller with specimen thickness.

Tab.1 Comparison between experimental and predicted results using transfer function of GMR-based probe

Frequency (kHz)	0.5		1	
Specimen Thickness(mm)	2	5	2	5
Excitation Peak Voltage(V)	2.70	2.70	2.70	2.70
Measurement Voltage(mV)	117.8	88.2	44.6	35.3
Measurement Phase difference(◦)	43.6	48.1	64.8	68.4
Predicted Voltage(mV)	119.1	89.4	46.2	34.6
Predicted Phase difference(◦)	42.9	46.8	62.7	65.0

To evaluate the proposed self-compensating GMR-based probe, two aluminum samples (240 ×150×5 mm^3) were prepared. One has no cracks used for the identification of the transfer function of GMR-based probe, and the other has slots with different depths to simulate subsurface

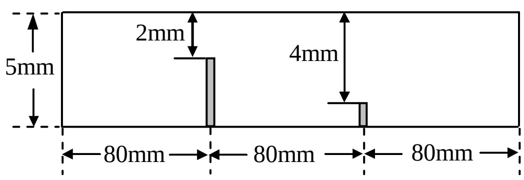
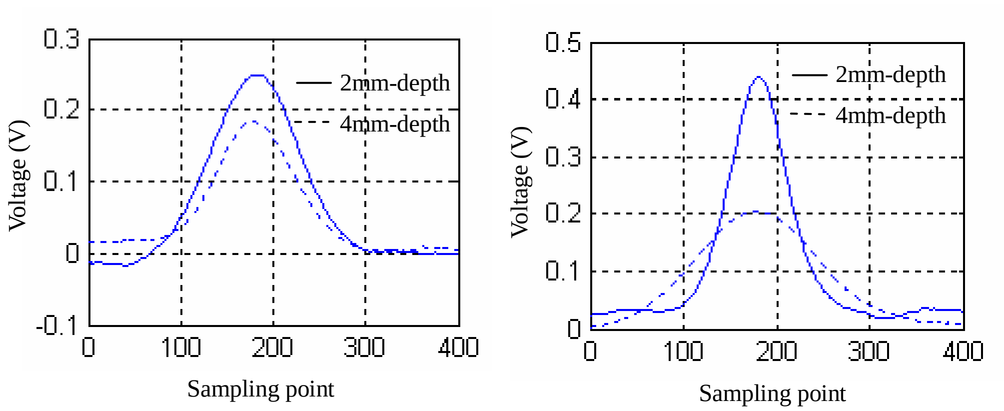


Fig.4 View of test sample and subsurface slots

discontinuities as depicted in Fig.4.

Fig.5 shows the inspection signals of 2mm-depth and 4mm-depth hidden cracks respectively, depicted in Fig.4, using excitation frequency 1k and 500Hz. In case of absolute GMR-based probe, the signals caused by buried cracks in tested sample were masked by noises, because of very small signal changes and lower gain of experimental system, thus it makes far more difficult to design conditioning circuit, and sometimes even could not separate the useful signal from the noises; while using self-nulling GMR-based probe proposed in this paper, the experimental results of hidden cracks has much higher SNR, and it is relatively much easier to detect them. Therefore, it is obvious that the newly devised probe has much larger dynamic range and is more sensitive to



(a) working frequency *f*=0.5kHz (b) working frequency *f*=1.0kHz

Fig.5 Signals for subsurface slots: 2mm-depth and 4mm-depth.

deep cracks in conductive materials.

5. Conclusion

In eddy current testing, improving the probe performance plays a critical role in detecting hidden cracks in metallic structures. To extend the application of ECT technique, this work designs a novel self-compensating GMR-based probe. The relationship between the excitation and response of GMR-based probe is seen as a linear system, thus it can be described by a transfer function, which reveals the dynamic characteristics of GMR-based probe on tested object free of cracks. Subsequently, the system identification techniques are employed to estimate the parameters of the transfer function. Then the determined transfer function combined with known excitation is used to predict the output of GMR sensor, according to which the compensating signal can be obtained by varying the phase and amplitude of the excitation signal. Experiments on hidden cracks confirm that using the developed GMR-based probe improves detectability of the experimental setup for the hidden crack. Future research will focus on the quantification of deeper cracks in thick and multi-layered conductive structures using sell-compensating GMR-based probe put forward in this research.

Acknowledgments

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