APPLICATION OF A GIANT MAGNETORESISTIVE (GMR) SENSOR FOR CHARACTERIZATION OF CORROSION IN A LABORATORY SPECIMEN

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ABSTRACT. This paper describes the use of a Giant Magnetoresistive (GMR) sensor to detect thickness variation in a multi-layered specimen. A series of frequency-response and modes-of-operation tests has been carried out to characterize a GMR sensor. Both the first and second harmonics of the GMR signal for corrosion detection were collected and analyzed. The experimental data showed that phase approach seemed to have better thickness discrimination over that of the magnitude approach.

INTRODUCTION

Results from a previous automated corrosion-detection program (ACDP) have demonstrated that some NDI technologies can be used to detect hidden corrosion in the first layer of aging aircraft fuselage skins [1]. In detecting corrosion deeper than the top layer in a multi-layered aluminum structure, both conventional ultrasonic and eddy current methods have limitations. In the case of ultrasonic testing, the presence of a gap between layers in a multi-layered structure becomes a strong reflector of sound waves, and this gap makes the detection in the subsequent layer difficult. In eddy current testing, low frequency is often required to induce currents in thick and highly conductive materials like aluminum alloys. However, use of lower frequencies often means low sensitivity and low resolution.

The giant magnetoresistive (GMR) effect was first reported in 1988 because of the huge resistance changes that were observed when thin layers of magnetic materials were subjected to magnetic fields [2]. This discovery has changed the capability in the head that reads the bits from a storage disk and thus substantially increased the storage of computer hard drives over ten gigabytes. In the late 1990s, a few NDE demonstrations focusing on crack detection started to appear [3-5]. The application of the GMR on corrosion detection, however, was sporadic. The objective of this work is twofold: (1) to conduct experiments to characterize a GMR sensor and (2) to find suitable metrics for monitoring the hidden corrosion.
FIGURE 1. A schematic view of an experimental setup for characterizing the frequency response of a GMR sensor. Note that bias was not used for the 2nd harmonic measurement.

EXPERIMENTAL SETUP FOR GMR SENSOR CHARACTERIZATION

The frequency response of a GMR sensor was measured with five coils generating magnetic fields of various frequencies. These homemade bobbin coils were wound around plastic forms. A capacitor was put in series with a coil to provide a resonance at a certain frequency. For example, the coil made with the lowest resonant frequency was 400 Hz with a 3dB bandwidth of 1 kHz. The dimensions of this bobbin coil were 7 mm high, 10 mm ID, and 21 mm OD. It was made of 1000 turns of AWG 34 copper wire. The capacitor was measured at 22 microfarads.

In this experiment, the coil was connected to a function generator that sent a sinusoidal frequency corresponding to the resonant frequency of the coil, as shown in Figure 1. The GMR sensor was connected to a DC power supply. An oscilloscope was used for the measurement of the amplitude of the received signal directly from the GMR sensor. For the 2nd harmonic mode measurement, the GMR sensor was not biased with an external magnetic field. For the 1st harmonic measurement, a small magnet was applied to shift the operating point of the GMR sensor.

RESULTS OF GMR SENSOR CHARACTERIZATION

Figure 2 shows received GMR signals from both the 1st and 2nd harmonic modes. They were taken from two separate tests. The 1st harmonic signal was taken with a small magnet moving toward the GMR sensor, and the signal was acquired when the amplitude was maximized. The 2nd harmonic signal was acquired without any external bias. The 1st harmonic signal had the same period as that from the excitation coil (not shown), and the 2nd harmonic signal had a rectified form as compared to that from the excitation coil. This was because the GMR sensor was not discriminating in the direction of the magnetic field. The minor un-balance in the 2nd harmonic signal might be due to the magnetic hysteresis in the sensor. It can be seen that the amplitude of the maximized 1st harmonic signal was about twice that of the 2nd harmonic mode and the period was doubled. The background level was also plotted for comparison.

By taking a Fourier transform of the above waveforms, the frequency spectra are shown in Figure 3. It is noticed that signals of both the 1st and 2nd harmonic modes were
at least 30 dB higher than the background noise, and the noise levels were of the same order for both modes. The peak amplitude of the 1st harmonic mode was 6 dB higher than that of the 2nd harmonic mode. It was also noticed that in the un-biased case, the 1st harmonic mode was also observed along with the 2nd harmonic mode, but the 1st harmonic was 16 dB lower. This extra 1st harmonic mode signal in the un-biased case was also found in the time domain signal.

By repeating the experiment with coils of different sizes and measuring the outputs at the resonant frequencies from the oscilloscope and normalized with that at 1 MHz, Figure 4 shows the results of frequency response of a GMR sensor in an un-biased case. An exponential curve fit was also added to show the trend. It is noticed that the GMR sensor had flat frequency response from DC to 1 MHz and then the response dropped sharply after 1 MHz.
The two characteristics of this GMR sensor that could be useful in nondestructive testing are bandwidth and low frequency response. The broad bandwidth could have an advantage over the conventional coil for those tests in which more than one frequency is needed. Potential applications of this characteristic are multi-frequency testing and pulsed eddy current testing. The low frequency response characteristic, on the other hand, makes the GMR sensor a good sensor for detecting hidden anomalies under highly conductive materials such as aluminum alloys in which the depth of penetration is often limited. In this paper, an application of a GMR sensor on thickness variation as it occurs in hidden corrosion is discussed in the following.

APPLICATION OF A GMR SENSOR FOR THICKNESS VARIATION MONITORING

For a changing magnetic field involving an infinite half-space [6], the skin effect can be described in two ways: (1) the exponential decay of current density into materials and (2) the linear phase lag with depth. Both of these provide a basis for the application of a GMR sensor for thickness variation monitoring.

The experimental setup for thickness monitoring is shown in Figure 5. It is slightly different from that used in the sensor characterization with three new features: specimen, detecting unit and interface. A multi-layer laboratory specimen was placed between the GMR sensor and the excitation coil. This specimen was made of seven layers of aluminum alloy - each square layer being 76 mm and 0.76 mm in thickness. A series of impedance measurements was started with a maximum thickness, of 5.33 mm, and repeated with a layer removed each time. A lock-in amplifier was used to drive the coil while monitoring the in-phase and quadrature outputs from the GMR sensor. The data acquisition to the PC was made through an IEEE488 interface using a LabWindows / CVI driver. Since the measurement was done with an un-biased GMR sensor, the output mode was thus set to the 2nd harmonic frequency in the lock-in amplifier.
RESULTS OF GMR SENSOR FOR THICKNESS VARIATION MONITORING

All the data of the in-phase component and the quadrature component from the 2\textsuperscript{nd} harmonic output were collected and analyzed. Figure 6 shows these curves in an impedance plane after a rotation of $-106$ degrees around the origin. Each curve represents the output of a certain thickness over the frequency range measured. For comparison, the beginning frequency is marked on each curve with a circular symbol and the ending frequency is marked with a triangular symbol. It is noticed that as the frequency or
thickness increased, the trend spirals down towards the origin of the coordinate in the figure.

Another way to represent the data is by taking the magnitude and phase plot versus the frequency. The magnitude was calculated by taking the square root of the sum of both of the components in square while the phase was the arctangent of the ratio of the quadrature component over the in-phase component. Figures 7 and 8 show these plots respectively. For the magnitude plot, the value decreases as the frequency increases. For thicker materials, the change with frequency becomes less drastic than that of the thinner material. For the phase plot, a phase wrap around phenomena was noticed when the phase value is beyond the range of +/- 180 degrees. Then the phase would add or subtract 360 degrees. Correction of the wrap around could be done either by rotating the impedance plane or changing the reference phase value in the lock-in amplifier. In this figure, the phase showed a monotonous trend with thickness over a frequency range of 1300 Hz to 2500 Hz.

FIGURE 7. Magnitude output from a multi-layered laboratory specimen at various frequencies.

FIGURE 8. Phase output from a multi-layered laboratory specimen at various frequencies.
FIGURE 9. Variation of magnitude from a multi-layered laboratory specimen with thickness at three representative frequencies.

FIGURE 10. Variation of phase from a multi-layered laboratory specimen with thickness at three representative frequencies.

To better represent the data, Figures 9 and 10 show the magnitude and phase values against the thickness for three representative frequencies. The magnitude decreases exponentially as the thickness increases. As the thickness becomes large, the amplitude variation for all frequencies becomes small. On the other hand, the phase variation among frequencies increases as the thickness increases. In addition, this phase change also bears a linear relationship with the thickness. This indicated that the phase value could be a potential tool for monitoring thickness variation as it occurs in the hidden corrosion case.
CONCLUSION

In characterizing a GMR sensor, experimental results showed that the GMR sensor had a flat frequency response from DC to 1 MHz that could be useful for detecting hidden anomalies in highly conductive materials. As an application of this GMR sensor to find metrics for hidden corrosion detection, both the magnitude and phase approaches were investigated. Additional experimental results on the laboratory specimen showed that the phase approach seemed to be more discriminative than the magnitude approach. Therefore, the phase information could be a potential candidate for monitoring the thickness variation caused by hidden corrosion. Further studies will continue to characterize the resolution of a GMR sensor as well as the evaluation of phase approach in the hidden corrosion detection.

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