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Development of a polymer based fiberoptic magnetostrictive metal detector system

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Abstract

This paper presents a new metal detector using a fiberoptic magnetostriction sensor. The metal sensor uses a fiber-optic Mach-Zehnder interferometer with a newly developed ferromagnetic polymer as the magnetostrictive sensing material. This polymeric magnetostrictive fiberoptic metal sensor is simple to fabricate, small in size, and resistant to RF interference (which is common in typical electromagnetic type metal detectors). Metal detection is based on disruption of the magnetic flux density across the magnetostriction sensor. In this paper, characteristics of the material being sensed and magnetic properties of the ferromagnetic polymers will be discussed.

Keywords

metal detector; fiber-optic sensor; polymeric magnetostrictive material; ferromagnetic polymer; Mach-Zehnder interferometer

I. Introduction

Currently metal detectors operate on three basic technologies: very low frequency (VLF), pulse induction (PI), and beat-frequency oscillation (BFO). VLF systems consist of two coils that are electrically balanced. When metal is in close proximity to the coils, they become unbalanced [1]. PI systems use short powerful bursts (pulses) of current through a coil of wire, instead of steady RF frequency. Each pulse generates a brief magnetic field. When the pulse ends, the magnetic field reverses polarity and collapses very suddenly, resulting in a sharp electrical spike. If the metal detector is over a metal object, the pulse creates a magnetic field in the opposite direction in the metal object. Due to the opposite magnetic field created in the object, the reflected pulse persists longer, thus detecting metal [2]. In a BFO system, there are two coils of wire: one large coil in the search head and a

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smaller coil in the control box. Each coil is connected to an oscillator that generates thousands of current pulses per second. The frequency of these pulses is slightly offset between the two coils. As the pulses travel through the coils, radio waves are generated. A receiver within the control box picks up the radio waves and creates an audible series of tones (beats) based on the difference between the frequencies. If the coil in the search head passes over a metal object, the magnetic field caused by the current flowing through the coil creates a magnetic field around the object. The object's magnetic field interferes with the frequency of the radio waves generated by the search-head coil [3]. As the frequency deviates from the frequency of the coil in the control box, the audible beats change in duration and tone. The detector is able to discriminate between different metals because each metal has a unique phase response when exposed to alternating current.

These different types of sensors appear in everyday life as either a walk-through or hand held device. They are commonplace in airports, libraries, prisons, stores and shops. However these devices share two disadvantages. First, they are relatively bulky and large. Second, they are highly affected by the interference caused by the surrounding electronics. If these devices are used in a hospital or laboratory setting, where space is limited and equipment is prone to electromagnetic interference, these detectors often fail.

In this paper, we present a compact metal detector that overcomes these problems. The metal detector uses a newly developed polymeric fiber-optic Mach-Zehnder magnetostrictive sensor that we have previously reported [4]. The detector utilizes a simple DC magnetic field detection scheme and a Mach-Zehnder fiber optic interferometer for metal detection. The basic concept of the metal detection is based on monitoring strain-induced optical path length change in the interferometer stems from the magnetic field induces magnetostriction effect. The magnetostrictive device can produce polarized magnetic fields that have temporal characteristics, similarly generated from walk-through metal detectors. Advantages of using this fiber-optic magnetostrictive metal detector is that it is far less complex than current metal detectors, it is smaller in size, and it is much easier to fabricate. In addition, this metal detector is not undermined by RF interference. In this paper, the theory, design and preliminary results on the metal detection are presented. The polymer has also been improved from our previous design [4] to increase its field detection.

II. Theory

The basic concept of magnetostrictive metal detectors is based on the magnetostrictive sensor, which was first proposed by Yariv et al [5]. The Mach-Zehnder fiber-optic interferometer is employed to measure the magnetic field-dependent strain in a ferromagnetic material and is shown in our previous experiments [6]. Here the ferromagnetic polymer is coated directly onto the cladding of the sensing arm of the optical interferometer. The intensity of the resulting strain on the magnetostrictive material is measured based on the field induced phase shift in the interferometer given by [5],

$$\Delta\phi = \frac{2\pi nL}{\lambda} \left(\frac{\Delta L}{L} + \frac{\Delta n}{n} \right) = \frac{2\pi nL}{\lambda} \left\{ \varepsilon_3 - \frac{n^2}{2} [(p_{11} + p_{12}) \varepsilon_1 + p_{12} \varepsilon_3] \right\} \quad (1)$$

Where longitudinal strain $L/L = \varepsilon_3$, ε_1 is transverse diagonal strain index of refraction based on the phase retardation of the propagating light in the fiber caused by the strain induced by the B field, using the form of a photoelastic tensor p_{ik} is given as $n = n^3 / 2[(p_{11} + p_{12})\varepsilon_1 + p_{12}\varepsilon_3]$. The fiber is assumed to be an isotropic medium and light is polarizing along the transverse direction. Using data for fused quartz, $p_{11} = 0.12$, $p_{12} = 0.27$, $n = 1.46$ and $\varepsilon_1 = -\varepsilon_3/2$ (assume zero net-volume change) [5], equation (1) will reduce to following equation.

$$\Delta\phi = \frac{2\pi n L}{\lambda} 0.92 \varepsilon_3 \quad (2)$$

where the photoelastic effect due to ε_1 and ε_3 nearly cancel so that the main contribution is due to physical elongation of the fiber $\varepsilon_3 = kH^2$ where k is a constant depends on the ferromagnetic material used. For our case, the ε_3 will be empirically determined due to the fact that the material is our specially formulated ferromagnetic polymer. The general equation for the two output channels of the Mach-Zehnder fiberoptic interferometer (Figure 1) is given as

$$\begin{aligned} I &= I_o \alpha (A + B \cos \Delta\phi) \\ I' &= I_o \alpha (C - B \cos \Delta\phi) \end{aligned} \quad (3)$$

Where $a_t = a_s = a$, $A = k_1 k_2 + (1 - k_1)(1 - k_2)$, $B = 2 \sqrt{k_1 k_2 (1 - k_1)(1 - k_2)}$, $C = k_1(1 - k_2)(1 - k_2)(1 - k_1)K_2$, a_t , a_s are optical loss associate with reference and signal paths assume to equal and k_1 and k_2 are coupling ratios for first and second 2×2 coupler.

III. Experimental

A. Ferromagnetic polymer

The metal sensing arm is coated with a 30 cm long and 1.36 mm thick ferromagnetic polymer (WC-WSJOSH-2) (Figure 2). In this paper, we change the layout and geometry of the sensor from our previous reported design [4]. In this case, the sensing fiber is bent into a snake shape in order to increase the sensing area (Figure 3). The magnetostriction material is also manipulated during fabrication to increase its sensitivity. The MH curve (magnetic moment vs. magnetic field strength) of the ferromagnetic materials were characterized by Vibrating Sample Magnetometer (VSM, LakeShore 7300). A rectangular shape of 2mm×5mm with 1.36mm thick sample was prepared for the test. The magnetic hysteresis loop of two different fabrication samples is shown in Figure 6. A summary of the magnetic properties of the ferromagnetic material are summarized in Table I.

B. Mach-Zehnder fiber-optic interferometer metal detector setup

The experimental setup for the magnetostriction metal detector system is shown in Figure 4. Schematic illustration of the sensor setup is as follows: the light input for the sensor is provided by a pigtail laser diode (Mitsubishi: MF-622DS-T12-241 No. 85263, $\lambda = 1.319\mu\text{m}$). The light introduced from the laser is coupled into one of the two input channels of a single mode 2×2 fiber-optic coupler (HOPECOM: WBSC-X-S-50-1315-9-C-H-100). Between the two 2×2 couplers, one of the output channel from the first 2×2 coupler is connected to a single mode fiber coated with ferromagnetic polymer (WC-WSJOSH-2). Both output

channels from the first 2×2 coupler are then connected to the inputs of the second 2×2 coupler. One of the output channels from the second 2×2 coupler is then connected to a fiber polarizer before connecting to a pigtail photodetector (JDS Uniphase EMP 6XX series). A home-made transformer coil is used as the driving coil to generate the magnetic field for the magnetostriction metal detector sensor, and magnetic field is monitored by a high sensitivity Hall Effect sensor made by Allegro, part number UGN 3503U, capable of detecting magnetic range from 0 to 900 Gauss. The home-made transformer coil calibration setup and calibration result is described in another publication [4]. The output intensity from the detector is converted into electrical signal and analyzed by a Fluke digital scopemeter (Fluke 199C Scopemeter Color, 200MHz 2.5 Gs/s) via USB data output.

C. Magnetostriction effect experiment

The magnetostriction of the sensor was tested using a Mach-Zehnder fiber-optic interferometer where the sensing arm is coated with a polymer based ferromagnetic material (WC-WSJOSH-2). The experiment setup has been described previously [7]. In this experiment, we varied the input AC voltage applied to the autotransformer from 0-17V which corresponds to an applied B field of 0 to 400 Gauss. The results from the tests are shown in Figure 7 and summarized in Figure 8.

D. Metal detection system

The experimental setup for the metal detection is shown in Figure 4. Metal detection exploits disruption of the magnetic flux density across the magnetostriction sensor. A quick swing of metal across the sensor, placed directly above the transformer, causes a localized magnetic disturbance which is picked up by the phase shift in the interferometer. Here a DC magnetic field is applied to the sensor. A Hall Effect sensor was placed directly above the sensor to provide a reference of the magnetic flux density. We affixed a steel rod to the rotor of a LEGO Mindstorm motor stage as shown in Figure 5. The lego rotor could hold a 12" × 3/8" metal rod. The rotor uses a 2:5 torque ratio. A torque ratio was used because the rotor needed to be powerful enough to sweep back and forth at continuous intervals without any irregularities.

The Lego motor stage rotated at a constant rotation speed of 1 rev/sec and held the metal rod at a height of 1 cm above the sensor. The rod passed the sensor once per revolution. The results of both signals from the fiber sensor and Hall Effect sensor are shown in Figure 9.

IV. Results and Discussions

Based on the plot of magnetization M for various field strengths H (Figure 6), one can clearly see the ferromagnetic material is relatively hard and has a fairly high remanence and coercivity. The material also requires a relatively large magnetic field to drive the material to saturation. Therefore, our sensor can operate in high magnetic fields within its saturation field H_s . In accordance with the MH curve, the novel ferromagnetic material WC-WSJOSH-2 and WC-WSJOSH-3 can cause larger magnetostrictive strain than conventional magnetostrictive materials. From the result of the MH curve, a summary of the magnetic properties of the ferromagnetic materials can be summarized in Table I. Currently more

ferromagnetic material are being fabricated and tested to improve the magnetostriction property of the material.

Based on results from the magnetostriction effect experiment (Figure 7), one can clearly see the changes in the output intensity due to the increase in applied magnetic field. The threshold input voltage, where output interference intensity has a one full 4π phase shift is 7V, shown in Figure 7(a). Further increase in the B field shows proportional increases in interference cycles in the output. According to Figure 7, we can clearly observe that the output interference intensity operates at a constant range from 0.35 V to 0.38 V. However, due to sinusoidal input, the output interference intensity will appear as frequency modulated sine wave as interference cycles increase with increasing input voltages (Figure 7b).

We fabricated the sensor to be as long as possible. We also assembled the mechanical fiber-optic couples far away from the autotransformer to avoid the unwanted vibration induced intensity modulation. Based on the current configuration, the average sensitivity of the sensor is around 70.7×10^{-3} rad/gauss (Figure 8) compare to our previous design of 52.1×10^{-3} rad/gauss [4]. Therefore, the current sensor using polymer (WC-WSJOSH-2) is roughly 1.4 times more sensitive than our previous sensor using WC-WSJOSH [4]. Overall the result is stable and repeatable.

The consistent sweep of metal across the metal detector shows us distinct peaks in our experiments results. For the metal detector test, A DC magnetic field varied from 0 to 300 gauss (corresponding input DC voltage of 0 to 3 V from the autotransformer). Based on the results shown in Figure 9, the fiber sensor shows a successfully metal detection such as steel rod (AISI 1566 steel) using the magnetostriction effect. It is clear that sensitivity is a function of the baseline magnetic flux density. Here we show that that magnetic flux density needs to reach at least 100 gauss for this sensor to be able to pick up this particular steel. The metal sensor (WC-WSJOSH-2), used in this paper, is more sensitive than our previous metal sensor (WC-WSHOSH) used in another publication [4]. Therefore, compared with previous results, we can use less magnetic field with 100 gauss to detect metal. Furthermore, we are trying to increase the sensitivity of the sensor by experimenting with different polymers and process. We are experimenting, with the goal of identifying polymers that maximize strain on the fiber optic without requiring an extremely high magnetic field to cause any detectable strain. Once refined, this technique would allow for optimum strain while minimizing the magnetic field. Aside from the baseline magnetic flux density, the sensitivity is also highly dependent on the separation distance between the metal object and the sensor. The current separation is quite small around 1 cm. We are currently working on improving the ferromagnetic material and also the optical system as well as the metal detection approach to improve the measurement. It is our hope that the sensitivity can be improved to the level where different permeabilities of steel or other metals can also be detected if some differential detection scheme can be used to filter out the air permeability.

V. Conclusion

In this paper, we presented a polymeric fiber-optic magnetostrictive metal detector system using a ferromagnetic magnetostrictive material (WC-WSJOSH-2). The result from the Mach

Zehnder interferometer shows that the ferromagnetic material works well as a metal detector. The work is still on-going in improving the materials, mechanics, magnetic properties and sensing sensitivity. We are pursuing studies of magnetostrictive materials; we are striving to improve the sensitivity of metal detection using the fiber-optic magnetostriction metal detector system described herein. Also, we hope this metal detection system can be extended to identify a variety of metals. The long term goal is to fabricate chip side sensors and actuators to use in a clean room environment.

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Figure 1.
Two coupler Mach-Zehnder Interferometer system

Figure 2.
The structure of magnetostrictive metal sensor

Figure 3.
The photo of magnetostrictive sensor (WC-WSJOSH-2)

Figure 4.
Scheme of polymeric fiber-optic magnetostrictive metal detector system

Figure 5.
Configuration of Lego motor stage and controller

Figure 6.
Hysteresis loops for ferromagnetic material (WC-WSJOSH-2 & WC-WSJOSH-3)

Figure 7.

Plot of output intensity from the magnetostrictive metal detector versus applied B field with input from VARIAC at (a) 7V, (b) 17V.

Figure 8.

Plot of induced phase shift versus applied B field with two sensors (WC-WSJOSH [4] and WC-WSJOSH-2)

Figure 9.

Plots of output intensity from magnetostrictive metal sensor with steel versus applied B field input from the EPSCO at (a) 0V, (b) 2V and (c) 3V.

TABLE I

Magnetic characteristic of investigated samples

Ferromagnetic material	<i>Coercive field H_c (kOe)</i>	<i>Remanence M_R (emu)</i>	<i>Saturation field H_s (kOe)</i>
WC-WSJOSH-2	2.035	0.317	9.104
WC-WSJOSH-3	3.033	0.461	9.504

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