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Development of a novel polymeric fiber-optic magnetostrictive metal detector

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Abstract

The purpose this paper is the development a novel polymeric fiber-optic magnetostrictive metal detector, using a fiber-optic Mach-Zehnder interferometer and polymeric magnetostrictive material. Metal detection is based on the strain-induced optical path length change stemming from the ferromagnetic material introduced in the magnetic field. Varied optical phase shifts resulted largely from different metal objects. In this paper, the preliminary results on the different metal material detection will be discussed.

Keywords

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

1. INTRODUCTION

Metal detectors are used extensively especially in the areas of defense, security and environmental applications. Modern metal detectors operate on three basic technologies: Very low frequency (VLF), Pulse induction (PI), and Beat-frequency oscillation (BFO). The VLF system is comprised of two coils that are electrically balanced, and when metal is introduced to their vicinity, they become unbalanced. What allows detectors to discriminate between metals is that every metal has a different phase response when exposed to alternating current [1]. For PI, instead of steady RF frequency, a powerful, short bursts (pulses) of current through a coil of wire was used. 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 an opposite magnetic field in the object. When the pulse's magnetic field collapses causing a reflected pulse, the magnetic field of the object increase the time for the reflected pulse to completely disappear [2]. In a BFO system, there are two coils of wire. One large

coil is in the search head, and a smaller coil is located inside the control box. Each coil is connected to an oscillator that generates thousands of pulses of current per second. The frequency of these pulses is slightly offset between the two coils. As the pulses travel through each coil, the coil generates radio waves. A tiny 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[3]. 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. As the frequency deviates from the frequency of the coil in the control box, the audible beats changes in duration and tone.

These sensors appear as a walk-through or hand held configurations that are commonly seen at the airports, libraries, prisons, stores, and shops. These devices however are relatively large, and are highly affected by the surrounding electronics. If magnetic sensors are to be used in the hospital or laboratory where limited space is available and equipments are susceptible to electromagnetic interference, these detectors will not work well. In this paper, we present a compact metal detector that can resolve these problems. The detector uses a newly developed polymeric fiber-optic Mach-Zhnder magnetostrictive sensor. The detector utilizes a simple DC magnetic field detection scheme and a Mach-Zhnder 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 stemming from the magnetic field induced magnetostriction effect. The magnetostrictive device can produce polarized magnetic fields that have temporal characteristics such as those generated from walk-through metal detectors. Based on the fact that different metal targets have different magnetic disturbances, different metal objects can be identified. This fiber-optic magnetostrictive metal detector is much less complex, relatively smaller in size, and easy to fabricate. Additionally the technique is free from RF interference. In this paper, the theory, design and preliminary results on the metal detection are presented

2. POLYMERIC FIBER-OPTIC MAGNETOSTRICTIVE METAL DETECTOR SYSTEM

2.1 Polymeric fiber-optic magnetostrictive metal detector system

The basic concept of magnetostrictive metal detectors is based on the magnetostrictive sensor, which was first proposed by Yariv et al [4]. 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 [5]. 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 [4],

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

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 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) [4], 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 a ferromagnetic polymer. The general equation for the two output channels of the Mach-Zehnder fiberoptic interferometer (Figure 1) is given as

$$\begin{aligned} I &= I_0 \alpha (A + B \cos \Delta\phi) \\ I' &= I_0 \alpha (C + B \cos \Delta\phi) \end{aligned} \quad (3)$$

where

$a_r = a_s = a$, $A = k_1 k_2 + (1 - k_1)(1 - k_2)$, $B = 2\sqrt{k_1 k_2 (1 - k_1)(1 - k_2)}$, $C = k_1(1 - k_2)(1 - k_1)k_2$
 α_r , α_s , are optical loss associated with reference and signal paths assumed to equal, and k_1 , and k_2 are coupling ratios for first and second 2x2 coupler.

2.2 Ferromagnetic polymer

The metal sensing arm is coated with a 36 cm long and 2.2mm thick ferromagnetic polymer (WC-WSJOSH) (Figure 2). This magnetostrictive metal sensor is one kind of ferrite power doping into elastomeric polymer material. (Due to the IP issue, the fabrication process cannot be discussed in this paper). We bent and tied the sensing fiber into a circle shape in order to increase the sensing area (Figure 3).

3. EXPERIMENTAL

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 2x2 fiber-optic coupler (HOPECOM: WBSC-X-S-50-1315-9-C-H-100). Between the two 2x2 couplers, one of the output channel from the first 2x2 coupler is connected to a single mode fiber coated with ferromagnetic polymer (WC-WSJOSH). Both output channels from the first 2x2 coupler are then connected to the inputs of the second 2x2 coupler. One of the output channels from the second 2x2 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 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.

3.1 Driving coil calibration

The setup for the driving coil calibration is shown in Figure 5. The input voltage is supplied by the DC power supply (made by EPSCO, model EC-2). The magnetic flux density across the first magnet coil measured at point 1, 2 and 3 ranges from 0 to 8V are shown in Figure 6. A linear response was observed between the input DC voltage and the output magnetic flux density. This linearity insures that no correction factor is needed to convert the input voltage from the power supply to the output magnetic flux density. For the experiment, we set the apply voltage to magnetic coil from 0 to 4 volts.

3.2 Faraday Effect testing

Faraday Effect in the sensor was observed prior to the experiment to insure the main phase modulation in the interferometer was mainly due to magnetostriction effect. The test was conducted using a bare fiber without the polymeric ferromagnetic coating for the sensing arm in the same optical setup as described in Figure 4. In this Faraday Effect experiment, we applied a 1–12 voltage to the autotransformer, which corresponded to an applied B field of 50 to 900 Gauss. Based on our previous results [6], the magnetic field did not seem to influence the output signal of this fiber-optic interferometer system.

3.3 Magnetostriction Effect testing

The magnetostriction effect of the sensor was tested using a fiberoptic MZI where the sensing arm is coated with a polymer based ferromagnetic material (WC-WSJOSH). The experiment setup has been described previously in another publication [6]. In this magnetostriction effect experiment, we varied the input voltage to autotransformer from 0-17V which corresponds to an applied B field of 0 to 300 Gauss. The results from the tests are shown in Figure 7.

One can clearly see the changes in the output intensity due to the increase in applied magnetic field. The interference intensity reaches one full 2π cycle 4.5 V input voltage. Further increasing the B field shows more cycles in the output. Based on the results, we found ferromagnetic polymer coated fiber sensor was successful in detecting the field based on magnetostriction experiment. Based on the current configuration, the sensitivity of the sensor is around 8.5×10^{-3} rad/gauss.

3.4 Metal detection system

The experimental setup for the metal detection is shown in Figure 4. The way the metal detection works is based on disruption of the magnetic flux density across the magnetostriction sensor. A quick swing of the metal across the sensor placed directly above the transformer causes a localized magnetic disturbance which is pick 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 provides a reference to the magnetic flux density

sensor is monitoring. We tested two metal objects composed of steel and aluminum (Figure 9). All of the metals are round rods with same geometry and affixed to the rotor of a LEGO Mindstorm motor stage as shown in Figure 8. The mechanical and magnetic properties of investigated samples are shown in Table 1. The stage is rotating at a constant velocity of 1 Hz and a height of 1.5 cm above the sensor. However, the rod passed the sensor twice in each revolution. Therefore in the results shows 2 cycle revolution. The results of both signals from the fiber sensor and Hall Effect sensor are shown in Figure 10.

4. RESULTS AND DISCUSSIONS

For the metal detector test, the magnetic field varied from 0 to 300 gauss (corresponding 0 to 3 V from the autotransformer). Based on the results shown in Figure 10, the sensor shows that it can successfully detect relatively high permeability metal such as stainless steel using 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 150 gauss for this sensor to be able to detect this particular stainless steel. Aside from the baseline magnetic flux density, the sensitivity is also a function of the distance separation between the metal and the sensor. The current separation is set around 1.5 cm. Another problem is that we did not use a very sensitive magnetostrictive polymer in the experiment. We are currently working on improving the polymer and also the optical system as well as metal detection approach to improve the measurement. It is our hope that the sensitivity can be improve to the level where negative permeability such as aluminum can also be detected if some differential detection scheme can be used to filter out the air permeability.

5. CONCLUSIONS

In this paper, we presented a polymeric fiber-optic magnetostrictive metal detector system using a polymeric magnetostrictive polymer (WC-WSJOSH). 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 material, mechanical, and magnetic properties. We hope with further study of this magnetostrictive material we will eventually be able to improve the sensitivity of the metal detection for the current fiber-optic magnetostriction metal detector system. Also we hope this metal detection system can identify several metals in the future. The long term goal is to eventually enable us to fabricate chip side sensors and actuators to in the 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)

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

Figure 5.

Driving coil calibration setup. The input voltage is monitored by a Fluke multimeter (Fluke 73) and Fluke Scopemeter with channel A observe the input voltage to the transformer and channel B measuring output from the Hall Effect sensor.

Figure 6.
Driving coil calibration curve: magnetic flux observed at point 1 to point 3

Figure 7. plot of output intensity from the magnetostrictive metal detector versus applied B field with input from the VARIAC at (a) 0V, (b) 5V, (c) 10V, (d) 17V.

Figure 8.
Configuration of Lego motor stage and controller

Figure 9.
Photo of investigated objects : Aluminum and Steel

Figure 10.

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

Table 1

The characteristic of investigated samples

Objects	Radius	Density (kg/m ³)	Relative Permeability(μ / μ_0)
Stainless Steel 304	1 cm	8.000	200
Aluminum 2011	1 cm	2820	1.000022