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Fiberoptic metal detector capable of profile detection

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Abstract

The purpose of this paper is to develop a novel ferromagnetic polymeric metal detector system by using a fiber-optic Mach-Zehnder interferometer with a newly developed ferromagnetic polymer as the magnetostrictive sensing device. This ferromagnetic polymeric metal detector system is simple to fabricate, small in size, and resistant to RF interference (which is common in typical electromagnetic type metal detectors). Metal detection is made possible by disrupting the magnetic flux density present on the magnetostrictive sensor. This paper discusses the magnetic properties of the ferromagnetic polymers. In addition, the preliminary results of successful sensing of different geometrical metal shapes will be discussed.

Keywords

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

1. INTRODUCTION

Metal detector systems are widely used in airport, library and security environments. 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 a metal object is in close proximity to the coils, they become unbalanced [1]. Instead of steady RF frequency, PI systems make use of short powerful pulses of current through a wire coil. 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 a metal object is present, the pulse creates a magnetic field in the opposite direction in the metal object. Due to the opposite magnetic field created from the metal object, the reflected pulse persists longer, thus it is possible to detect the presence of metal [2]. A BFO system includes two wire coils: one large coil in the search

head and a smaller coil in the control box. Each coil is connected to an oscillator that generates thousands of 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 beats. If the large coil in the search head passes near a metal object, 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 metal detector is able to identify different metals based on each metal's unique phase response when exposed to alternating current.

Every day, we encounter these different types of metal sensors in the form of walk-through and hand held metal detector devices. Metal detection systems are common in prisons, libraries, airports, stores and shops. However these devices share three shortcomings. First, they are relatively bulky and large. Second, they are subject to interference caused by the surrounding electronics components. If used in a hospital or laboratory environment, where space is limited, these devices often experience electromagnetic interference, yielding inaccurate results. Third, conventional metal detectors are unable to detect the geometric shape and dimension of metal objects. In this paper, we describe a compact metal detector system that overcomes the aforementioned problems. As we have previously reported [4], our metal detector uses the fiber-optic Mach-Zehnder ferromagnetic polymeric sensor. This metal detector utilizes a simple DC magnetic field detection scheme and a Mach-Zehnder fiber-optic interferometer for the main structure of the metal detection system. Metal detection is made possible by monitoring strain-induced optical path length change in the interferometer which stems from the magnetostriction effect induced by the magnetic field. This ferromagnetic polymeric metal sensor can produce polarized magnetic fields that have temporal characteristics, similar to those generated by walk-through metal detector system. When compared to conventional metal detectors, this novel fiber-optic magnetostrictive metal detector system is: smaller in size, less complex, and much easier to fabricate. In addition, the performance of this metal detector is not degraded by RF interference. It is noteworthy that the fiber-optic magnetostrictive metal detector can identify the general geometrical shape and width of metal objects. This paper presents the theory, design and preliminary results. The detection of metal objects has been improved from our previous design [5]; it is now possible to detect the direction of movement and the width of metal objects.

2. FIBER-OPTIC FERROMAGNETIC POLYMERIC METAL DETECTOR SYSTEM

2.1 Polymeric fiber-optic magnetostrictive metal detector system

The magnetostrictive sensor, which was first proposed by Yariv et al [6], serves as the foundation for the metal detector described in this paper. The Mach-Zehnder fiber-optic interferometer is employed to measure the magnetic field-dependent strain in a ferromagnetic material, see our previous experiments [4, 5] for greater detail. Here, the ferromagnetic polymer is coated directly onto the cladding of the sensing arm of the optical

interferometer. Measurement of the intensity of the resulting strain on the magnetostrictive material is based on the magnetic field induced phase shift in the interferometer given by [6]:

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

In this equation, longitudinal strain $\Delta L/L = \varepsilon_3$, 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) [6], equation (1) will reduce to following equation:

$$\Delta\varphi = \frac{2\pi nL}{\lambda} 0.92\varepsilon_3 \quad (2)$$

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 that 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

$$I = I_o \alpha (A + B \cos \Delta\varphi) \quad (3)$$

where $\alpha_r = \alpha_s = \alpha$, $A = k_1 k_2 + (1 - k_1)(1 - k_2)$, $B = 2\sqrt{k_1 k_2 (1 - k_1)(1 - k_2)}$, $C = k_1(1 - k_2)(1 - k_1)k_2$

α_r , α_s are optical losses associated with reference and signal paths and assumed to be equal, and k_1 and k_2 are coupling ratios for first and second 2x2 coupler.

2.2 Ferromagnetic polymer device

The metal sensing device is the fiber arm coated with a ferromagnetic polymer material (WC-WSJOSH-2) (30 cm long and 1.36 mm thick, see Figure 2). In this paper, we use the same layout and geometry that we reported previously [5]. In this case, the sensing fiber is bent into a snake shape in order to increase the sensing area (Figure 3), and the magnetostrictive material is manipulated during fabrication to increase sensitivity..

3. EXPERIMENTAL

3.1 Mach-Zehnder fiber-optic interferometer metal detector setup

The overall experimental setup for the magnetostrictive metal detector system is shown in Figure 4. The light input for the sensor is provided by a pigtail laser diode (Mitsubishi: MF-622DS-T12-241 No. 85263, $\lambda = 1319\text{nm}$). 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 channels 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). Members of the research team fabricated the transformer coil, i.e., the driving coil used to generate the DC magnetic field for the magnetostrictive metal detector sensor. The magnetic field is monitored by a high sensitivity Hall Effect sensor made by Allegro (UGN 3503U), capable of detecting magnetic fields ranging from 0 to 900 Gauss. The fabricated transformer coil calibration setup and results are described in another publication [4]. The output intensity from the detector is converted into an electrical signal and analyzed by a Fluke digital scopemeter (Fluke 199C Scopemeter Color, 200MHz 2.5 Gs/s) via USB data output.

3.2 Metal detection system

As shown in Figure 4, metal detection exploits disruption of the magnetic flux density across the magnetostrictive sensor. The metal objects were mounted on a wooden cart, which is placed on an adjustable wooden track stages (Figure 5). The metal objects were placed under the cart, parallel to the metal detector. When a metal object is directly above the transformer, a localized magnetic disturbance is created. This disturbance results in a phase shift that is observed in the output interferogram. To provide a reference magnetic flux density, a constant DC magnetic field is applied to the metal sensor, with a Hall Effect sensor placed directly above the metal sensor (~ 8mm above the autotransformer). To test different geometries of metal objects, we affixed two different steel objects to the cart (Figure 6). Table 1 provides details on the size and shape of the metal samples. The space between the metal and the detector is 5mm. The cart was moved back and forth by hand, striving for a constant speed. Previous methods of testing [4], only allowed for detecting the presence of metal objects, but these methods were incapable of mapping its shape. By mounting metal objects on a wooden cart and moving the cart over the sensor, it becomes possible to attempt numerous metal detection trials. We use the results of these trials to determine the shape and size of the object. The resulting signals from both the metal sensor and Hall Effect sensor are shown in Figure 7.

4. RESULTS AND DISCUSSIONS

Based on our previous experiment [4], we know that the interference intensity reaches one full (2π) cycle at an input peak voltage of 4.5 V (autotransformer operates at 60Hz). The corresponding magnetic flux density is 450 gauss measured at the surface of the transformer. Increasing the B field causes a proportional increase in the number of interference cycles in the output intensity. Based on the results, the sensitivity of the sensor reached 8.5×10^{-3} rad/gauss. For metal detection, a stainless steel type 304, 1.5 cm from sensor was detected at a DC input magnetic flux density of 150 gauss.

In this paper, we further improved the sensor's capability by using the sensor to create a 2D profile of the object. Based on previous results, we established that the metal detector works

best when the sensor is located at the inflection point of the interference cycle between the maximum and minimum peaks. We also found best results when the corresponding magnetic flux density was approximately 300 gauss. For the experiment reported here, two sets of metal samples were tested: (1) two identical steel rods, and (2) a metal plate and a steel rod. In Figure 7, a Hall Effect sensor provides a reference magnetic flux density observed by the metal sensor, the measurement of the Hall Effect sensor is shown in the primary y axis, while the output intensity from the magnetostrictive metal sensor is shown in the secondary y axis. Thus, Figure 7 shows that the magnetostrictive metal sensor can distinguish between different shapes of metal. The graphs show that as the width of the metal increases the period of detection by the sensor also increases. We derived the following equation to calculate the size of the metal object based on the period of time it is detected and the velocity of the object being detected:

$$d = V \times \Delta t - w \quad (4)$$

where d is the distance that is trying to be determined (width of the metal), V is the average velocity of the object being measured, t is the change in time from when the object is just starting to be detected to when it has just stopped being detected in Figure 7, and w is the width of the sensor. By multiplying the time in which the object is being detected by the velocity of the object we can then find the change in displacement which is d since $V = dx/dt$. The width of the sensor needs to be subtracted from this value because without it we are assuming our sensor is a point particle with no width. However, our sensor is not a point particle and so when it detects an object it senses the object for longer than it actually should. This error can be correct simply by subtracting the width of the sensor. The velocity of the object was determined by filming the object as it was passed over top of the sensor. We placed a ruler along the path of the object and were able to figure out a change in position over a change in some time interval thus giving us an average velocity of our object as it passed over top of our sensor.

From equation (4) we were able to calculate the values of the widths of the metal objects, these values are shown in Table 2. The values calculated were very close to the actual dimensions of the objects. The percent errors between the calculated distances and the actual distances ranged from 4.4% to 14.4%. These errors could be due to a number of factors. The biggest error probably comes from the calculation of velocity. The velocity was calculated with a camera that shot 30 frames per second. An even faster camera would give an even more precious measurement of velocity. Also even with a very fast camera the velocity of the cart is not constant and the method used currently assumes that the velocity is constant which is why we called it an “average” velocity. If a method was used that could measure this changing velocity then a very accurate distance could be calculated. The fiber-optic system is also highly sensitive to environment changes. Either thermal or vibratory behavior will interfere with the optical signal. Therefore, in the future a heterodyne interferometer or phase modulator will be added to compensate for the drift due to the environment. 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. Although the distance can be improved by increase the input magnetic flux density, it will be more practical that we work on improving the ferromagnetic material,

the optical system, and the metal detection approach to increase the distance between the object and the sensor. It is our hope that the sensitivity can be improved to the level where we can identify metals of different permeabilities and increase the accuracy of determining the dimensions of the metals.

5. CONCLUSIONS

In this paper, we presented a ferromagnetic polymeric metal detector system using a ferromagnetic magnetostrictive material (WC-WSJOSH-2). The result from the fiber-optic system shows that the ferromagnetic material works well as a metal detector. In addition, this sensor (WC-WSJOSH-2) can roughly identify different metal shapes with varied widths. The work is still on-going in improving the sensor materials, mechanics structure, ferromagnetic properties and sensing sensitivity. However, 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 with different geometries. It is our hope that the sensitivity can be improved to the level where we can identify metals of different permeabilities and also increase the accuracy of width detection of the metals. The final goal of this sensor is to identify and calculate the shape of more complicated metal objects. The long term goal is to fabricate chip side sensors and actuators to use in a clean room environment.

Acknowledgments

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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 magnetostriuctive sensor (WC-WSJOSH-2)

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

Figure 5.
Configuration of wooden track and cart

Figure 6.
Configuration of metal positions. (a) two steel rods (b) one steel rod and one steel plate (c)
cross section of metal position

Figure 7.

Plots of output intensity from magnetostrictive metal sensor with steels versus applied B field (a) two steel rods with same geometry, (b) one steel rod and one steel plate.

Table 1

The dimensions of investigated samples

Objects	Thickness	width
Steel rod	0.9 cm	0.9 cm
Steel plate	0.5 cm	2.5 cm

Table 2

The calculation result of investigated samples

Investigated samples	Object	Measured width	Actual width	error
Two rods (Figure 7(a))	1 st Steel Rod	0.94cm	0.9cm	4.44%
	2 nd Steel Rod	1.012 cm	0.9cm	12.44%
one plate and one rod (Figure 7(b))	Steel Plate	2.86cm	2.5cm	14.4%
	Steel Rod	0.94cm	0.9cm	4.4%