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A Wireless, Passive Load Cell based on Magnetoelastic Resonance

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Abstract

A wireless, battery-less load cell was fabricated based on the resonant frequency shift of a vibrating magnetoelastic strip when exposed to an AC magnetic field. Since the vibration of the magnetoelastic strip generated a secondary field, the resonance was remotely detected with a coil. When a load was applied to a small area on the surface of the magnetoelastic strip via a circular rod applicator, the resonant frequency and amplitude decreased due to the damping on its vibration. The force sensitivity of the load cell was controlled by changing the size of the force applicator and placing the applicator at different locations on the strip's surface. Experimental results showed the force sensitivity increased with a larger applicator placing near the edge of the strip. The novelty of this load cell is not only its wireless passive nature, but also the controllability of the force sensitivity.

Keywords

Magnetoelastic; resonance; magnetic; load cell; force

1. Introduction

Most force transducers today are based on, but not limited to, resistive, capacitive, and/or optical sensing technologies. Resistive based sensing platforms monitor force through devices that change electrical resistance in response to an applied load. For instance, piezoresistive sensors primarily consist of materials whose electrical resistance changes with force. One such device, the Tekscan Flexiforce, utilizes semi-conductive ink sandwiched between conductive polyester sheets as the force sensitive element. An applied load alters the resistance of the ink, thus changing the overall resistance measured on the active conducting sheets [1]. Capacitive based sensing platforms take advantage of the changes in observed sensor capacitance as a means to monitor force application. One such system was developed for use with endoscopic tools and is comprised of an array of capacitive elements with a total size of less than 1 mm² [2]. Similar to resistive and capacitive technologies, optical sensors function as a result of an observed change in the intensity, frequency, and spectrum of light due to an applied force. For instance, the LED Microshift, consisting of a glass cube with a cavity protected by a silicon diaphragm, was deployed for blood pressure monitoring in catheters based on the change in light spectrum [3]. These force monitoring devices, while highly useful and well established, often lack wireless and passive sensing capability, which not only limits long term use but also prevents application as embedded sensors.

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Wireless, passive versions of force sensors have been developed based on electromagnetic coupling. For example, sensors based on radio frequency identification devices (RFID), which consist of strain gauges incorporated onto the RFID tags for electromagnetically coupling to a remote detector, were reported for use in structural health monitoring [4]. Magnetic materials were also used for wireless force monitoring. For instance, a sensor was reported for wireless force mapping and consisted of three strips of a soft amorphous magnetoelastic material, Metglas 2826MB, adhered to a polycarbonate block with appropriate load applicators placed on top of the strips [5]. Under excitation of an AC magnetic field, the magnetoelastic material generated magnetic field at higher frequencies (higher order harmonic fields) capable of being remotely monitored with a detection coil. Applied force resulted in an increase in the observed amplitude of the higher order harmonic fields due to an increase in the sensor's magnetic permeability. The force profile could then be determined by processing the higher-order magnetic field responses of all strips [5].

Another sensor design based on the interference between a magnetically soft material and a permanent magnet was also developed for stress and force monitoring. The sensor design consisted of a magnetically soft material placed adjacent to a permanent magnet. Force or pressure altered the separation distance between these two magnetic elements, changing the magnetization response of the magnetically soft material. The change was reflected in the shift in higher-order harmonic field pattern [6]. This sensor was applied to measure mechanical force loading [7] as well as atmospheric [6] and liquid pressures [8].

Magnetoelastic resonance sensors are another type of wireless sensors that have been demonstrated for force or stress monitoring. When subjected to an AC magnetic excitation field, these sensors experience a mechanical resonance as a result of their magnetoelasticity. The experienced resonance produces a secondary magnetic flux that can be detected with an external pickup coil [9]. The application of a force dampens the vibration, reducing the resonant frequency and amplitude. This mode of sensing has been deployed for monitoring the elasticity and mass of a coating, and, with a mass-changing chemically sensitive coating, the concentration of various chemicals and biological agents such as glucose or *E. coli* [9, 10]. While the reported sensors are simple, they focused on uniform force loadings on the sensor surfaces, and there is no systematic way to control the stress sensitivity.

Presented here is a force sensor, or a load cell, based on the magnetoelastic resonance using non uniform force distribution for controlling stress sensitivity. The load cell consisted of a strip of magnetoelastic material and an associated permanent magnet to produce the biasing field for optimal magnetoelastic response [11]. Both elements were placed inside a rigid structure featuring an applicator that transferred force to the strip's surface. Since the strain of a magnetoelastic strip is zero at the center of the strip and maximum at the ends of its length, the effect of the force loading will be different depending on the loading location. This phenomenon was exploited for creating a wireless, passive load cell with controlled stress sensitivity.

2. Experiments

2.1. Sensor Fabrication

Two load cells were fabricated and tested. The first load cell consisted of a series of holes through which the force applicator can pass (see Figure 1a). Load Cell A, consisting of an array of loading positions for the force applicator, was used to characterize response of the magnetoelastic strip under loading at different positions. Load Cell B, with only one force loading position, was fabricated to demonstrate the application of this technology for wireless force measurement (see Figure 1b).

Load Cell A was milled from a piece of polycarbonate using a CNC Micro Milling Machine and measured 54.5 mm × 32.2 mm × 12.7 mm. The holes in the top piece, measuring 4.75 mm in diameter, were positioned at the center of the width of the strip and were spaced along the length of the strip. Force was applied through applicators consisting of polycarbonate shafts with an attached metal rod for applying weight during testing. Three force applicators were fabricated and used to investigate the effect of loading area on the load cell sensitivity and dynamic range. The applicators consisted of a polycarbonate shaft with a rod affixed to the top for applying weights. The area of force application was controlled by adhering rubber tips to the head of the applicator. Three such applicators were fabricated with circular rubber tips having diameters of 0.7 mm, 1.6 mm, and 2.48 mm respectively.

Similarly, Load cell B was milled from a block of polycarbonate using a CNC Micro Milling Machine. The top and bottom pieces measured 35 mm × 25 mm × 5.85 mm and were held together by nuts and bolts at the corners. An applicator head consisting of two pieces of polycarbonate rod and a small metal tip was also fashioned. The top of the applicator measured 11.15 mm in diameter with a height of 4.2 mm, the shaft measured 4.7 mm in diameter with a height of 5.9 mm, and the metal tip measured 1.5 mm in length extending out of the shaft. A hole was milled for the applicator head and a guide rod was used to prevent the applicator from rotating and minimized tilting during testing.

The bottom pieces of both load cells consisted of two wells, one for placing the magnetoelastic strip and the other for the permanent magnetic strip. The well dimensions for the magnetoelastic strip and the permanent magnetic strip were 38.65 mm × 12.52 mm × 0.5 mm and 14.63 mm × 4.0 mm × 0.5 mm for Load Cell A and 30 mm × 8 mm × 0.5 mm and 15 mm × 6.5 mm × 0.5 mm for Load Cell B, respectively. The magnetoelastic strips were sheared from a ribbon of 26 μm thick Metglas 2826 MB ribbon ($\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$) purchased from Metglas Inc, Conway, SC, USA and the permanent magnetic strips were cut from 0.05 mm thick ribbon of Arnokrome™ 3 (Arnold Magnetic Technologies). It is worth noting that the permanent magnetic strips can be replaced by an external DC magnetic field.

2.2. Experimental Setup and Procedure

Figure 2 illustrates the experimental setup. The load cell was attached to the test platform with double sided adhesive tape and was positioned in front of the excitation and detection coils. The detection coil connected to a Stanford Research Systems SR810 Lock in Amplifier which captured the sensor resonance and sent it to a PC for further analysis. A customized Visual Basic program was used to automate the measurement process. The excitation coil consisted of a 50 turn 18-gauge circular coil connected to a Fluke 271 10 MHz AC function generator responsible for producing the necessary frequency sweep. An audio amplifier (Tapco J1400) was used to amplify the excitation signal.

During all experiments, loads were applied to the applicator heads in 0.049 N intervals from 0 to 0.311 N for the multi-position load cell and 0 to 0.203 N for the smaller load cell (the applicator heads themselves weighed 0.017 N and 0.007 N, respectively, which was not considered in the load calculation). Testing was then repeated from maximum load to zero in order to test sensor repeatability and hysteresis. Before running experiments, the sensors were removed from in front of the detection coil and a background sweep was performed to remove ambient noise and the resonance of the coil from the obtained results. Following sufficient testing with both sensors, Load Cell B was further characterized through hysteresis and movement (along the x , y , and z axis) testing.

3. Results and Discussion

3.1. Effect of Loading Position and Applicator Head Size

As shown in Figure 3, force loading on the magnetoelastic sensor through an applicator at a portion of the sensor surface increased the resonant frequency. As expected, the resonant amplitude decreased with increasing loading due to damping on the vibration.

Applying loads along the length of the sensor demonstrated an increase in sensitivity as the position of force application moved away from the center of the strip. This can be explained by examining the equation of motion of the sensor, which is described as [12]:

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{E}{1 - \sigma^2} \frac{\partial^2 u}{\partial y^2} \quad (1)$$

where t is time, y is the length direction, u is the displacement along the length direction, ρ is the density of the sensor material, E is the elasticity of the material, and σ is the Poisson ratio. For a free standing sensor with no rigid restraints at the ends of its length, the displacement u will be at the largest at the ends of the length and smallest at the center. Assuming the center of the sensor is at $y = 0$, a solution for Eq. (1) that fulfills the boundary conditions of a free standing sensor is:

$$u = 2Be^{-j\omega_n t} \sin\left(\frac{n\pi y}{L}\right) \quad (2)$$

where B is a complex number, n is the resonance mode, ω_n is the longitudinal resonant radian frequencies of the sensor, and L is the sensor's length. Eq. (2) indicates the vibration amplitude of the sensor, at the fundamental resonant frequency, should be zero at the center and largest at the ends. The vibration amplitudes have a large effect on the stress sensitivity of the sensor, as demonstrated by the results in Figure 4. As expected from Figure 4, the largest frequency shift occurred in Position 1 (farthest from the center of the strip); whereas the smallest shift occurred in Position 4 (at the center of the strip).

To quantify the effect of altering the loading position along the sensor's length on sensitivity and range, the curves in Figure 4 were fitted with a decaying exponential in the form of:

$$\Delta f = A(1 - e^{-kF}) \quad (3)$$

where Δf is the resonant frequency shift, F is the applied load, and A and k are coefficients describing the curve. The coefficients A and k were obtained from curve fitting the collected data. Figure 5 shows that A and k increased with distance from the center, indicating a proportional relationship with the sensor's sensitivity and dynamic range.

The size of the applicator head also had a distinct effect on sensor range and sensitivity (see Figure 6). During experimental testing it was observed that smaller heads were less sensitive to overall change in force applicator, but also demonstrated the capacity for a larger overall sensing range. Figure 7 plots the coefficients of the equation for lines in Figure 6 against the applicator head size, demonstrating the capacity to alter sensor sensitivity and range by altering the surface area of the force applicator.

3.2. Effect of Load Cell Location from the Excitation/Detection Coils

In addition to force monitoring, the sensor response under zero loading conditions, when incrementally moved on the x , y , and z axis was also observed (see Figure 8). The x -axis testing demonstrated a gradual decrease with increasing distance from the coil, which is to

be expected as the field experienced and captured by the detection coil decreased as the magnetoelastic strip was moved away from the coil (see Figure 8a). Along the y -axis, the measured amplitude increased as the sensor moved closer to the center of the detection coil and then decreased as that center passed (see Figure 8b). This result is explained by the fact that the peak signal amplitude will be experienced when the sensor is at the center of the coil. A similar result was seen along the z -axis (see Figure 8c).

3.3. Performance of the Magnetoelastic Load Cell

Following testing with Load Cell A, Load Cell B was fabricated and tested (see Figure 9). As expected from the previous testing, the sensor was highly sensitive to load application and was capable of detecting loads as low as 0.049 N. Additionally, the sensor saturated at 0.2 N, which was earlier than Load Cell A at 0.311 N. This is to be expected since the applicator head was located closer to the front of the strip. Moreover, the sensor's overall size was decreased, resulting in a decreased overall sensor range and sensitivity regardless of the position of loading and/or the size of the applicator head. The sensor also demonstrated a decaying exponential response, and repeatability testing (see Figure 10) produced a consistent response over the course of 10 loading cycles.

4. Conclusion

The fabrication and testing of a wireless passive load cell based on the magnetoelastic resonance sensor has been presented. The performance of this load cell was first evaluated by applying loads at multiple locations along the length of the strip and with applicator heads of varying sizes. Testing occurred from 0 to 0.311 N and demonstrated that the largest range and sensitivity was experienced at the edges of the strip, along its length, while the center of the strip exhibited small change in resonance as a result of force application. Additionally, larger force applicator heads resulted in more sensitive sensing response but significantly decreased range. A smaller load cell with a pin point applicator head situated near the front of the strip was also fabricated. The load cell was tested from 0 to 0.2 N at 0.049 N intervals with acceptable repeatability between tests.

The presented sensor represents, given further development, a new method for wireless passive long term force monitoring with the capacity to be modified for varying ranges and sensitivities based on the location of load application, the size of the applicator head, and the overall size of the magnetoelastic strips. Future works include further miniaturization of the sensor and optimization of the excitation and detection system to provide for a more portable and size appropriate detection system.

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References

1. Lebosse C, Renaud P, Bayle B, de Mathelin M. Modeling and Evaluation of Low-Cost Force Sensors. *IEEE Transactions on Robotics*. 2011; 27(4):815–822.
2. Puangmali P, Althoefer K, Seneviratne LD, Murphy D, Dasgupta P. State-of-the-art in force and tactile sensing for minimally invasive surgery. *IEEE Sensors Journal*. 2008; 8(3–4):371–381.

3. Polygerinos P, Zbyszewski D, Schaeffter T, Razavi R, Seneviratne LD, Althoefer K. MRI-Compatible Fiber-Optic Force Sensors for Catheterization Procedures. *IEEE Sensors Journal*. 2010; 10(10):1598–1608.
4. Ikemoto, Y.; Suzuki, S.; Okamoto, H.; Murakami, H.; Xin, Lin; Itoh, H.; Asama, H. Force sensor system for structural health monitoring using passive RFID tags for structural health monitoring" 2008 IEEE Interdisciplinary Conference on Portable Info Devices (PORTABLE) – Polytronic 2008; IEEE Conference on Polymers and Adhesives in Microelectronics and Photonics; 2008. p. 1-6.
5. Pereles BD, DeRouin AJ, Dienhart TA, Tan EL, Ong KG. A Wireless, Magnetoelastic-based Sensor Array for Force Monitoring on a Hard Surface. *Sensor Letters*. in press.
6. Pereles BD, S R, Tan EL, Ong KG. A Remote Query Pressure Sensor Based on Magnetic Higher Order Harmonic Fields. *IEEE Sensors Journal*. 2008; 8(11):1824–1829.
7. Ee Lim T, Pereles BD, Ranyuan Shao, Ong J, Keat Ghee Ong. A wireless, passive strain sensor based on the harmonic response of magnetically soft materials. *Smart Materials and Structures*. 2008; 17(2):025015.
8. Ee Lim T, Pereles BD, Ong KG. A Wireless Embedded Sensor Based on Magnetic Higher Order Harmonic Fields: Application to Liquid Pressure Monitoring. *IEEE Sensors Journal*. 2010; 10(6): 1085–1090. [PubMed: 20514363]
9. Grimes CA, Roy SC, Rani SJ, Cai QY. Theory, Instrumentation and Applications of Magnetoelastic Resonance Sensors: A Review. *Sensors*. 2011; 11(3):2809–2844. [PubMed: 22163768]
10. Ong KG, Zeng K, Yang X, Shankar K, Ruan C, Grimes CA. Quantification of multiple bioagents with wireless, remote-query magnetoelastic microsensors. *IEEE Sensors Journal*. 2006; 6(3):514–523.
11. Ong KG, Mungle CS, Grimes CA. Control of a magnetoelastic sensor temperature response by magnetic field tuning. *IEEE Trans. Magnetics*. 2003; 39(5):3319–3321.
12. Grimes CA, Ong KG, Loiselle K, Stoyanov PG, Kouzoudis D, Liu Y, Tong C, Tefiku F. Magnetoelastic sensors for remote query environmental monitoring. *Smart Materials & Structures*. 1999; 8(5):639–646.

1a

1b

Figure 1.

(a) Load Cell A was designed to allow for loading at multiple positions. (b) Load Cell B consisted of a single loading position, but was significantly smaller than Load Cell A.

Figure 2.
The full experimental setup illustrating the AC excitation coil, detection coil, function generator, amplifier, and magnetoelastic load cell.

Figure 3. Force applied to the magnetoelastic strip resulting in an increase in the peak resonant frequency and a decrease in the resonant amplitude.

Figure 4.

The results of multi-position load testing show the sensitivity and dynamic range of the sensor decreased when the load position moved away from the center of the sensor.

Figure 5.

The coefficients of the equation describing the sensor behavior demonstrate an inverse relationship (for A) and proportional relation (for k) as the loading moved away from the center of the strip.

Figure 6. The results of loading with different applicator heads demonstrate a direct relationship linking the sensor's sensitivity to the size of the applicator head.

Figure 7.

The coefficients of the equation describing the sensor behavior demonstrate a direct relationship between the coefficients and the size of the applicator head.

8a

8b

8c

Figure 8.

The effects on the measured sensor amplitude while the sensor was moved along the (a) x , (b) y , and (c) z axis.

Figure 9.

The results of testing Load Cell B demonstrate a decaying exponential behavior with high sensitivity but low range.

Figure 10.

Hysteresis testing with Load Cell B demonstrates consistent results over multiple force loading cycles.