Size dependency in sensor response of a flexible tactile sensor based on inductance measurement

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***Abstract*— This paper describes a flexible tactile sensor in which magnetorheological and nonmagnetic elastomer layers are simply laminated on an inductor. This sensor has potentially high durability against shocks since the sensing part has only flexible elastomer layers and a printed circuit. Because the magnetorheological elastomer (MRE) contains iron powder, the distance between the MRE and the inductor determines its inductance. Therefore, the sensor can detect surface deformation around the inductor by measuring the change in its inductance. The sensor response versus applied normal force curve was obtained, and the signal-to-noise ratio (SNR) was found to be high (approximately 53 dB). We investigated the response properties with inductors having different sizes and confirmed that the SNRs were lower for the inductor with a smaller diameter. This result suggests a trade-off between the SNR and the density of the inductor layout. The results also indicate that the sensor has a point-symmetric bipolar spatial response with a large response region compared with the inductor diameter.**

Keywords—tactile sensor; force and tactile sensing; flexible sensor; magnetorheological elastomer; inductance measurement;

I. INTRODUCTION

Several types of flexible tactile sensors using elastic materials as covers have been developed [1][2][3]; however, their properties such as the durability, maintainability, sensitivity, and mechanical complexity should be further improved. We previously developed a flexible sensor whose surface contains no transducers, wiring, and solids [4][5] because these elements inside the flexible cover deteriorate the durability and maintainability. The sensor surface consists of magnetorheological and nonmagnetic elastomers while the sensor bottom has a magnet and magnetic sensor pair, which measures the magnetic flux that changes depending on the deformation of a magnetorheological elastomer (MRE) containing iron powder.

In this study, we propose another type of flexible tactile sensor whose structure was simplified to improve the durability and reduce the mechanical complexity. We removed the magnet and magnetic sensor pair and installed a printed inductor instead. Since the MRE contains iron powder, the distance between the MRE and inductor determines its inductance. Hence, the sensor can detect surface deformation around the inductor by measuring the change in its inductance. It is predicted that an inductor with a large diameter could have a large response and large spatial response region. From the sensor structure, the sensor will have a point-symmetric spatial response at the center of the inductor, which will be also the most sensitive point, i.e., a peak position in the spatial response. However, the complex deformation of the dual-layer elastomer makes it difficult to predict the sensor response.

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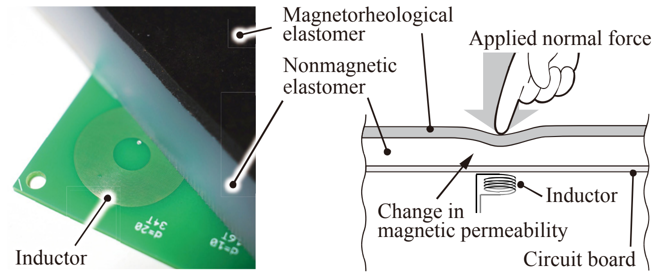

Fig. 1. Appearance of the proposed sensor and its cross-sectional schematic. An inductor is printed on a circuit board while magnetorheological and nonmagnetic base elastomers cover the board.

In order to confirm these sensor characteristics, we first investigated the response curve of the proposed sensor in terms of the applied normal force and signal-to-noise ratio (SNR) as fundamental properties of the sensor. Second, as a preliminary experiment for implementing a large-area sensor, we investigated the spatial responses with inductors having different sizes and examined the changes in the sensor response region and SNR depending on the inductor size.

II. PROPOSED SENSOR

Figure 1 shows the appearance of the proposed sensor and its cross-sectional schematic. An inductor is printed on a circuit board, which is covered by an MRE layer and a nonmagnetic base elastomer (BE) layer. The MRE contains particles with a high magnetic permeability, e.g., iron powder.

In such a structure, the MRE functions for an inductor as a magnetic core that increases the inductance. The normal force applied to the sensor surface changes the distance between the inductor and the MRE. This distance determines the inductance; thus, the sensor can measure the applied force as the inductance changes.

III. Experiment

Figure 2 shows the setup for investigating the sensor response. The proposed sensor was mounted to a three-axis robot stage (IAI Corp., TTA-C3-WA-30-25-10) with a force–torque sensor (F/T sensor; BL Autotech LTD., Mini 2/10-A) for measuring the applied force. The F/T sensor was equipped with a plastic cylindrical indenter with a diameter of 10 mm. A personal computer (PC) captured the output of the F/T sensor via a 16-bit analog-to-digital converter (CONTEC Corp., AI-1664LAX-USB). A 28-bit inductance-to-digital converter (Texas Instruments Corp., LDC1614) measured the inductance values at 100 Hz and transmitted the values to the PC.

Figure 3 illustrates the developed two-layered planar spiral inductor and the inductor parameters. The spiral inductor was printed on both surfaces of a rigid circuit board with a thickness of 1.6 mm. The trace width and the spacing between the traces were 0.1 mm. We prepared three inductors having different diameters, as listed in Table 1. The inductor diameters were set to the same diameter as the indenter (10 mm), a larger one (20 mm), and a smaller one (8 mm, the minimum diameter working in this setup). The size of the elastomer layers was determined to be 150 mm on both sides. The thickness of the MRE and BE were 10 mm and 2 mm, respectively. These layers were made of a platinum-cured silicone rubber (Smooth-On Inc., Ecoflex 00-30). Iron particles with a diameter of 50 μm were mixed with the MRE at a volume ratio of 20%.

A. Sensor Response Curve

The sensor response curve with the type A inductor was measured in accordance with the following steps [4][5]: (1) lower the indenter at a speed V = 1 mm/s until the surface of the sensor descends to depth of 6 mm, which corresponds to half of the thickness of the elastomer; (2) wait for 10 s; (3) raise the indenter to its initial position at a speed of V; (4) wait for 10 s; (5) repeat the above steps 10 times.

Figure 4 shows the sensor response versus the applied normal force. The inset shows a magnification of the initial part of the curve. The solid line and dots are the average values of the measured inductance across 10 trials, and the shaded gray regions are twice the standard deviation (2σ) of the inductance. The arrows indicate the direction of the applied force. The measured inductance increased monotonically versus the applied normal force, although the curve exhibited hysteresis. To evaluate the measurement noise, we calculated the maximum variance, and this value was 7.609×10^{-7} μH^2. In addition, the SNR of 53.85 dB was obtained by the following equation: $20\log_{10}(A_S/A_N)$ where A_S is the maximum inductance change from the initial inductance and A_N is the maximum peak-to-peak inductance under no load. The small 2σ region compared with the sensor range also indicates the high repeatability of the inductance across 10 trials.

B. Spatial Response Properties

The spatial response should be investigated to determine a spatial layout of inductors for large-area implementation. An inductor with a small diameter allows a spatially massive implementation; however, miniaturization of the inductor could lower the sensitivity and SNR. To investigate the relationship between the sensor response and the diameter of the inductor, we used three inductors having different sizes, as listed in Table 1. The sensor responses were measured using the same equipment. The indenter applied a force to the sensor surface at two-dimensional grid points in 1 mm steps. At each contact point, a vertical deformation of 6 mm was applied.

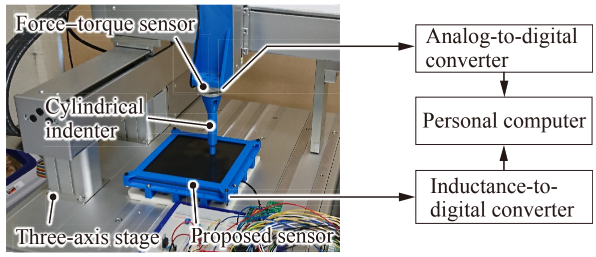

Fig. 2. Experimental setup for measuring the sensor response curves. A normal force was applied to the sensor surface by a three-axis robot stage with a cylindrical indenter. A personal computer captured the inductance and the outputs of a force–torque sensor via an inductance-to-digital converter and analog-to-digital converter.

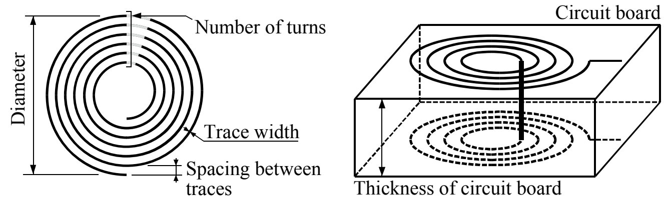

Fig. 3. Inductor parameters of a two-layer planar spiral inductor printed on both surface of a rigid circuit board.

TABLE I. CHARACTERISTICS OF THE PREPARED INDUCTORS

Type	Diameter [mm]	Number of turns	Initial inductance [μH]
A	20	32	51.3721
B	10	16	5.26445
C	8	14	2.73450

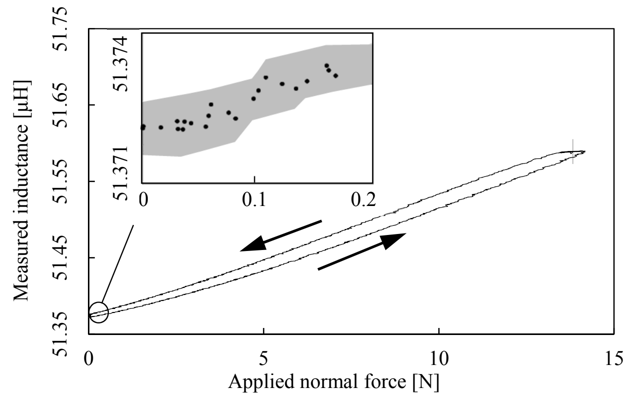

Fig. 4. Measured sensor response curves versus the applied normal force across 10 trials. The inset shows a magnification of the initial part of the curve. The solid line and dots indicate the mean value of the inductance, and the arrows depict the direction of the applied normal force. The shaded region indicates twice the standard deviation (2σ) of the inductance.

Figure 5 shows the measured spatial response with the type A inductor, whose center was the coordinate origin. The colors indicate the different values of the inductance from its initial value. The response shape was bipolar whereas the one for conventional sensors is generally Gaussian-like. We describe such sensor response with three sensor parameters (i.e., the positive peak value and the average diameters of the positive and negative regions), because the measured bipolar response was almost point-symmetric. Table 2 summarizes these measured sensor parameters for three different inductors. The smaller inductors show a smaller variation in the inductance and SNRs; in contrast, the positive and negative response regions did not significantly change in accordance with the inductor diameter.

IV. Discussion

The monotonic response of the sensor indicates that the proposed sensor can measure the applied normal force by using only the inductor as a sensing transducer. Since the inductor can be easily implemented by the traces of a circuit board, the sensor can be fabricated at a lower cost compared with our previously proposed sensor using a magnetic sensor and magnet [5]. The advantage is that a circuit board itself becomes the transducer without specific technologies.

The second experiments revealed that the spatial shape of the response was point-symmetric and bipolar. However, there was a slight distortion in the point-symmetric response for the negative response region. This distortion could be caused by the slightly nonuniform distribution of the iron powder in the handmade MRE layer due to the high sensitivity of the proposed sensor. The results also demonstrate that a negative response occurs when the sensor surface is pushed down at a certain distance from the inductor. This negative response can be explained by the following two mechanisms. 1) MRE stretching above the inductor decreases the permeability; thus, this lowers the inductance, which causes the negative response. Such MRE stretching can occur when the MRE is pushed down at some surface point because the MRE is stretched to the side and thinned. 2) BE bulging occurs around the inductor, in which the distance between the MRE and the inductor is extended by the BE, thereby causing the negative response. Such bulging can occur around the edge of the pushed region because the elastomer layers of the sensor are made of an incompressible material. Further analyses, e.g., observation of surface bulging, are required to conclude which mechanism causes the negative response.

The bipolar response could be useful for detecting contact regions. In general, tactile sensor responses contain no information about the contact points, e.g., it is difficult to discriminate between a small force applied near the sensor and a large force applied far from the sensor. In contrast, the negative response of the proposed sensor indicates that the contact point is a certain distance from the inductor. Thus, the proposed sensor could express the information of a contact point, which could help to detect contact regions.

Table 2 indicates that small inductor has small inductance changes, and the SNR gradually decreased with the diameter. These results suggest a trade-off between the SNR and the density of the inductor layout. On the other hand, the diameters of the positive and negative response regions were larger than the inductor diameter. This is because the elastomer surface near the inductor smoothly deforms even though a contact force is applied to a region far from the inductor. Such a large response region can be utilized for a superresolution method [6] that can enhance the spatial resolution, even with a spatially sparse layout of the inductor. In future works, this method will be employed to balance the SNR and the spatial resolution.

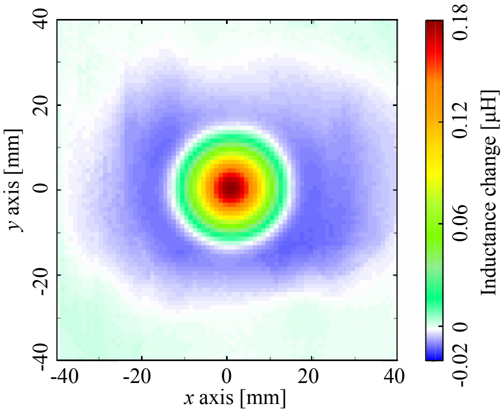

Fig. 5. Spatial response of the sensor with a type A inductor. The color indicates that the inductance changed from its initial value.

TABLE II. Summary of the Measured Responses

Type	Positive peak [μH]	Diameter of positive response [mm]	Diameter of negative response [mm]	Signal-to-noise ratio [dB]
A	0.184721	25	68	53.85
B	0.010937	24	68	46.80
C	0.004181	22	68	41.80

V. Conclusion

This paper proposed a flexible tactile sensor based on inductance measurement. The sensor can measure the applied normal force with low noise (an SNR of ~53 dB), even though the sensor structure is very simple and easy to fabricate. We investigated the sensor response properties (i.e., the SNR) and spatial response, which has a bipolar shape. We conclude that the proposed sensor has a trade-off between the diameter of the sensing inductor and its SNR.

We will try to mount such inductors onto a flexible printed circuit board for implementing the sensor onto a complex surface such as robot skin. In other future work, the three-axis forces will be obtained by improving the sensor structure.

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