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Bioinspired Piezoresistive Acceleration Sensor Using Artificial Filiform Sensillum Structure

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Hairlike structures can be found in many living things, and are considered to be the fundamental sensing structure, especially for insects. In this paper, we present a bioinspired hairlike acceleration sensor using an artificial filiform sensillum structure. The hairlike acceleration sensor is fabricated using a rigid metal rod attached to a thin piezoresistive membrane. When external acceleration is applied to the rod, the torque generates the rotational angle, thus resulting in the deflection of the membrane. The noise equivalent input acceleration resolution, the input acceleration range, and the sensitivity of the fabricated sensor are 86 mg, ±5 g, and 0.576 mV/g, respectively.

1. Introduction

Hairlike structures can be found in many living things: insect's filiform sensillum,(1,2) fish's neuromast,(3) spider's hair,(4) and human's ear.(5) The biggest similarity among these hairlike structures is that they sense the displacement or movement of the fluid surrounding them. The stiffness and flexibility of a hairlike structure determine the functionality of sensors. When hairlike structures are flexible with low frequency dynamics, the structures act as flow sensors. When hairlike structures are rigid with high frequency dynamics, the structures act as vibration sensors.

Trichoid sensilla (hair sensilla) are considered to be the fundamental sensing structure for insects.(6) There are two types of insect hair-type sensilla: thick bristles and trichobothria.(2) A typical illustration of an insect's hairlike sensor is shown in Fig. 1.

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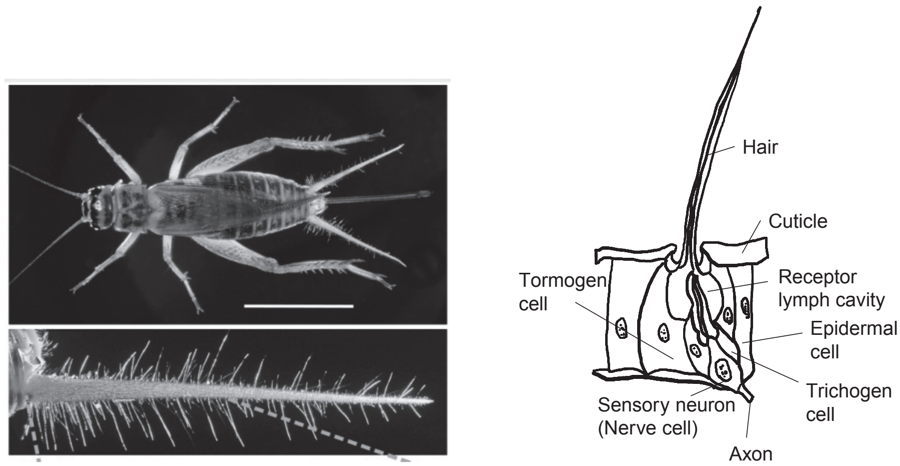


(a) (b)

Fig. 1. Filiform mechanosensory hair sensor of insects: (a) filiform mechanosensory hairs on the cerci of an *Acheta domesticus* cricket[7] and (b) typical structure of hair sensor.

The typical filiform mechanosensory hairs on the cerci of the *Acheta domesticus* cricket are shown in Fig. 1(a).[7] A magnified illustration of the hair sensor is shown in Fig. 1(b).

The hairlike sensilla are the first-order levers, which transmit the deflection of the hair to the dendrite tip. The dendrite tip consists of microtubule structures that, upon lateral deflection, would open a series of ion channels on their walls.[2] The ions will be transmitted as neuron signals to the nervous system of the insect. From the mechanical point of view, the hair structure can be modeled using a second-order system with torsional inertia, a spring, and a damper.[8–10]

Many studies on biomimetic hairlike sensors were performed. The hairlike structures are used extensively in many living things to achieve merged functionalities including flow sensing, temperature sensing, vibration sensing, and so on. The biomimetic sensors based on the hairlike structures offer possibilities for multifunctional miniaturized sensor platforms, because many mechanical and chemical sensing functions can be integrated to the hairlike structures.

Biomimetic hair sensors for air flow sensing[8,11,12] and acoustic sensing[13] were reported. Biomimetic hair sensors based on cricket hair were also reported.[14,15] Biomimetic hair-based structures had been exploited earlier with applications in both actuation and sensing,[16,17] but seldom for inertial measurement. Previously, a hairlike accelerometer was investigated;[18] however, its response to external acceleration was not demonstrated.

In this paper, we present a bioinspired hairlike acceleration sensor using an artificial filiform sensillum structure. The design, fabrication, and experimental evaluation of the bioinspired hairlike sensor will be discussed.

2. Design and Modelling

The concept of the presented artificial hairlike acceleration sensor is shown in Fig. 2. A rigid metal rod is attached to a thin membrane. When external acceleration is applied to the rod, the torque generates the rotational angle, thus resulting in the deflection of the membrane. The resistances of Wheatstone bridge piezoresistors are changed owing to the deflection of the membrane. The applied acceleration can be sensed by measuring the voltage between the output nodes of the bridge resistors. The fabrication process flow of the hairlike acceleration sensor is shown in Fig. 3. After preparing the piezoresistive membrane sensor [Fig. 3(a)], adhesive glue is dispensed on the membrane sensor [Fig. 3(b)], and then the cylindrical metal rod is attached using the adhesive glue to the membrane sensor [Fig. 3(c)].

The hairlike acceleration sensor can be modeled as a second-order rotational mechanical system with the moment of inertia J, rotational stiffness S, and rotational damping R, as shown in Fig. 4. The rotational angle due to the external acceleration is written as

$$\theta(\omega) = \frac{T_a}{S - J\omega^2 + j\omega R}, \quad (1)$$

where $\theta(\omega)$ is the rotational angle and T_a is the amplitude of the torque applied to the hair structure. The radius and length of the metal rod are 0.5 and 14 mm, respectively.

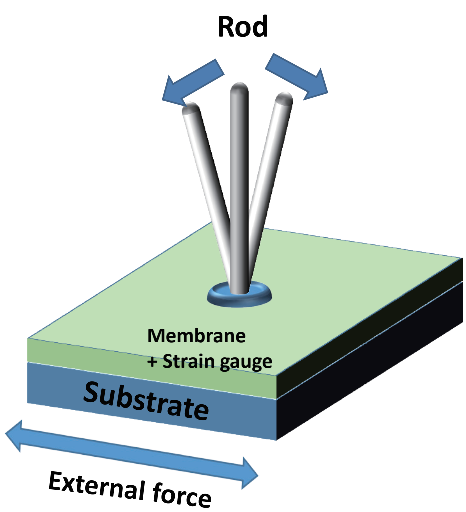


Fig. 2. (Color online) Concept of artificial hair-like acceleration sensor.

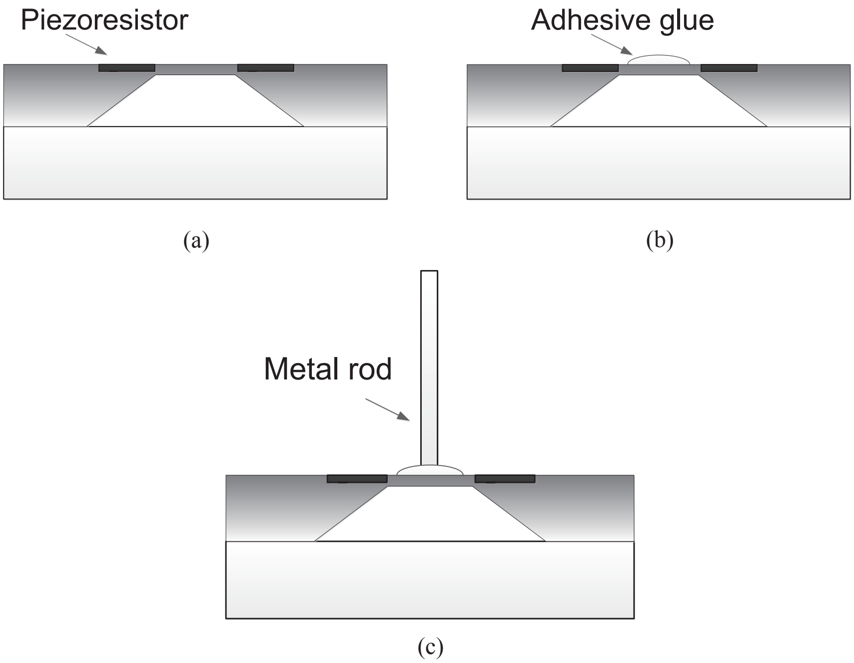


Fig. 3. Fabrication process flow of hairlike acceleration sensor: (a) piezoresistive membrane sensor preparation, (b) adhesive glue dispense, and (c) metal rod attachment.

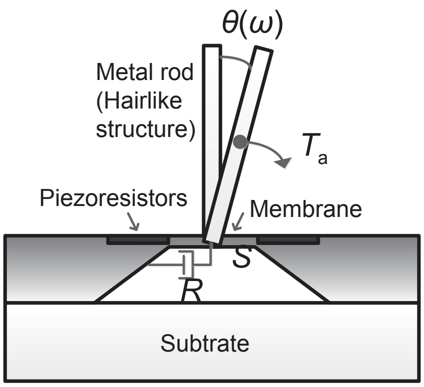


Fig. 4. Mechanical modeling of hair-like acceleration sensor.

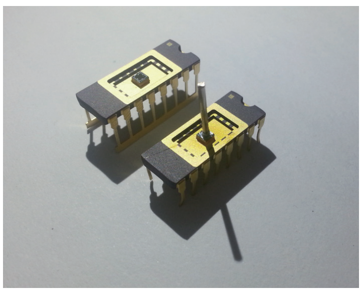
The deflection of the membrane is measured using the piezoresistive membrane-type transducer. The transducer utilizes the Wheatstone bridge configuration and is implemented using the anodically bonded glass to a chemically etched silicon diaphragm. The typical impedance and sensitivity of the bridge are 5 kΩ and 0.35 mV/psi, respectively.

3. Experimental Results

The fabricated hairlike acceleration sensor is shown in Fig. 5. The piezoresistive membrane sensor is wirebonded to a 16-pin ceramic package (left), and the metal rod is attached to the membrane using adhesive glue.

For performance evaluation, the fabricated sensor and the reference accelerometer, B&K8305, are mounted on the vibration exciter, as shown in Fig. 6. The sensitivity of the reference accelerometer is 1.25 pC/g, and the deviation of the sensitivity from 0.2 to 3750 Hz is less than 1%. The excitation source from a function generator is amplified using the power amplifier, and the power amplifier shakes the vibration exciter. The output signals of the fabricated sensor and the reference accelerometer are measured using the oscilloscope and the spectrum analyzer.

The measurement results are shown in Fig. 7. The output spectrum and the time domain outputs with the input sinusoidal acceleration of 40 Hz, 5 g are shown in Figs. 7(a) and 7(b), respectively. The signal level, noise level, and signal-to-noise ratio are measured to be −50.7, −92, and 41.3 dB, respectively. The noise equivalent input acceleration resolution is measured to be 86 mg. The time domain outputs of the fabricated sensor and reference accelerometer are shown in Fig. 7(b). The fabricated sensor shows almost the same output as the reference accelerometer. The input-output characteristics at 40 Hz input acceleration are shown in Fig. 7(c). The input acceleration range, the sensitivity of the fabricated sensor, and the square of the correlation coefficient, R^2, are ±5 g, 0.576 mV/g, and 0.9997, respectively.



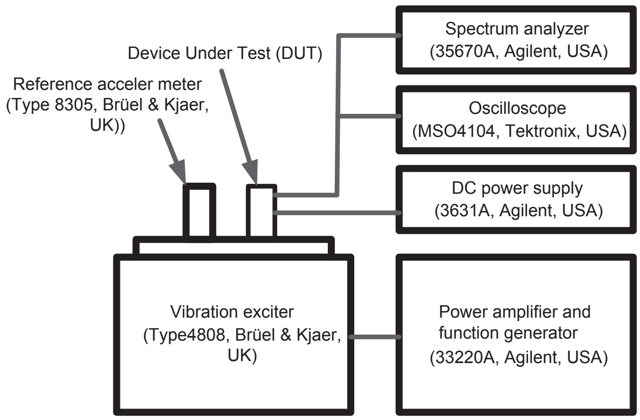


Fig. 5 (left). (Color online) Fabricated hair-like acceleration sensor.
Fig. 6 (right). Setup for performance evaluation.

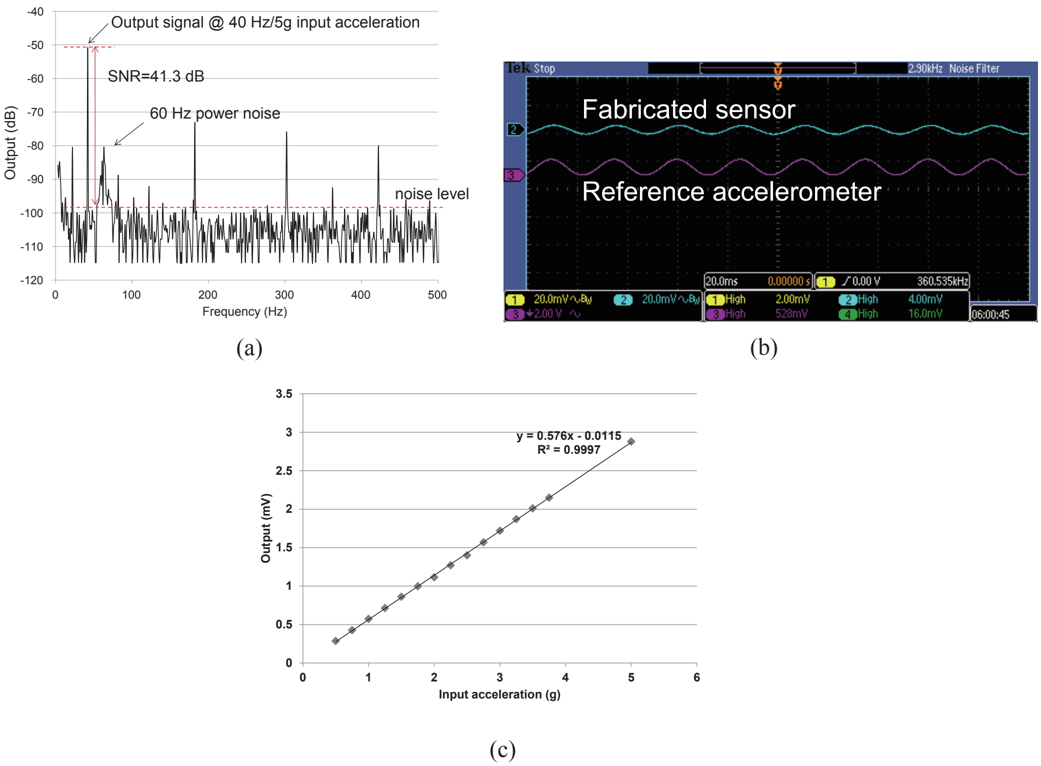


Fig. 7. (Color online) Measurement results: (a) output spectrum at 40 Hz, 5 g input acceleration, (b) time domain output of fabricated sensor and reference accelerometer, and (c) input-output characteristics at 40 Hz input acceleration.

4. Conclusions

In this paper, we present a bioinspired hairlike acceleration sensor using an artificial filiform sensillum structure. The hairlike acceleration sensor is fabricated using a rigid metal rod attached to a thin piezoresistive membrane. When external acceleration is applied to the rod, the torque generates the rotational angle, thus resulting in the deflection of the membrane. The resistances of Wheatstone bridge piezoresistors are changed owing to the deflection of the membrane. The applied acceleration can be sensed by measuring the voltage between the output nodes of the bridge resistors. The noise equivalent input acceleration resolution, input acceleration range, and the sensitivity of the fabricated sensor are 86 mg, ±5 g, and 0.576 mV/g, respectively. The fabricated sensor prototype shows a high linearity. The resolution can be further improved with a low-noise analog front end.

Acknowledgements

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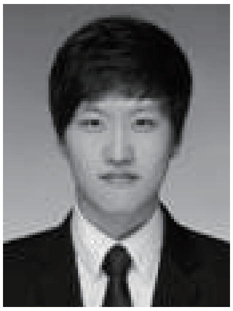

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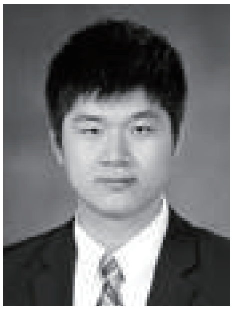

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