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Exploitation of aeroelastic effects for drift reduction, in an all-polymer air flow sensor

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ABSTRACT

This paper presents a vibration amplitude measurement method that greatly reduces the effects of baseline resistance drift in an all-polymer piezoresistive flow sensor or microtuft. The sensor fabrication is based on flexible printed circuit board (flex-PCB) technology to enable the potential for low-cost and scalable manufacture. Drift reduction is accomplished by discriminating the flow-induced vibration ('*flutter*') amplitude of the microtuft-based sensor as a function of flow velocity. Flutter peak-to-peak amplitude is measured using a microcontroller-based custom readout circuit. The fabricated sensor with the readout circuitry demonstrated a drift error of 2.8 mV/h, which corresponds to a flow-referenced drift error of 0.2 m/s of wind velocity per hour. The sensor has a sensitivity of 14.5 mV/(m/s) with less than 1% non-linearity over the velocity range of 5–16 m/s. The proposed vibration amplitude measurement method is also applied to a sensor array with a modified structure and a reduced dimension, which demonstrated a sensitivity of 13.2 mV/(m/s) with a flow-referenced drift error of 0.03 m/s of wind velocity per hour.

1. Introduction

Flow sensors are of great interest to applications such as process control, metrology [1] and flight control involving unmanned aerial vehicles (UAVs) [2]. Among different types of flow sensors, bio-mimetic flow sensors mimicking fish hairs and cricket filiform hairs are the subject of much research. Typically, the nature-inspired bio-mimetic flow sensor has a three-dimensional (3D) out-of-plane cantilever with a sensing element to detect the air flow around it. Advances in microelectronics and micromachining technologies enable the fabrication of MEMS bio-mimetic flow sensors with good performance, based on silicon and/or polymer micromachining technologies. A bio-mimetic silicon-based capacitive flow sensor array with high-aspect ratio SU-8 microtufts was recently reported and demonstrated sensitivities of the order of 1 mm/s [3]. A silicon-based piezoresistive air flow sensor with SU-8 cilia has also been reported [4]. Although these approaches demonstrate good sensitivity, they require relatively complex fabrication sequences. Further, being silicon-based, it is challenging to cover large areas of vehicle wings with these flow sensors in a cost-effective manner. Polymer-based devices may overcome these challenges, at the expense of specific performance, and further exhibit good flexibility and scalability. These features are extremely important in applications requiring distributed sensor arrays in large and uneven surfaces such as UAV applications [2]. We have already demonstrated a 3D out-of-plane micromachined flexible piezoresistive all-polymer flow sensor array based on low-cost flexible-PCB technologies [5]. The piezoresistive all-polymer sensor provided a large resistance change without complex sensing circuitry for compensation and amplification of the sensor output. However, a significant resistance drift in the sensor output was observed [5], potentially limiting the applicability of the sensor.

In this paper, we propose a reduced-drift sensor measurement method that exploits aeroelastic '*flutter*' effects [6,7] and demonstrate its application to a flex-PCB-based all-polymer flow sensor. The sensor comprises a 3D out-of-plane polymer cantilever member that can protrude into an embedding flow, and a piezoresistive readout element in the polymer member. Positioning the flexible polymer sensor in a flow results in a static deflection of the sensor, as well as a vibratory sensor flutter caused by aeroelastic effects. The amplitude of the flutter depends on the surrounding flow velocity and is empirically characterized. Microcontroller-based circuitry is used to extract the peak-to-peak vibration amplitude from the sensor output. Since the sensor output is now primarily dependent on the vibration-induced resistance change, as opposed to static deflection, the sensor output is relatively insensitive to DC resistance drift.

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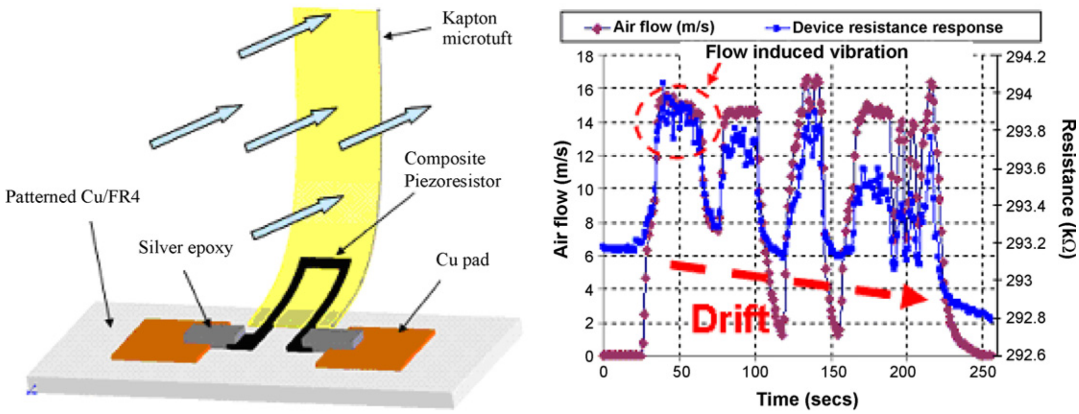

Fig. 1. Flex-PCB-based bio-mimetic air flow sensor and sensor output [5].

2. Principle of flow-induced vibration and its application to all-polymer flow sensor

Fig. 1 shows an all polymer flow sensor and its output response to air flows, previously reported by our research group [5]. The sensor comprises a 3D out-of-plane Kapton microtuft (length: 1.5 mm, width: 0.4 mm, thickness: 7.6 μm) and a carbon-black-loaded polydimethylsiloxane (PDMS) piezoresistor. Air flow across the microtuft causes deformation of the microtuft. The deformation, which is proportional to the distributed force on the microtuft, in turn, induces the strain in the piezoresistor [8]. The resistance of the piezoresistor therefore changes as a function of the strain induced by the applied wind velocity [8]. The relation between the resistance change and the strain is given by:

$$\frac{\Delta R}{R} = G\varepsilon,$$

where G (around 7.3) is the gauge factor of the piezoresistor, and ε is the strain in the piezoresistor [5].

We demonstrated the scalability and flexibility of the all-polymer flow sensor array, while addressing the sensor output resistance drift. This drift may be caused by various factors, including temperature variations and material property changes in elastomeric piezoresistive materials [5,9,10]. However, by closely observing the sensor output response, a fluctuating resistance is seen. This fluctuation is caused by flow-induced vibration of the cantilever beam, i.e., a '*fluttering*' or '*galloping*' effect, which refers to self-excited vibration of a bluff object induced by aerodynamic lift and drag forces [6,11,12]. The self-excited vibration is a result of negative damping due to aerodynamic lift forces acting in the direction of the motion of the bluff object [11,12]. Theoretically, the vibration amplitude of the fluctuation is proportional to the wind velocity [12]. In order to verify this phenomenon, the resistance change in the previously reported all-polymer flow sensor is empirically characterized with varying wind velocity using a digital multimeter (Keithley). In order to facilitate the vibration of the microtuft [6], the sensor which is used for the evaluation has a longer cantilever-like microtuft, which measures 3.5 mm long, 0.6 mm wide and 7.6 μm thick. As shown in Fig. 2, the amplitude of the vibration-induced resistance increases as the wind velocity increases. This confirms the validity of the proposed vibration amplitude measurement method.

Based on this observation, the sensor readout scheme of Fig. 3 is proposed. As shown in Fig. 3, the amplitude of changes in the vibration-induced resistance increases when the wind velocity becomes larger, independent of the absolute value of resistance. Therefore, the baseline drift can be reduced by filtering out low frequency signals from the sensor output, followed by signal pro-

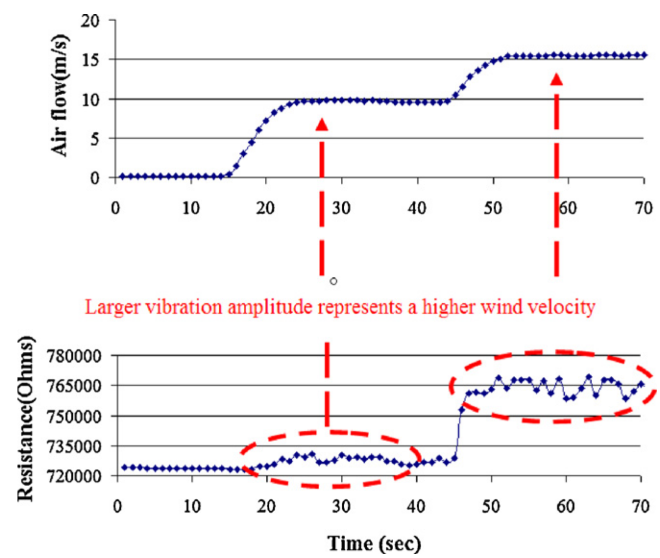

Fig. 2. Sensor output of the polymer-based flow sensor using direct resistance measurement with different wind velocities applied: wind velocity profile (upper) and sensor output (lower). Note that the vibration amplitude increases as the wind velocity increases.

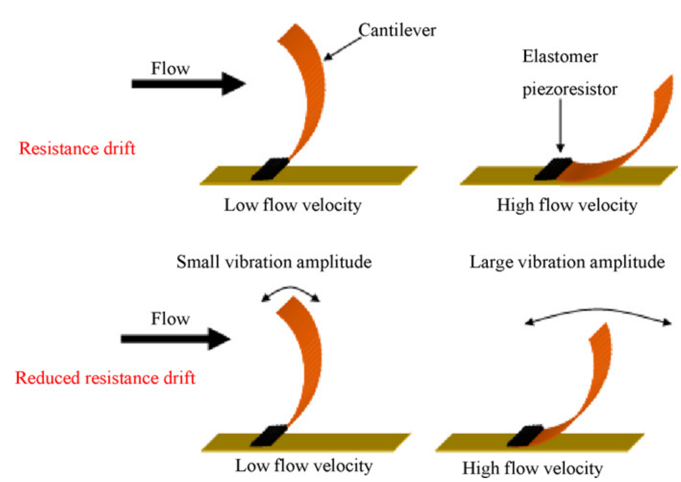

Fig. 3. (Top) Conventional piezoresistive-based airflow sensor. (Bottom) Concept of the proposed vibration amplitude measurement method using flow-induced vibration.