# 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 flow-referenced drift error of 0.2m/s of wind velocity per hour, a substantial improvement over previous sensors of this type using standard piezoresistive readout. The sensor has a sensitivity of 14.5mV/(m/s) with less than 1% non-linearity over the velocity range 5-16m/s.

## KEYWORDS

Vibration-amplitude measurement, all-polymer air-flow sensor, flow-induced vibration, drift reduction, flex-PCB

## INTRODUCTION

Advances in microelectronics and micromachining technologies make flow sensors more attractive not only in traditional process control and metrology [1] but also in flight control applications involving unmanned aerial vehicles [2]. MEMS-enabled flow sensors are therefore subjects of much research activity. A bio-mimetic silicon-based capacitive flow sensor array with high-aspect ratio SU-8 microtufts was recently reported with sensitivities on the order of 1mm/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 difficult to cover large areas of vehicle wings with these sensors without tiling or similar approaches. A flexible PCB-based hot-wire flow sensor system, which indirectly measures flow velocity, has been successfully demonstrated and applied to non-planar structures such as an unmanned aerial vehicles (UAV) [2]. We have also demonstrated an out-of-plane micromachined flexible piezoresistive all-polymer flow sensor array based on low-cost flex-PCB technologies [5]. Although the piezoresistive all-polymer sensor provided a large output without complex sensing circuitry for compensation and amplification of the sensor output, a significant resistance drift in the sensor output was observed [5-7], potentially limiting the applicability of the sensor.

In this paper, we report a reduced-drift sensor measurement method that exploits aeroelastic effects [8, 9] and demonstrate its application to a flex-PCB-based all-polymer flow sensor. The sensor comprises a polymer member that can protrude into an embedding flow, and piezoresistive readout of the position of the polymer member. Positioning the flexible polymer sensor in an embedding 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 magnitude of the surrounding flow. This flow-induced vibration is empirically characterized for measurement of flow magnitude. 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, the sensor output is relatively insensitive to DC resistance drift.

## FLOW-INDUCED-VIBRATION IN ALL-POLYMER FLOW SENSOR

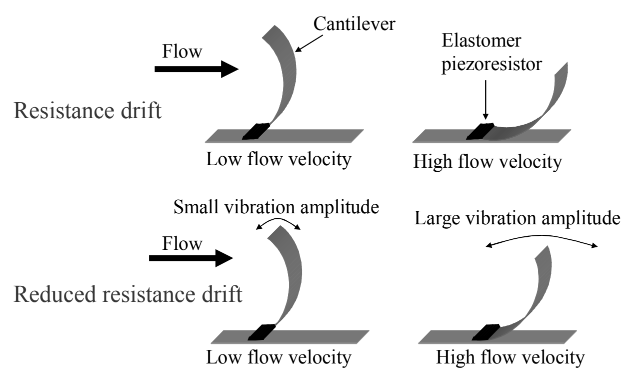


***Figure 1:*** *(Top) Conventional piezoresistive-based airflow sensor. (Bottom) Concept of the proposed vibration-amplitude measurement method using flow-induced vibration.*

Figure 1 shows a comparison between the conventional flow velocity measurement method and the proposed vibration-amplitude measurement method. In the conventional measurement method, air flow across the microtuft causes deformation of the microtuft. The deformation, in turn, induces a strain in the piezoresistor on the microtuft. The resistance changes as a function of the strain induced by the applied wind velocity [10]. However, this direct measurement method is likely to be vulnerable to resistance drift. This drift can be due to multiple causes, including temperature variations and material property changes in elastomeric piezoelectric materials (especially in the case of an all-polymer flow sensor) [5-7]. Measurements of all-polymer sensors fabricated in this work show significant baseline drift (Figure 2), but also show the effect of aeroelastic vibration due to the embedding flow.

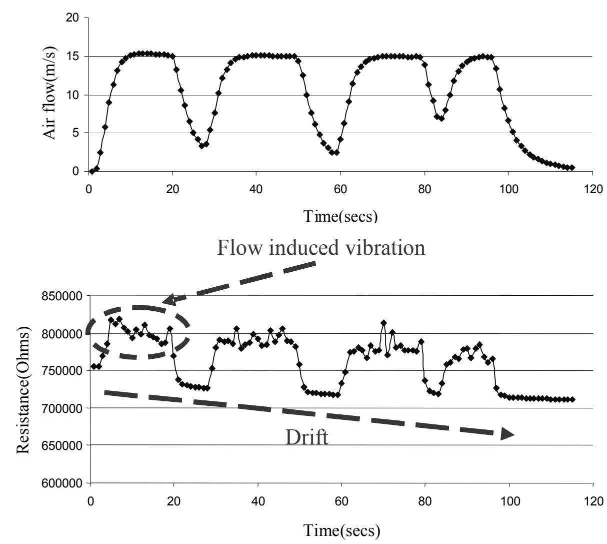


***Figure 2:*** *Sensor output of the all-polymer flow sensor using direct resistance measurement: wind velocity profile (upper) and sensor output (lower). Note that the output signal also contains information of flow-induced vibration.*

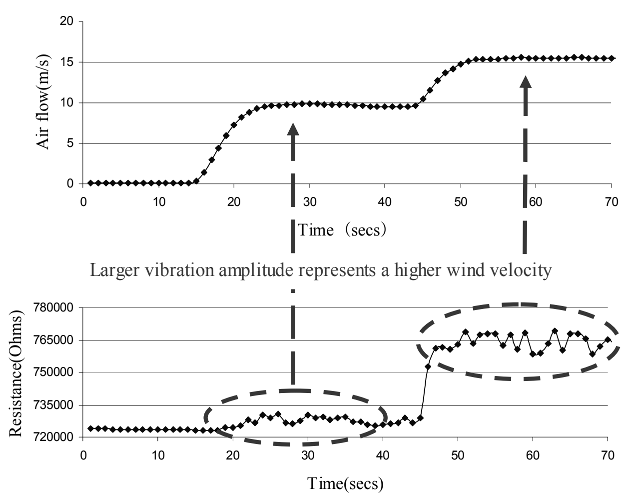


***Figure 3:*** *Sensor output of the polymer-based flow sensor using direct resistance measurement with different wind velocities applied: wind velocity profile (upper) and sensor output (lower). Note that the vibration amplitude increases as the wind velocity increases.*

The flow sensor microtuft experiences vibration when it is exposed to the air flow [8, 9]. The vibration induces alternating strain changes in the piezoresistor on the microtuft, which subsequently results in a vibration-modulated resistance change of the piezoresistor. In order to confirm this phenomenon, the changes in the resistance, due to the flow-induced vibration in the all-polymer air flow sensor are investigated with varying levels of applied wind velocity. As shown in Figure 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 processing for peak-to-peak amplitude calculation, assuming that baseline drift is slow compared to the time scale of the flow-induced sensor vibration.

## FLOW SENSOR FABRICATION

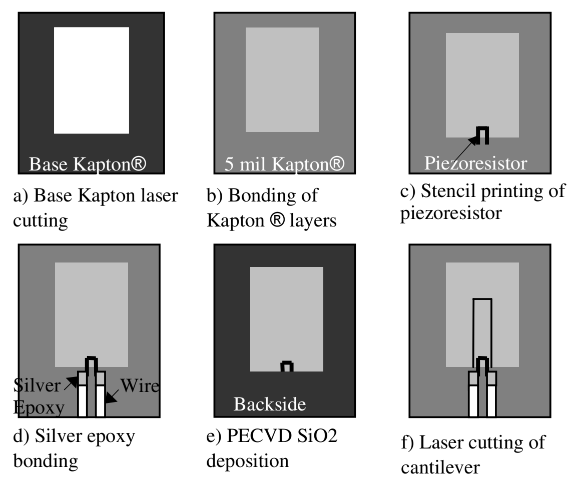


***Figure 4:*** *Fabrication process sequence*

The flow sensor used in the experiment is fabricated using the previously reported flex-PCB-based process [5], incorporating laser-micromached Kapton® (Dupont) and a stencil–printed piezoresistive elastomer (Elastosil® LR3162, Wacker Chemie AG). A 125µm thick Kapton film is laser machined using a $CO_2$ laser (Gravograph Newhermes) and laminated with a 7.6µm thick Kapton film to form the base and device layers, respectively (Figure 4(a), (b)). A piezoresistor is then stencil-printed on the device Kapton layer and cured at 130℃ for 2 hours (Figure 4(c)). Interconnections between the piezoresistor and the external circuitry are achieved using silver epoxy (Figure 4(d)), followed by plasma enhanced chemical vapor deposition (PECVD) of $SiO_2$ on the opposite side to the piezoresistor (Figure 4(e)). Finally, the out-of-plane microtuft is realized by a stress-gradient induced curvature by plasma enhanced chemical vapor deposition (PECVD) of silicon dioxide film deposited on the device Kapton and subsequent release by excimer laser(248nm, Lambda Physik) cutting of the in-plane cantilevers (Figure 4(f)).

Figure 5 shows the fabricated all-polymer piezoresistive flow sensor. The cantilever-like microtuft is 3.5mm long, 0.6mm wide, and 8.2μm thick. The elastomeric piezoresistor is 110μm wide, 1.9mm long, and has an average thickness of 13μm. The measured resistance of the piezoresistor in its initial undeformed state is approximately 700kΩ .

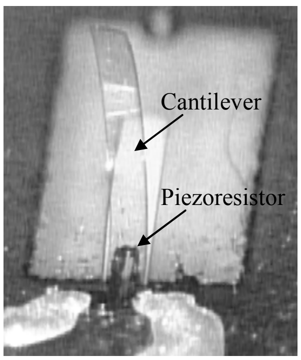


***Figure 5:*** *Fabricated all-polymer flow sensor*

## SENSOR READOUT CIRCUIT

A block diagram of the readout circuit for the all-polymer piezoresistive sensor is shown in Figure 6. The piezoresistor is connected to a single-element-varying, voltage-driven Wheatstone bridge composed of three 700kΩ non-variable resistors and the all-polymer piezoresistive sensor as the varying element. The output of the bridge is fed to an instrumentation amplifier (INA122, Texas Instruments) with a gain of 6. In order to extract the peak-to-peak vibration amplitude of the sensor output and convert the resistive output to a voltage output, a microcontroller (MSP430F2012, Texas Instruments) with built-in 10-bit successive approximation (SAR) analog-to-digital converter (ADC) is used for data acquisition and signal processing. A light-emitting-diode (LED) is optionally connected to demonstrate real-time visualization of the measured wind velocity.

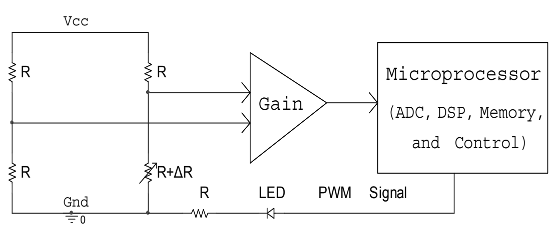


***Figure 6:*** *Schematic illustration of sensor readout circuit*

The microcontroller samples the amplifier output at a sampling rate of 500Hz and stores 20 sampled data points in its internal memory. The peak-to-peak vibration amplitude of the output voltage is derived from this data set by determining the difference between the maximum and minimum values in the stored data. Seven of these peak-to-peak measurements are then averaged to produce the final output of the sensor read-out circuitry, which indicates the flow-induced vibration amplitude. Finally, the microcontroller generates pulse-width-modulated (PWM) signals for the LED, in correspondence with the extracted peak-to-peak vibration amplitudes, resulting in an LED brightness which is proportional to the applied wind velocity.

## WIND TUNNEL TESTING

The fabricated all-polymer flow sensor with the readout circuitry is tested in a bench top wind tunnel (ST 180 Scantek 2000), as shown in Figure 7. A thermal anemometer (Omega FMA-605-I) with a measurement range of 0-25m/s is used as a reference sensor for measuring the mean free stream wind velocity. The fabricated all-polymer flow sensor is connected to the above-described readout circuitry.

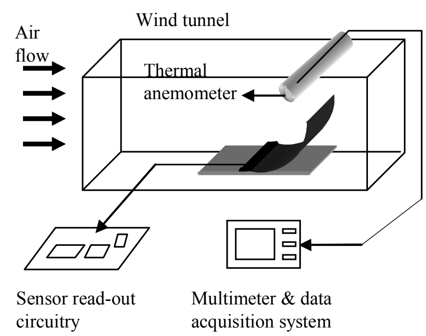


***Figure 7:*** *Schematic illustration of sensor testing*

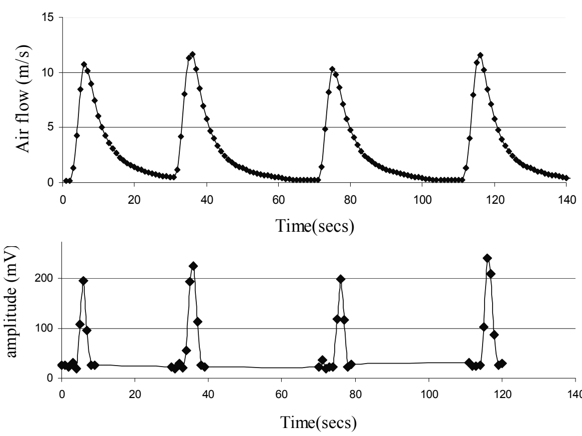


***Figure 8:*** *Output of the all-polymer flow sensor from the proposed vibration-amplitude measurement method: Reference wind velocity (upper) and the measured sensor response (lower).*

Figure 8 shows the sensor response and the reference sensor output as the airflow is repetitively cycled between 0m/s and 12m/s. The results show that the baseline drift which is typically observed in conventional measurement method shown in Figure 2 has been greatly reduced. The maximum output of the sensor output is 225mV when the wind velocity is 12m/s. The sensor exhibits a thresholding effect and is sensitive to velocities in the range of 5-12m/s; this range is adjustable by changing the geometry of the sensor.

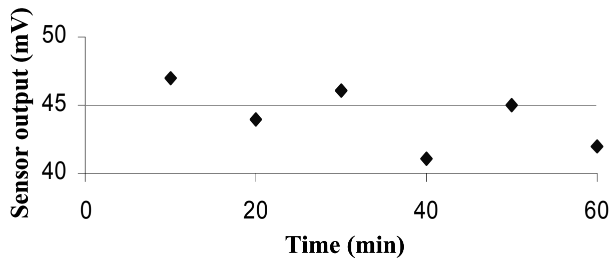


***Figure 9:*** *Zero-input drift of the all-polymer flow sensor as a function of time using the reduced-drift measurement approach.*

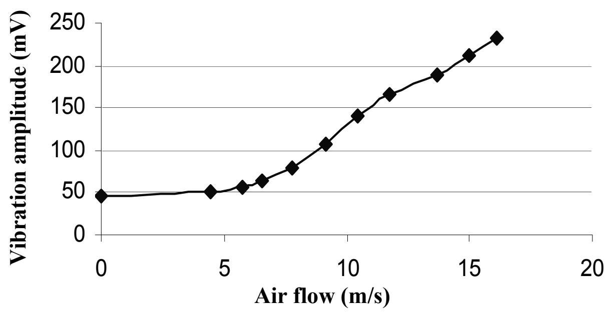


***Figure 10:*** *Sensor output as a function of the wind velocity, acquired by the vibration amplitude measurement method*

The sensor is also tested without applied wind velocity in order to characterize the new value of reduced sensor drift, as shown in Figure 9. The standard deviation of the sensor output is 2.8mV from one-hour data acquisition, which corresponds to a flow-referenced drift error of 0.2m/s of wind velocity per hour.

Figure 10 shows the measured vibration amplitude of the all-polymer flow sensor when the wind velocity varies between zero and 16m/s. With an amplifier gain of 6 and a Wheatstone driving voltage of 5.12V, the sensitivity of the sensor measures 14.5mV/(m/s), with non-linearity of 5% over the range 0-16m/s wind velocity, and 1% over the range 5-16m/s wind velocity, respectively.

## CONCLUSION

This paper demonstrates a peak-to-peak vibration amplitude measurement method for wind velocity sensing as a baseline resistance drift-reduction method. The proposed method exploits flow-induced vibration and has been validated by the wind tunnel test of a flex-PCB based all-polymer piezoresistive air flow sensor. The measured characteristics demonstrate a significant reduction of output drift compared to the conventional direct measurement method. The measurement method is promising since it greatly reduces the drift caused by the intrinsic property of the materials as well as environmental changes.


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