Design and Characterization of a Novel Bio-inspired Hair Flow Sensor Based on Resonant Sensing

X Guo 1,2, B Yang 1,2, Q H Wang 1,2, C F Lu 1,2, and D Hu 1

1 School of Instrument Science & Engineering, Southeast University, Nanjing 210096, China
2 Key Laboratory of Micro-Inertial Instrument and Advanced Navigation Technology, Ministry of Education, Nanjing 210096, China

Correspondence: 101011019@seu.edu.cn

Abstract. Flow sensors inspired by the natural hair sensing mechanism have great prospect in the research of micro-autonomous system and technology (MAST) for the three-dimensional structure characteristics with high spatial and quality utilization. A novel bio-inspired hair flow sensor (BHFS) based on resonant sensing with a unique asymmetric design is presented in this paper. A hair transducer and a signal detector which is constituted of a two-stage micro-leverage mechanism and two symmetrical resonators (double ended tuning fork, DETF) are adopted to realize the high sensitivity to air flow. The sensitivity of the proposed BHFS is improved significantly than the published ones due to the high sensitivity of resonators and the higher amplification factor possessed by the two-stage micro-leverage mechanism. The standard deep dry silicon on glass (DDSOG) process is chosen to fabricate the proposed BHFS. The experiment result demonstrates that the fabricated BHFS has a mechanical sensitivity of 5.26 Hz/(m/s)^2 at a resonant frequency of 22 kHz with the hair height of 6 mm.

1. Introduction

Nature has gradually become a significant source of inspiration for engineering since it has evolved to make the optimal design. Therefore, many innovative solutions can be inspired by imitating natural engineering designs. A large quantity of natural creatures such as arthropods, aquatics and mammals are equipped with extraordinary sensitive and robust hair structures to help them assess the surrounding environment parameters and rapidly changing inertia parameters for their survival and locomotion [1]. The bio-inspired hair flow sensor (BHFS) based on natural hair structures is a potential biomimetic flow sensor combining the micro-electro-mechanical system (MEMS) technology.

Based on the sensing principle, a few published bio-inspired hair flow sensors can be classified into several categories, namely, piezo-resistive, capacitive, piezo-electric and optical sensors [2]. Hair flow sensors based on the lateral line perception system of aquatics and piezo-resistive detection have been published in the literature [3]. Reference [4] presented a BHFS with a capacitance signal detector and a micro-hydraulic amplification mechanism. A hair flow sensor based on piezo-electric transductor with an array of micro-pillars was developed for monitoring turbulent flow [5]. Reference [6] developed a BHFS adopted a photo-electronic sensing mechanism for dual-axis air flow and dynamic pressure detecting.
Compared with the traditional sensing principles, there is a great potential for improving the sensitivity of BHFS based on the principle of resonant sensing since the resonators are highly sensitive, highly stable, and able to output quasi-digital signal. In this paper, a novel bio-inspired hair flow sensor based on resonant sensing with a unique asymmetric design is presented to achieve a better performance on the sensitivity, structural stability and durability.

2. Device Description and Simulation analysis

2.1. Device design
The structure scheme of proposed bio-inspired hair sensor is shown in Figure 1. The device adopts a unique asymmetric design. A hair transducer is attached to a planar silicon micro-detector which is constituted of a two-stage micro-leverage mechanism and two symmetrical resonators. Then the signal detector is bonded to a Pyrex glass wafer by bonding anchors. A novel lever pivot which is constituted of a rotational anchor and eight rotational beams is adopted to ensuring the rotational movements of main frame in the plane, and four groups of swing suppression beams are adopted to suppress structural swing of main frame for accuracy and device safety. The drag force derived from the external fluid interact with the hair transducer is amplified by the two-stage micro-leverage mechanism and applied to the resonators to induce the natural frequency drifts of resonators. Then, the input air flow velocity can be calculated by detecting the shifts of natural frequencies of resonators.

![Figure 1. Schematic of bio-inspired hair flow sensor. (a) Three layers; (b) Signal detector.](image)

2.2. Theoretical description
Hypothesize the flow velocity around the hair post is approximately constant. The drag force caused by air flow exerted on the hair post can be expressed as [7]

\[ F_j = \frac{1}{2} C_D \rho D L u^2 \]  

(1)

where \( u \) is the flow velocity, \( C_D \) and \( \rho \) are the drag coefficient and density of the specified fluid, \( D \) and \( L \) are the diameter and length of the hair post. The moment applied to the hair post can be simplified as

\[ M_j = \frac{1}{4} C_D \rho D u^2 L^2 \]  

(2)

The theoretical mechanical sensitivity of the proposed BHFS for air flow velocity measurement can be approximately expressed as

\[ S_j = \frac{df}{du^2} \approx \frac{\lambda^2 \eta A C_D \rho D L f_0}{2 E h v^3} \]  

(3)
where $\lambda$ is the attenuation coefficient of resonator, $f_0$ is the natural frequency of resonator without axial force $F$. $h$ and $w$ are the thickness and width of resonant beam, $L$ is the length of coupling combs. The frequency variation is theoretically linear with the square of flow velocity.

2.3. Simulation and Optimization

The natural frequency and natural modes of proposed BHFS can be analyzed by modal analysis. The vibration characteristics determine the response of structure to various input loads. A modal simulation is implemented by commercially available Finite Element Method (FEM) program ANSYS to determine the geometric properties. The first twelve mode frequencies are shown in Table 1 and the three effective modes are shown in Figure 2. The simulation results confirm that the effective modes and the interference modes are effectively isolated, the feasibility of structural design is verified.

| Modal | 1  | 2  | 3  | 4  | 5  | 6  |
|-------|----|----|----|----|----|----|
| Frequency (Hz) | 471 | 565 | 1364 | 1624 | 11251 | 12068 |
| Modal | 7  | 8  | 9  | 10 | 11 | 12 |
| Frequency (Hz) | 15257 | 18892 | 18905 | 19889 | 19891 | 20963 |

**Figure 2.** Effective modes of bio-inspired hair flow sensor. (a) Sensing mode; (b) Resonator working mode 1; (c) Resonator working mode 2.

A fluid-structure interaction simulation is implemented to evaluate the performance of the proposed BHFS. Figure 3 shows the simulation of structural deformation at an input air flow of 10 m/s. The sensitivities of proposed BHFS are 3.48 Hz/(m/s)$^2$ in height of 3 mm and 5.88 Hz/(m/s)$^2$ in height of 6 mm and 8.1 Hz/(m/s)$^2$ in height of 9 mm, respectively. The simulation result demonstrates that the increase of the hair height will improve the sensitivity which is consistent with the theoretical analysis since the drag force is positively related to the surface area of hair post.
3. Fabrication and Experiments

3.1. Fabrication

The standard deep dry silicon on glass (DDSOG) is chosen to fabricate the novel BHFS. As shown in Figure 4, the DDSOG process starts with a 200 µm thick monocrystalline and a 500 µm thick Pyrex glass substrate. The photoresist is patterned and etched via the deep reactive ion etching (DRIE) to define the bonding anchors. Then a Cr/Ti/Au stack layer is sputtered to define the electrode wires and pads in the Pyrex glass wafer. The silicon wafer and the Pyrex glass wafer are connected via an electrostatic anodic bonding process. A wet etching process is adopted to decrease the thickness of the silicon wafer. Subsequently, the silicon wafer is lithographically patterned and etched to release the mechanical structures via the DRIE. Finally, a micro-assembly process is adopted to install the metal hair. The optical micrograph of BHFS is shown in Figure 5. The fabricated bio-inspired hair flow sensor has a size of 5100 µm (length) × 5100 µm (width) × 100 µm (height) with a hair diameter of 1 mm and a height 6 mm.

![Figure 4. DDSOG process flow of BHFS.](image)

![Figure 5. Optical micrograph of BHFS](image)

3.2. Performance experiments

After the hair post assembly and encapsulation, the performance of BHFS was preliminarily tested. DC power supply, spectrum analyzer, digital multimeter, DC brushless fan and wind speed sensor are
used to evaluate the electromechanical characterization of the fabricated prototypes. The amplitude-frequency response curves of DETFs are obtained by the spectrum analyzer, the subsequent experiments demonstrate that the symmetrical resonators have natural resonant frequencies of 22.280 kHz and 21.960 kHz with quality factors of 40.5 and 40.7, respectively. The quality factors of two resonators are smaller than conventional ones due to the large damping coefficient in the air.

The air flow measurement can be implemented by using the anemometer to calibrate the wind speed produced by the DC brushless fan. The output frequency difference of prototype is shown in figure 6(a). Figure 6(b) demonstrates the linearity of the square of input air flow rate and the output frequency difference, which is also consistent with the previous theoretical analysis. The air flow measurement result demonstrates that the fabricated prototype with a hair height of 6 mm has a mechanical sensitivity of 5.26 Hz/(m/s)^2.

![Figure 6](image)

**Figure 6.** Relationship between input air flow and output frequency difference. (a) Output frequency difference with input air flow. (b) Output frequency difference with the square of input air flow.

4. Conclusions

This paper presents a novel bio-inspired hair flow sensor with a unique asymmetric design. The mechanical sensitivity of the proposed BHFS is improved significantly by adopting a signal detector which is constituted of a two-stage micro-leverage mechanism and two symmetrical resonators. The DDSOG process is chosen to fabricate the proposed BHFS. The fabricated bio-inspired hair flow sensor has a size of 5100 μm (length) × 5100 μm (width) × 100μm (height) with a hair diameter of 1 mm and a height 6 mm. The preliminary experiment result demonstrates that the fabricated BHFS has a mechanical sensitivity of 5.26 Hz/(m/s)^2 at a resonant frequency of 22 kHz.

5. References

[1] Rizzi F, Qualtieri A, Dattoma, T, Epifani G, and de Vittorio M 2015 Biomimetics of underwater hair cell sensing *Microelectronic Engineering* 132(c) pp 90-97
[2] Tao J and Yu X 2012 Hair flow sensors: From bio-inspiration to bio-mimicking—A review *Smart Mater. Struct.* 21(11) pp 1451-1466
[3] Chen N, Tucker C, Engel J, Yang Y, Pandya S and Liu C 2007 Design and characterization of artificial haircell sensor for flow sensing with ultrahigh velocity and angular sensitivity *J. Microelectromech. S* 16(5) pp 999-1014
[4] Sadeghi M, Peterson R and Najafi K 2011 Micro-hydraulic structure for high performance biomimetic air flow sensor arrays *In Proceedings of 2011 IEEE International Electron Devices Meeting* 47(10) pp 29.4.1–29.4.4
[5] Tao J, Yu X, and Berilla J 2011 Micropillar sensing element for bio-inspired flow sensors *In Proceedings of 8th Int. Workshop on Structural Health Monitoring* vol 2 pp 1732-1739
[6] Huang K Y and Huang C T 2011 Hair sensor using a photoelectronic principle for sensing airflow and its direction *Optical Engineering* 50(1) pp 123-128
Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant No. 61571126), the Equipment pre-research field foundation (Grant No. 6922001217), the NSAF (Grant No. U1230114), the Aviation Science Foundation (Grant No. 20150869005), and the China Academy of Space Technology Innovation Foundation and the Eleventh Peak Talents Programme Foundation in the Six New Industry Areas.