HIGHLY-SENSITIVE, BIOMIMETIC HAIR SENSOR ARRAYS FOR SENSING LOW-FREQUENCY AIR FLOWS

R.K. Jaganatharaja^{}, C.M. Bruinink, B.M. Hagedoorn, M.L. Kolster, T.S.J. Lammerink,
R.J. Wiegerink and G.J.M. Krijnen*

Transducer Science and Technology group, MESA+ and IMPACT Research Institutes,
University of Twente, P.O. Box. 217, 7500 AE Enschede, the Netherlands

ABSTRACT

In this paper, we report, to the best of our knowledge [1, 2], the most sensitive artificial hair-based flow-sensor arrays operating in air, to date. Artificial hair sensors are bio-inspired from the cerci of crickets, one of nature's best in sensing small air flows. The presented hair sensor arrays aim to realize comparable sensitivity to nature by means of model-based design optimizations and were fabricated using advanced MEMS technologies. The presented artificial hair sensor arrays display a clear figure-of-eight response and show remarkable sensitivities to oscillating air flows down to 0.85 mm/s surpassing noise levels at 1 kHz operational bandwidths.

KEYWORDS

MEMS Sensor Arrays, Biomimetic MEMS, Flow sensing, Artificial Hair Sensors

INTRODUCTION

Crickets and most other Orthopteroid insects have evolved with a brilliant sensory system [3, 4], which plays a pivotal role in their essential survival mechanism. Located at the rear-end of the crickets (Figure 1), are a pair of sensory appendages called cerci carrying numerous mechano-receptive filiform hairs which are capable of detecting minute air fluctuations, down to 0.03 mm/s amplitude in their environment [3]. The filiform hairs respond by rotation to air movement, thereby initiating a neural response. The cercal filiform hair sensors have fascinated biologists and recently inspired MEMS engineers [1, 2, 5] in developing a new line of bio-inspired mechanical sensors.

Figure 1: Crickets' cerci containing numerous mechano-receptive filiform hairs. [Courtesy: G. Jeronimides, University of Reading, UK]

We recently successfully developed arrays of artificial hair sensors operating in air using differential capacitive readout [5]. Being significantly improved over our previous generation of hair sensors, the present generation of hair sensor arrays feature an optimized design based on a sensor model and now are fabricated using a refined fabrication process. In this paper, we report on our new artificial sensors capable of performing close to the actual hair-sensors of the crickets themselves and report on the results from extensive characterization.

SENSOR DESIGN OPTIMIZATION

Principle Of Operation

Each artificial hair sensor consists of a suspended membrane with a ~1 mm long hair centrally mounted on top of it. A pair of electrodes on top of the membrane, together with a common bottom electrode forms two sensing capacitors (Figure 2). An air flow around the sensors causes a drag-force induced deflection of the hair, and a simultaneous tilt of the suspended membrane. The change in the sensor capacitances and hence, air flow are measured by means of differential capacitive sensing,

Figure 2: Schematic representation of an artificial hair sensor with differential capacitive flow sensing upon flow-driven membrane tilts.

A 1 μm thin, silicon-rich nitride layer is used as the suspended membrane (after the sacrificial layer removal) and a ~100 nm thick aluminum layer serves as top electrode. The artificial hair was developed using the standard SU-8 photolithography. Bulk silicon acts as the bottom electrode of the capacitive sensors.

Design Optimization

The design optimization for our hair sensor has been discussed extensively in our earlier work [6]. We define a figure of merit (FoM) as a product of low-frequency flow sensitivity and the usable bandwidth and given as:

$$FoM \propto \sqrt{\frac{L}{\rho \cdot S \cdot D^{4/3}}} \quad (1)$$

Where L , D and ρ are length, diameter and density of the hair, respectively and S is the torsional spring constant of the suspension beams. Based on this, the current generation of the hair sensors features the following design improvements:

- Hair length is increased from 450 μm to 900 μm (ensuring increased drag-torque pick up.)
- Reduced torsional spring constant by increasing the spring length and decreasing the spring width.
- Reduced diameter of the top hair layer which significantly reduces the hair moment of inertia (ca. 65%) and hence, allowing us to maintain sufficient bandwidth while despite reduction of the torsional spring constant.

In addition to this, the capacitive sensitivity, η is proportional to the change in sensor capacitance per unit angular rotation and given as:

$$\eta = \frac{\epsilon_0 \cdot w \cdot l^2}{(d_0 + \delta) \cdot d_0} \quad (2)$$

Where w and l are width and length of the membrane, respectively, ϵ_0 is the dielectric constant, d_0 is the effective dielectric distance and δ is the curvature at the membrane edges. Equation 2 motivates to design sensors with reduced inter-electrode gap (1 μm to 0.5 μm) and to opt for low-stress electrode material to overcome the membrane curvature.

FABRICATION

Figure 3 shows the exploded view of the hair sensor and step-by-step fabrication process. A thin silicon-rich nitride (SiRN, 200 nm) layer was deposited on a highly conductive silicon wafer (the bottom electrode) by low-pressure chemical vapor deposition (LPCVD) which serves as etch-stop layer during later sacrificial layer etching. The sacrificial poly-silicon (Poly-Si) layer was deposited by LPCVD and patterned by reactive-ion etching (RIE) to form protection trenches. A second 1 μm -thick SiRN layer was deposited by LPCVD to form the actual membrane and torsion beams. A ~ 100 nm thick layer of low-stress aluminum was sputtered at room

temperature and patterned by wet-etching. The fabrication of 900 μm long SU-8 hairs, was done by two consecutive photolithographic patterning steps of 450 μm thick layers. After the development step of SU-8 hairs, the sacrificial poly-silicon was removed by plasma etching to release the sensor membranes. The complete fabrication procedure is discussed elaborately in our previous work [5].

Figure 3: SEM images of the successfully microfabricated hair sensor arrays and an exploded design view of a single hair sensor showing: (1) highly conductive silicon bulk (bottom electrode), (2) 200 nm thick SiRN layer for isolation and etch-stop, (3) Poly-Silicon layer after the final sacrificial layer removal, (4) 1 μm thick SiRN layer patterned into membranes, (5) 100 nm thick Aluminum for the top electrodes and (6) two 450 μm thick SU-8 layers patterned into a long hair

SENSOR CHARACTERIZATION

Hair sensor arrays were subjected to extensive and multi-faceted characterization measurements, which can be classified into: (1) height profile measurements by white light interference microscopy (WLIM), (2) sensitivity to acoustic flows by capacitive measurements and (3) acoustic flow characterization by optical measurements using a laser vibrometer.

Height Profile

Characterization of the quality of the fabricated membranes is crucial, since the sensor capacitance depends on it (see equation 2). The previous generation of sensor arrays suffered from a significant membrane curvature of ~ 2.5 μm at the edges, affecting the sensor capacitance.

Figure 4: 3D height profile image of the sensor membrane by a white light interference microscope (WLIM)

Figure 4 shows the WLIM 3D height profile of the sensor membrane (without hair) and a trace line along the metal line (not shown here) confirmed a nearly-flat SiRN membranes (i.e. curvature less than ~ 200 nm) by choosing low-stress aluminum as electrode material

Acoustic Flows – Capacitive Measurements

The sensor arrays were investigated upon subjection to acoustic flows by placing the sensors in the very near-field of a loudspeaker [7]. Figure 5 shows a schematic of the measurement setup where two 1 MHz electrical signals are 180° out of phase with each other (for acquiring differential-mode rotational signal) are fed to the top electrodes. A loudspeaker generates flows, to which the sensors react by hair deflection, inducing capacitive amplitude modulation of the electrical signals through the bottom electrode. This modulated signal is amplified and demodulated before being fed to the lock-in amplifier to finally obtain the LF signal. This setup can be used to measure two significant properties of the sensors i.e. sensitivity and directionality of the sensors.

Figure 5: Measurement setup for the acoustic flow driven capacitive characterization of the sensors.

Figure 6: Sensitivity measurements at three different frequencies, with the horizontal lines indicating the RMS noise level for different bandwidths.

For determining the flow sensitivity, the loudspeaker is characterized to produce a wide range of flow velocities in the near-field ranging from $0.5 - 300$ mm/s at different frequency settings (10, 100 and 400 Hz). Using the setup with additional filtering and noise measurements, the sensor response is measured and plotted against the applied flow amplitude. The flow sensitivity limit of the sensors can be determined by the intersection of the measured signals (at 1 Hz bandwidth) and the noise values obtained in a certain bandwidth (0.01, 0.1 and 1 kHz). For the sensor response at 400 Hz, the lowest sensitivity limit was observed to be 0.85 mm/s (Figure 6). It is noteworthy that the actual cercus of the crickets has a sensitivity limit at ~ 0.03 mm/s [3].

Figure 7: Directionality measurements on the hair sensor arrays at three different frequencies showing a clear figure-of-eight response

Figure 8: Schematic of optical measurements setup using a laser vibrometer and a loudspeaker

Using a similar measurement setup and by placing the sensor array on a rotary stage, the signal response was recorded for every 10° rotation angles with respect to the source. Figure 7 shows a clear figure-of-eight response from the sensor arrays at different frequencies confirming a preferred directional sensitivity of the sensors.

Acoustic Flows – Optical Measurements

Optical measurements on the sensor arrays were done using a laser vibrometer (Polytec, MSA 400) with a loudspeaker as the acoustic flow source. Figure 8 shows the schematic of the setup, where the flow-induced membrane deflections of the sensors are accurately measured by a laser vibrometer. The loudspeaker was characterized for the generated flow velocities at a fixed supply voltage and different frequencies. Laser scan points are fixed on the membrane and its deflections corresponding to different actuation frequencies were recorded. The rotational tilt angles, normalized to the respective flow velocities were plotted and found to be in reasonable agreement with the model predictions (Figure 9).

Figure 9: Normalized angular amplitudes (optically measured) from the sensors showing satisfying agreement with the model

CONCLUSIONS

We have presented the most sensitive, artificial hair sensor arrays operating on air up to date, with a sensitivity limit of 0.85 mm/s at 400 Hz. Along with the optimized designs and a significantly improved fabrication process, our sensors exhibit a clear figure-of-eight directional flow sensitivity as measured in the very near-field. Optical characterization shows satisfying agreement between the model and the measurements.

REFERENCES

- [1] Y. Ozaki, T. Ohyama, T. Yasuda, I. Shimoyama, "An air flow sensor modeled on wind receptor hairs of insects", *Proc. IEEE Int. Conf. MEMS*, 2000, pp. 531-536.
- [2] N.Chen, C. Tucker, J.M. Engel, Yingchen Yang, S. Pandya, C. Liu "Design and characterization of artificial hair cell sensor for flow Sensing with ultrahigh velocity and angular sensitivity", *J. Microelectromech. Syst.*, Vol. 16, No. 5, (2007), pp. 999-1014.
- [3] T. Shimozawa, J. Murakami, T. Kumagai, "Cricket wind receptors: thermal noise for the highest sensitivity known", Chapter 10, *Sensors and Sensing in Biology and Engineering*, ed. F.G. Barth, J.A.C. Humphrey and T.W. Secomb, Springer, Vienna, 2003.
- [4] T. Steinmann, J. Casas, G. Krijnen, O. Dangles "Air-flow sensitive hairs: boundary layers in oscillatory flows around arthropod appendages", *J. Exp. Biol.*, 209, pp. 4398-4408
- [5] C.M. Bruinink, R.K. Jaganatharaja, M.J. de Boer, E. Berenschot, M.L. Kolster, T.S.J. Lammerink, R.J. Wierink and G.J.M. Krijnen, "Advancements in technology and design of biomimetic flow-sensor arrays", *Proc. IEEE Int. Conf. MEMS*, 2008, pp. 152-155
- [6] G.J.M. Krijnen, A. Floris, M. Dijkstra, T.S.J. Lammerink, R. Wierink, "Biomimetic micromechanical adaptive flow sensor arrays", in *SPIE Microtechnologies for the New Millennium*, Gran Canaria, 2007, pp. 6592-6616.
- [7] H-E. de Bree, V.B. Svetovoy, R. Raangs, R. Visser, "The very near field, theory, simulations and measurements", in *Proc. of 11th International Congress on Sound and Vibration*, St. Petersburg, 2004.

CONTACT

*R.K. Jaganatharaja, tel: +31-53-489-4438;
r.kottumakulal@ewi.utwente.nl