ADVANCEMENTS IN BIOMIMETIC HAIR FLOW-SENSOR ARRAYS

A.M.K. Dagamseh, T.S.J. Lammerink, R.J. Wiegerink and G.J.M. Krijnen

University of Twente, MESA$^+$ Research Institute, Transducers Science and Technology, P.O. Box 217
7500AE, Enschede, The Netherlands

Abstract — **In this paper we present the latest developments in the design, fabrication and application of single and arrays of biomimetic hair flow-sensors towards high-resolution air-flow imaging. Redesigning the electrode system of the hair sensor (using SOI wafer technology) has led to improve the detection limit down to 1 mm/s air-flow amplitude using 3 kHz measurement bandwidth. SOI technology facilitates the fabrication of wafer-scale arrays, which can be interrogated individually using a smart array interfacing scheme e.g Frequency Division Multiplexing (FDM). The combination of high-sensitive hair sensors and FDM opens possibilities for high spatial-resolution air-flow measurements. A chip-scale single hairs array is used to demonstrate flow-pattern measurements by reconstructing the field of a dipole projected at its position. The separation distance between array elements is determined using the reconstructed dipole field.**

Keywords : **Biomimetic hair, FDM, spatio-temporal flow pattern**

I - Introduction

Biomimetics is a growing field that examines principles and solutions for challenging environmental interaction problems as derived from biological examples. The added values aimed at in using bio-inspired sensor designs are mainly to surpass the performance and robustness of traditionally engineered sensory systems. This attains e.g. improvements in sensitivity, detection limit, operational capabilities, reliability, size, robustness, costs and ease of use of such sensory system. Additionally, the availability of such biomimetic sensory systems helps scientists to understand nature. Imitating the principles from eyes to spike based cameras, from whiskers of rodents to sensors for collision avoidance, from biological neurons to artificial neural networks, from sonar systems in bats to acoustic detectors and from cricket or fish hair-sensors to artificial hair flow-sensors are examples of biomimetic sensors and sensory systems. The last example forms the core of the study presented here.

The sensing hairs of crickets and the cilia-based lateral-line system of fish are examples of array-based sensory systems used to detect flows in air and water, respectively. A large mechano-sensory hair-array resides on the cerci of crickets, at the rear of their abdomen, forming the sensing part of a cricket's escape mechanism for example during spider-attacks [1]. Typically, air movement due to approaching predators causes crickets to turn rapidly away from the stimulus. The large number of hairs, their mechanical properties and directivity result in a smart sensory system. This system enables the cricket to detect, localize and distinguish between various predators using the detected hydrodynamic air-flow signatures [1].

II - Artificial hair flow-sensor

Recently, the mechano-sensory hairs of crickets have been a common research topic for both biologists and engineers [2]. Biologists try to understand nature by investigating their hypotheses using man-made hairs while engineers try to design high-performance sensory systems based on their knowledge of the biological systems.

Inspired by crickets and using MEMS technological advances, we developed artificial hair flow-sensors mimicking the hair-sensors of crickets [3,4]. Our hair flow-sensors were fabricated using a surface micro-machining technology to form a suspended silicon nitride membrane with ~ 1 mm long SU-8 hair on top. The detection principle is based on differentially measuring capacitance changes between two electrodes deposited on top of the membrane with a common underlying electrode i.e. the silicon substrate. Due to the viscous drag torque acting on the hair, the membrane tilts and in consequence to that the capacitors, on both halves of the sensor, change equally but oppositely. Two out-of-phase alternating voltage sources (carrier signals at ~ 1 MHz) are used to detect capacitance changes and convert these to voltage signals by modulation of the carrier amplitude (AM signal). Subsequently a synchronous demodulation technique is used to recover the original (baseband) air-flow signal. Figure 1 shows our artificial hair sensor and its source of inspiration.

A. Hair sensor detection limit

Sensor interfacing is a crucial factor affecting the detection-limit. Parasitic capacitances, inherent to the use of capacitors, pose limitations in attaining highly-sensitive flow sensors. We look at improvement of the detection-limit by reducing the parasitic effects using Silicon-on-Insulator (SOI) wafer technology. This technology enables us to measure small capacitance changes and, hence, to fabricate sensitive hair sensors. This allows to drastically reduce the number of hairs per device (previously up to 124 sensors in parallel) to ultimately a single-hair sensor. Figure 2 illustrates the fabrication scheme of the current hair-sensor design using SOI technology.

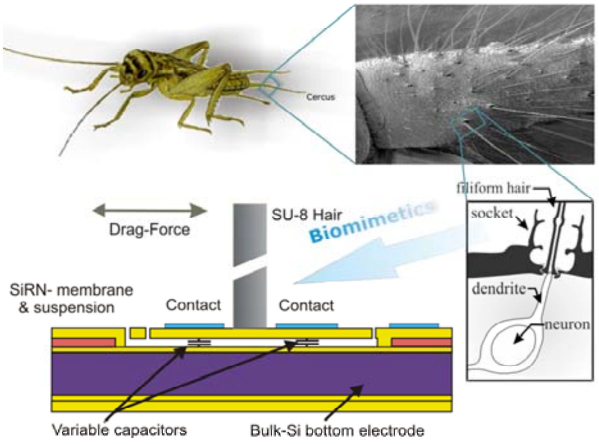

Figure 1: *Schematic representation of flow sensors inspired by crickets. (SEM close-up of a cricket's cercus, courtesy of Prof. J. Casas, Institut de Recherche sur la Biologie de l'Insecte, Tours, France).*

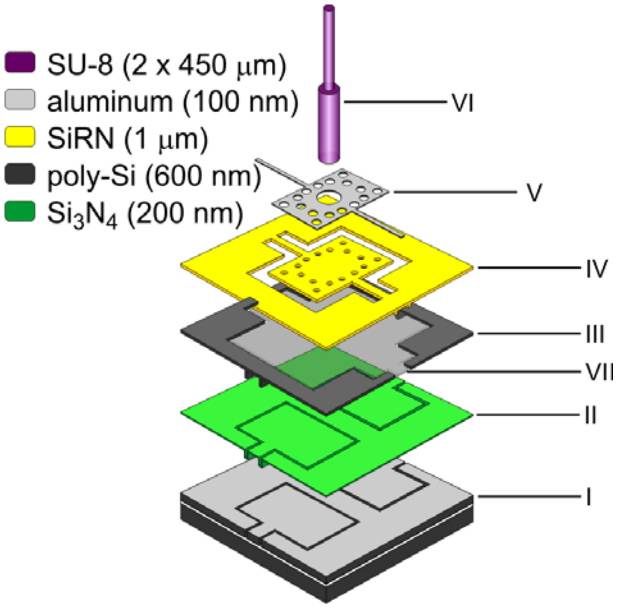

Figure 2: *Schematic representation of hair sensor: (I) RIE of the isolation trenches in the device layer of the SOI wafer; (II) LPCVD of an insulating Si_3N_4 layer; (III) LPCVD of sacrificial poly-Si and RIE of the insulation trenches in poly-Si; (IV) LPCVD of a silicon-rich nitride (SiRN) layer and RIE of membrane/torsion beam structures; (V) Sputtering of Al and wet etching of the top electrode; (VI) Two-step SU-8 processing of the hair; (VII) Sacrificial layer etching with XeF_2.*

To investigate the improvements due to the adapted hair sensor design, the threshold limits of the single-hair sensor (current design using SOI) and the hair sensor array (previous design with the substrate as common electrode) are measured and compared. The detection limit is defined as the air-flow amplitude at which the sensor output voltage has a signal-to-noise ratio (SNR) equal to one. The results show that the detection limit of the single-hair sensor is improved by 52 % (down to 1 mm/s air-flow amplitude as measured with a bandwidth of 3 kHz) compared to the previous hair-sensor. Figure 3 shows an example of the output voltage of both hair sensors as function of air-flow amplitude oscillating at 250 Hz [5].

B. Interfacing hair sensor arrays

Flow-sensor arrays, using sensitive hair sensors, have the potential to measure flow patterns rather than just 'single-point' flow measurements. However, smart interfacing mechanisms are needed to interrogate individual hair elements. Frequency Division Multiplexing (FDM) is a possible mechanism for interrogating each element in the array simultaneously while maintaining continuous interfacing and signal to noise ratio at a much reduced number of interconnects.

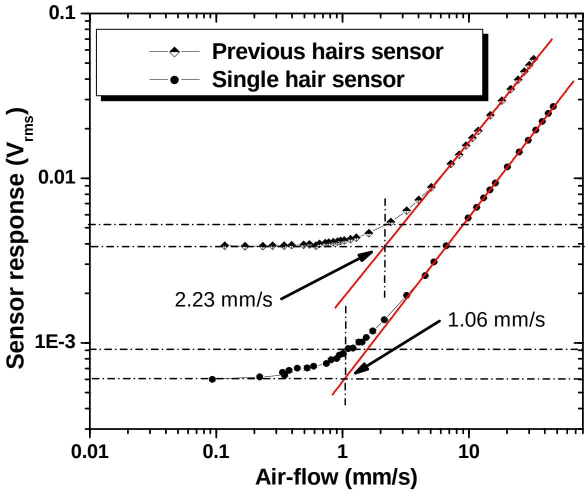

Figure 3: *Output voltage of previous hair sensor and new single-hair sensor as function of flow velocity amplitude at 250 Hz plotted together with the noise levels and the asymptotic lines (in red) to determine the threshold flow amplitude.*

Using FDM, different carrier frequencies are provided along each of the columns of the array for probing the hair sensors. The carrier signals are modulated by the sensors and along the rows the different carrier frequencies, which are mutually shifted in the frequency spectrum, are summed. Per row the stream of these amplitude-modulated signals is fed out of the array chip into a single charge amplifier, hence using a much reduced number of interconnects. Figure 4 shows the basic principle of the FDM array-interfacing scheme.

Figure 5 shows the frequency spectrum of the signals at the output of two charge amplifiers representing the four AM FDM channels from two rows. The results show that we are able to simultaneously retrieve the individual flow signals, as detected by different hair sensors at their position, off-chip. By multiplying the stream signal of each row with the same frequency as used at the columns side (i.e. synchronous demodulation), the information of the individual sensors is retrieved providing simultaneous real-time flow measurements from multiple hairs.

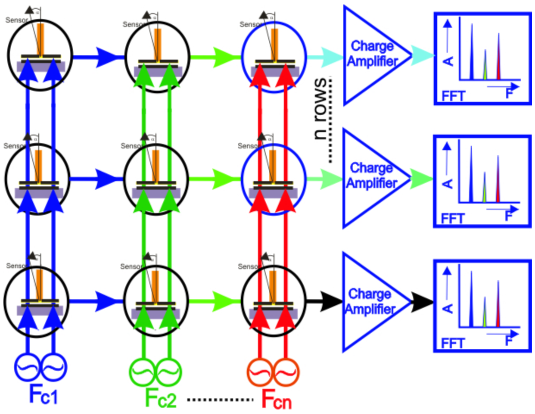

Figure 4: *Principle of FDM addressing technique as applied to our hair sensor array.*

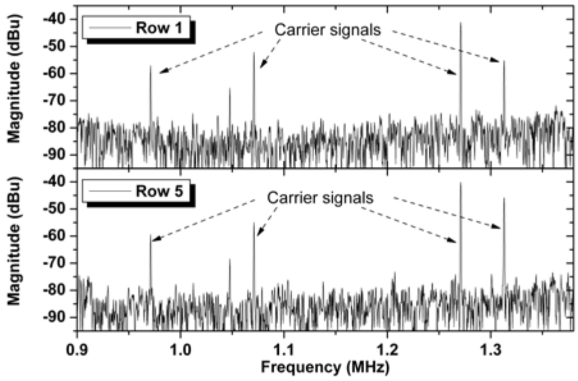

Figure 5: *FFT spectrum of AM signals from two rows at the output of the charge amplifiers while employing FDM.*

C. Flow pattern recognition

By obtaining signals from individual array elements, it is possible to form a real-time image of the air-flow and deduce extra information. The lateral-line system in fish is an example of arrays system used to localize preys by means of flow pattern recognition. Biologists try to understand fish techniques in source localisation by investigating different hypotheses [6,7]. One of these hypotheses is based on reconstructing the flow field generated by a moving dipole source and determining the characteristic points of the flow field. Since the characteristics of dipole sources are well-known from the literature [8], a vibrating sphere generating a dipole velocity field can be conveniently used to analyze object – sensor-array interactions. In an ideal fluid, a sphere vibrating parallel (//) to a linear array line generates a flow velocity in the direction of the *x-axis* (see Figure 6) with amplitudes [6,7]:

$$V_{x,//}(x) = s\omega a^{3}\frac{(2x^{2} - D^{2})}{(x^{2} + D^{2})^{5/2}}$$

where ω is the angular vibration frequency, a is sphere radius, s is sphere displacement amplitude and D is the distance between the centre of the sphere and sensor reference line. The distance D is reflected in the characteristics of the velocity fields [6,7]: for $V_{x,//}$ the distance between the two zeros equals $\sqrt{2}D$. Figure 6 shows simulated dipole velocity field as projected on the *x-axis*.

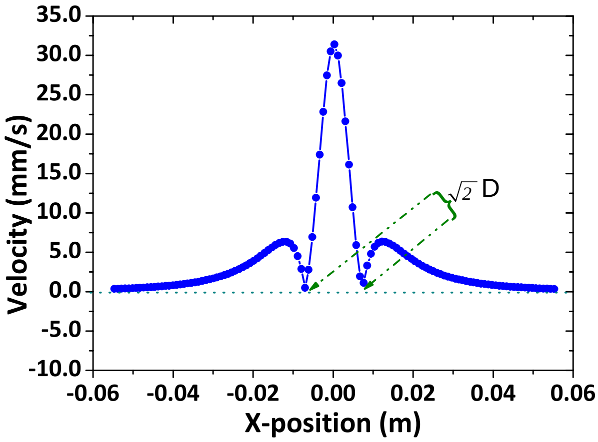

Figure 6: *Simulated velocity amplitude Vx as function of sensor position along the x-axis. The position of the dipole source is encoded in the distance between dipole characteristics.*

Figure 7 shows photograph for the measurement setup used in this study. As demonstration for successful reconstruction of flow fields by the hair-sensor array the dipole fields were measured along different rows and the relative positions of the dipole source to the array elements were determined. Figure 8 represents the dipole field measured simultaneously by each hair-sensor by means of a virtual lateral line system (shifting the dipole source in discrete steps to construct a lateral line system).

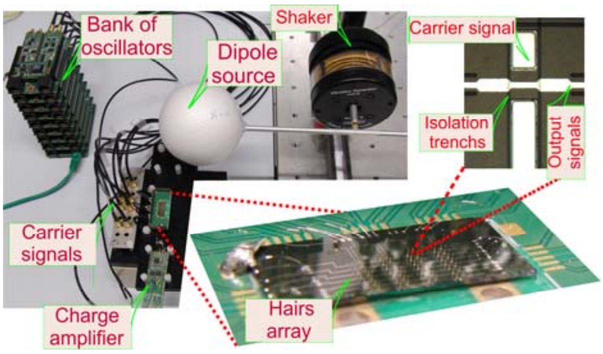

Figure 7: *Photograph of the measurement setup and sensor arrays. Isolation trenches are also shown.*

In these results the peak position represents the sensor output voltage when the dipole is positioned at its minimum distance to the sensor. The shift in peak position (2 mm) represents the column separation distance between sensors and perfectly matches the physical design distance. This proofs that each hair element faithfully reflects the dipole field, at its position, while employing the FDM technique.

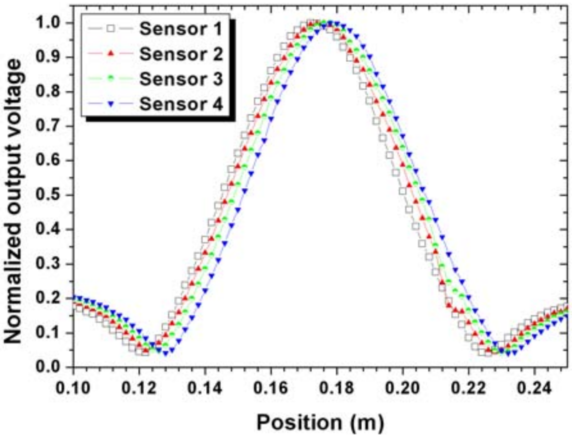

Figure 8: *Normalized flow field measurements simultaneously detected by 4 hairs in one row. The separation between peaks matches with the hair separation (2 mm).*

III - Conclusions

In conclusion, this contribution details the developments of biomimetic hair flow-sensor arrays. The improvement in the detection limit of our artificial hair flow-sensor results from the proper sensor electrodes design by means of reducing the parasitic capacitances. Taking advantage of deep isolation trenches to define electrode areas, SOI technology opens possibilities to fabricate wafer-scale arrays made of single-hair sensors. By obtaining signals from multiple sensors simultaneously (using FDM), it is possible to form real-time images of air-flow patterns. These arrays, by virtue of array signal processing techniques, will be beneficial for sensing and controlling functions of e.g. vehicles by imaging the surrounding environment even in total darkness.

References

[1] T, Shimozawa, T, Kumagai and Y. Baba, “Structural scaling and functional design of the cercal wind-receptor hairs of cricket”, *Journal of Comparative Physiology*, A183, pp. 171-186, 1998.

[2] (a) J. Casas, T. Steinmann and G. Krijnen, “Why do insects have such a high density of flow-sensing hairs? Insights from the hydromechanics of biomimetic MEMS sensors”, *Journal of the Royal Society Interface*, 7, pp. 1487-1495, 2010. (b) G.J.M. Krijnen, T.S.J. Lammerink, R.J. Wiegerink, and J. Casas, “Cricket inspired flow-sensor arrays” *In: IEEE Sensors*, USA., pp. 539-546, 2007.

[3] M. Dijkstra, J.J. Van Baar, R.J. Wiegerink, T.S.J. Lammerink, J.H. De Boer and G.J.M. Krijnen, ”Artificial sensory hairs based on the flow sensitive receptors hairs of crickets”, *Journal of Microelectronics and Microengineering*, 15, pp. S132-138, 2005.

[4] C.M. Bruinink et.al., ”Advancement in technology and design of biomimetic flow-sensor arrays”, *In Proceedings of the IEEE MEMS*, Italy, pp. 152-155, 2009.

[5] A.M.K. Dagamseh, C.M. Bruinink, R.J. Wiegerink, T.S.J. Lammerink, H. Droogendijk and G.J.M. Krijnen, “Developments in biomimetic hair flow-sensor towards high resolution sensitive arrays”, in progress.

[6] J-MP Franosch, A.B. Sichert, M.D. Suttner and J.L. Van Hemmen, ”Estimating position and velocity of a submerged moving object by the clawed frog Xenopus and by fish—A cybernetic approach”, *Biological Cybernetics* ; 93, pp. 231-238, 2005.

[7] A.M.K. Dagamseh, T.S.J. Lammerink, M. Kolster, C.M. Bruinink, R.J. Wiegerink and G.J.M. Krijnen, ”Dipole-source localization using biomimetic flow-sensor arrays positioned as lateral-line system”, *Sensors and actuators: A*, 162, pp. 355-360, 2010.

[8] H. Lamb, Hydrodynamics, 6th edn. Cambridge University Press, Cambridge, (1932).