MEMS based hair flow-sensors as model systems for acoustic perception studies

2006 Nanotechnology 17 S84

(http://iopscience.iop.org/0957-4484/17/4/013)

Nanotechnology **17** (2006) S84–S89 doi:10.1088/0957-4484/17/4/013

MEMS based hair flow-sensors as model systems for acoustic perception studies

Gijs J M Krijnen, Marcel Dijkstra, John J van Baar, Siripurapu S Shankar, Winfred J Kuipers, Rik J H de Boer, Dominique Altpeter, Theo S J Lammerink and Remco Wiegerink

Transducers Science and Technology group, MESA+ Research Institute, University of Twente, PO Box 217, 7500AE, Enschede, The Netherlands

E-mail: g.j.m.krijnen@el.utwente.nl

Received 11 August 2005
Published 25 January 2006
Online at stacks.iop.org/Nano/17/S84

Abstract
Arrays of MEMS fabricated flow sensors inspired by the acoustic flow-sensitive hairs found on the cerci of crickets have been designed, fabricated and characterized. The hairs consist of up to 1 mm long SU-8 structures mounted on suspended membranes with normal translational and rotational degrees of freedom. Electrodes on the membrane and on the substrate form variable capacitors, allowing for capacitive read-out. Capacitance versus voltage, frequency dependence and directional sensitivity measurements have been successfully carried out on fabricated sensor arrays, showing the viability of the concept. The sensors form a model system allowing for investigations on sensory acoustics by their arrayed nature, their adaptivity via electrostatic interaction (frequency tuning and parametric amplification) and their susceptibility to noise (stochastic resonance).

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Sensory systems in biology are among the most sensitive and evolved known to man. In comparing biological and engineered systems for similar functions one often finds striking differences in implementation: for example when taking a look at auditory sensing.

(1) In biological systems sensing elements are based on the flow-sensitivity of large arrays of parallel operating mechano-sensors (hairs, cilia).
(2) Biological systems rely heavily on mechanical filtering and amplification.
(3) Noise may play a beneficial role when perceiving signals near the noise limits.

Engineered systems for acoustic sensing on the other hand are based on pressure measurements using single moving structures (e.g. membranes as in microphones), perform filtering and amplification in the electronic domain (in a sequential manner), and generally see their usable dynamic sensing range being limited by noise. An example of mechanical filtering in biology is found in the auditory system of mammals where tapered 'sound-board'-like resonator structures (basilar membrane) with complex interacting inner and outer hair-cells perform distributed filtering, amplification and adaptation in the mechanical domain [1]. At the same time, parallelism helps to overcome the constraints of the bandwidth of the neural systems and provides robustness and gradual decline. Examples of how biological systems benefit from noise are seen in the form of stochastic resonance and amplification [2] as observed in crickets [3] and crayfish [4].

Despite the advancement of mankind in many areas of technology, it is still challenging for engineered systems to compete with biological systems. For example, the auditory capabilities of bats to perceive their environment, locate prey and to navigate at high velocities through complex surroundings (e.g. with leafed brushes and trees) has no manmade equivalent. Likewise, the sensitivity of hair-based auditory mechano-sensors found on insects [5] to perceive acoustic signals at thermal noise levels is astounding. It is this kind of performance that raises interest in biological systems with the purpose to improve engineered systems and gain extended functionality.

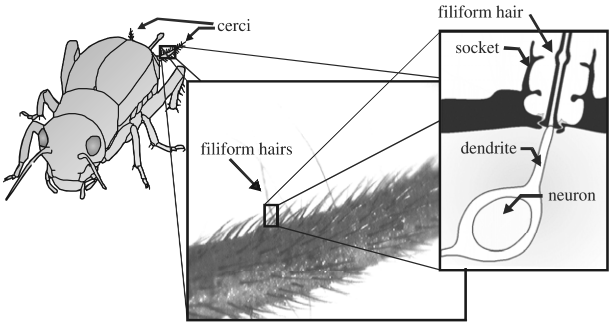

Figure 1. Filiform hairs on the cerci of crickets[1].

There seems to be a favourable size match between the primary sensing parts (e.g. mechano-sensing hairs found on cricket cerci with lengths roughly between 100 and 1000 μm) and what can be made by a technology generally denoted by 'micro-electro-mechanical systems' (MEMS). It allows, in principle, for bio-mimicking of biological sensory systems such as the flow-sensitive hairs of cricket, the tactile hair sensors on spiders [6], the lateral line sense organs of fish [7] and the mammalian cochlea [1].

2. Cricket sensory hairs

Crickets have achieved acoustic sensing in one form by evolving sensitive mechanoreceptive sensory hairs. These so called filiform hairs are highly perceptive to low-frequency sound with energy sensitivities below thermal threshold [5].

The sensory hairs of the cricket are situated on the back of the cricket's body on appendices called cerci. The hairs vary in length up to around 1 mm, with a bimodal distribution with concentrations around 150 and 750 μm [8]. Each hair is lodged in a socket, guiding the hair to move in a preferred direction. The hair is held in its socket by an elastic material surrounding the base. Airflow causes a neuron to fire, by rotation of the hair base (figure 1). The cricket is able to pinpoint low-frequency sound from any given direction using the combined neural information of all sensory hairs [9].

It is interesting to note that crickets have evolved flow sensitive hairs rather than pressure sensitive sensors. As Tautz has pointed out [20], this is more or less a necessity since important predators of crickets, such as wasps and spiders, are too small to produce any significant pressure variations at important frequencies of e.g. wing beats (tens to hundreds of Hz) in the far field. This observation is based on the fact that substantial pressure waves can only be emitted by moving bodies larger than $\approx 2\pi\lambda$, with λ the wavelength of the sound. Moreover, many attacks on spiders will take place at relative short distances such that the cricket may be considered in the near field of the sound producing predator, i.e. where particle velocity is more readily conceivable than pressure fluctuations.

The mechanics of the sensory hairs of crickets has been modelled extensively (e.g. [10, 11]). Filiform hairs can be described as an inverted pendulum, a second order mechanical system, which is fully determined by the torsional spring constant S, the moment of inertia J and the torsional resistance R. Typical values for cricket filiform hairs with a length of 200 μm are $S \approx 10^{-12}$ N m rad^{-1}, $J \approx 510^{-21}$ kg m^2 and $R \approx 10^{-16}$ N m s rad^{-1} [10]. This gives a critically damped system with a damping coefficient of 0.7. Resonance frequencies of filiform hairs are in the range of 85–500 Hz. Impedance matching between the torsional resistance R and the drag resistance on the hair allows for maximum energy transfer, hence optimized sensitivity of the sensory hairs [10].

[1] Photo courtesy of G Jeronimidus, R Seidel and K Winwood, Biomimetics Centre, Reading University.

The filiform hairs are deflected by drag-forces on the hair shaft, due to particle velocity surrounding the cercus. The frequency dependent velocity profile above a flat surface is given by [10, 11]

$$v_y(x,t) = V_0 \sin(\omega t) - V_0 \mathrm{e}^{-\beta x} \sin(\omega t - \beta x)$$
$$\beta = \sqrt{\frac{\omega}{2\nu}} \tag{1}$$

with ν being the kinematic viscosity, x the distance from the surface and ω the angular frequency of the harmonically oscillating flow. The boundary layer thickness depends on β^{-1}, being larger at lower frequencies.

The total torque on the filiform hairs can be calculated by integrating the drag-moment along the hair. The drag-forces can be determined by Oseen's drag-force approximation [9]:

$$F_{\mathrm{drag}}(x,t) = 8\pi\mu \frac{v_y(x,t)}{2S(x,t)+1}$$
$$S(x,t) = \ln\left(\frac{8}{\mathrm{Re}(x,t)}\right) - \gamma \qquad \gamma = 0.577 \tag{2}$$
$$\mathrm{Re}(x,t) = \left|\frac{2a v_y(x,t)}{\nu}\right|$$

with μ being the dynamic viscosity, a the radius of the hair and γ Euler's constant. In (2) v_y is actually the velocity difference between the flow and the hair. However, the stiffness of our hairs is on the order of 10^{-8} N m rad^{-1} and hair movement is expected to be so small in our structures that the velocity difference can be approximated by the flow velocity itself (equation (1)). In doing so we also neglect the effect of added mass of the air surrounding the hair. Using (1) and (2) the total drag-torque on the hairs is determined. This drag-torque increases approximately proportional to the hair length cubed $(L_0)^3$, when $L_0 < \beta^{-1}$, showing the importance of hair-length for optimized sensitivity. For a hair to effectively pick up particle velocity it is essential that it extends out of the boundary layer. With a viscosity of 1.8×10^{-10} N s m^{-2} for air [20] and at a frequency of 100 Hz this translates into a minimum hair-length of about 240 μm. For lower frequencies this length is even longer.

The drag-torque shows a high-pass frequency response to the free-stream velocity, with drag-torques up to 10^{-10} N m. The total response, including the mechanical response of the sensor, shows a band-pass behaviour. The many filiform hairs on the cricket's cerci vary in their band-pass behaviour, because the mechanical properties and drag-torque are dependent on the hair length. By combining many dissimilar filiform hairs the cricket is able to create a sensitive sensory system, which has a relatively balanced frequency spectrum [4, 8].

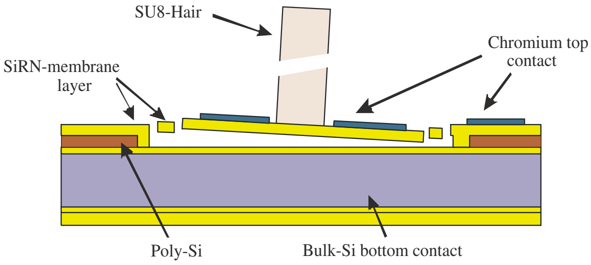

Figure 2. Sensor structure with SU-8 hair.

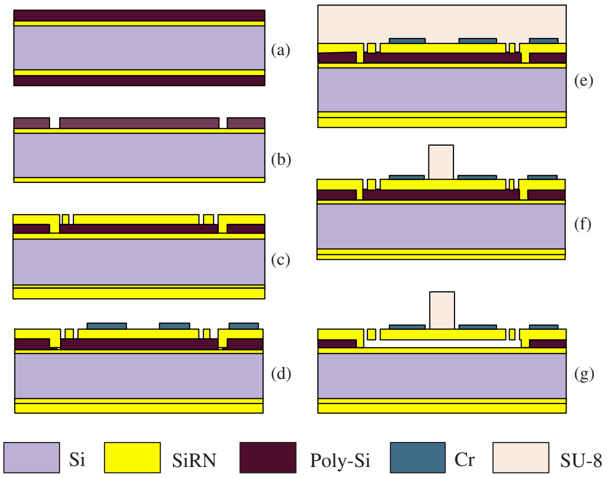

Figure 3. Condensed process flow of the sensors.

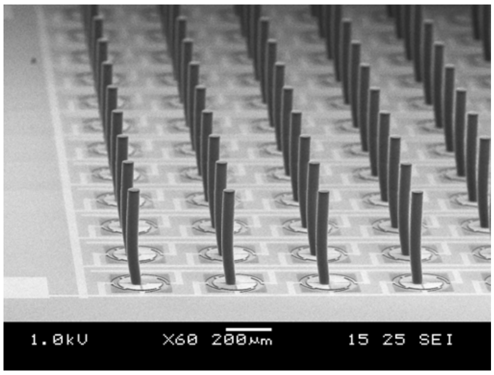

Figure 4. Array of spiral-suspended sensory hairs.

3. Artificial hairs

It is the aim of this work to learn from natural sensors as found on crickets and to produce comparable structures using MEMS technology. Several groups have worked on the realization of artificial hairs for flow sensing [12–16]. Fabrication of hairs in the wafer plane is straightforward since surface micromachining techniques can be used [13] and hairs can be erected after fabrication. To this end Li *et al* proposed to use the so-called plastic deformation magnetic assembly (PDMA) method [14, 15]. In the PDMA process, a magnetic field is used to bend surface micromachined beams. The beams are plastically deformed, so that they remain bent after the magnetic field is removed. Despite the ease of fabrication surface micromachined hairs cannot easily be combined into high-density arrays.

3.1. Fabrication

In this work hair-sensors are fabricated by a combination of a sacrificial poly-silicon technology, to form silicon nitride suspended membranes, and SU-8 polymer processing for hair fabrication. Figure 2 shows a schematic drawing of the proposed sensor structure. A condensed fabrication scheme is shown in figure 3.

Processing starts with a highly conductive silicon wafer, since the substrate is used as a common electrode for capacitive read-out. A 100 nm thin silicon-nitride layer is deposited by LPCVD, for the protection of the substrate during later etching of the sacrificial layer. A 1 μm sacrificial poly-silicon layer is deposited by LPCVD and patterned to form etch-stop trenches. A second, 1 μm thick silicon nitride layer is deposited and patterned to form the membranes and suspension springs, followed by sputtering of a 20 nm chromium layer. A layer of SU-8 photo-resist is spin-coated on the wafer surface. The SU-8 resist is illuminated and developed to create artificial hairs. Processing is completed by dry etching of the sacrificial poly-silicon layer, thereby releasing the sensor structures, without affecting the SU-8 hairs (figure 3(g)). Figure 4 shows an array of spiral-suspended sensory hairs with SU-8 hairs of 470 μm. The realization of SU-8 hairs on top of the sensor structure was achieved with high yield in a relatively simple fabrication process.

A disadvantage of SU-8 hairs is that the hair-length is fixed on a given substrate by the spun SU-layer thickness, except when multiple layers and exposures of SU-8 are used. Such processing also yields interesting possibilities to increase hair-length up to and above 1 mm with two, not necessarily identical, segments stacked on each other (see figure 5). Moreover, it is possible to vary the diameter of the artificial hairs, which can be used alternatively to vary the amount of drag-force on the hair and the resonance frequency.

3.2. Characterization

Characterization with acoustic flows was done employing capacitive amplitude modulation of two 1 MHz electrical signals. The electrical signals need to be taken in phase to acquire a common-mode translational signal from the sensor. A differential-mode rotational signal is acquired when the electrical signals are taken 180° out of phase (figure 5). The AM signal from the sensor is amplified and demodulated, by the charge amplifier and synchronous detector. The resulting signal is fed to a lock-in amplifier, which is used to lock-in on the frequency of the LF signal source. A flow source, a loudspeaker combined with a tube, was used to determine the frequency response measured with the artificial sensory hairs, applying a differential-mode measurement. A reference particle velocity sensor [17] was used for comparison.

Both measurements were normalized to the amplitude obtained at 41 Hz. Figure 7 shows that the flow source gives maximum output at 75 Hz, as measured by both sensors, whereas no clear indications are found for any resonances within the measurement range.

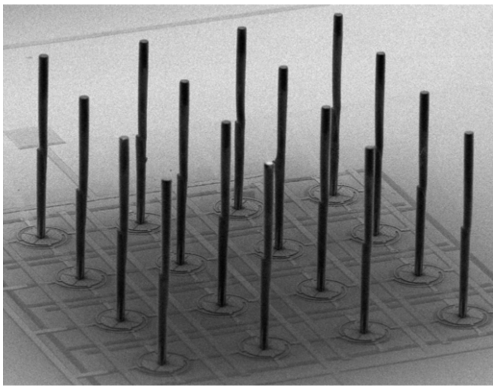

Figure 5. Arrays of hairs of double-spun and double-exposed SU-8 layers. Hair-length of up to 1 mm has been obtained.

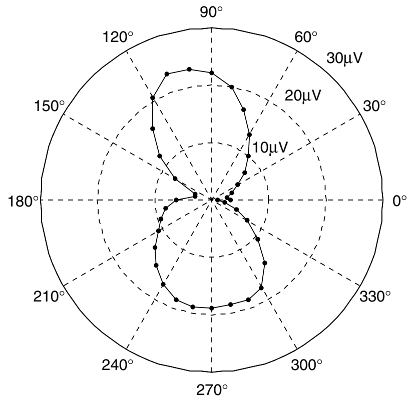

Figure 8. Directivity acoustic measurement on a spiral-suspended hair-sensor array: amplitude versus ϕ.

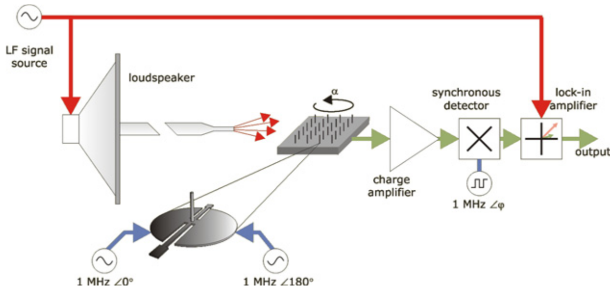

Figure 6. Acoustic flow measurement set-up.

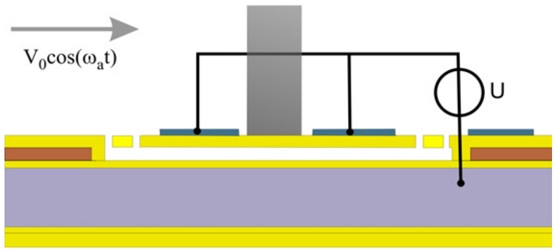

Figure 9. DC-biased hair sensor.

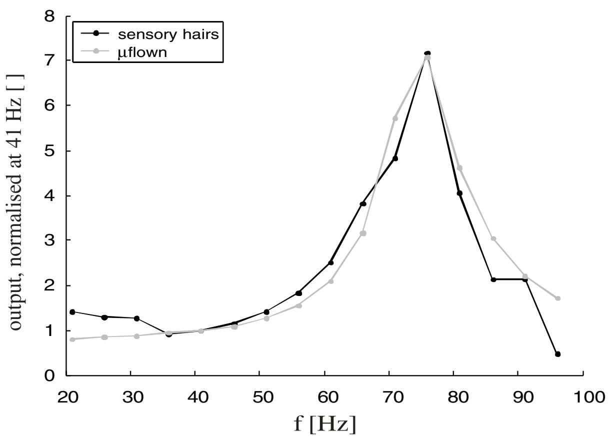

Figure 7. Frequency response of a spiral-suspended hair-sensor array.

Directional flow-sensitivity measurements have been carried out by arrays of artificial sensory hairs using a stepper-motor for rotation, and flow amplitudes in the range 0.1–1 m s^{-1}. The lock-in amplifier measures the amplitude and phase angle for each rotation angle ϕ of the device (figure 6). Figure 8 shows the results of a differential-mode rotational measurement on an array of hair sensors. The amplitude of the output of the sensor displays a figure of eight, showing that the sensor has a preferred directional sensitivity. A sharp transition can be observed in the phase at rotation angles of roughly 0° and 180° (not shown here), where the flow direction over the electrodes changes sign.

4. Artificial hairs as a model system

The availability of functional hair-sensor arrays forms an invitation for acoustic sensing and perception studies. Using the many hairs in parallel various aspects of biological sensing may be mimicked.

Using multiple spin and exposure cycles, arrays of dissimilar hairs showing variability in flow-sensitivity may be fabricated. This possibility is exemplified in figure 5.

A hair sensor may be fabricated using local variability in hair diameter and/or torsional suspension to obtain a localized frequency response in order to (partly) mimic cochlear functionality [1].

Adaptation may be obtained using DC biasing of the electrode structures to utilize effective stiffness weakening by electrostatic forces (figure 9). Using transduction theory it is easily derived that the effective torsional spring stiffness can be modulated according to

$$S_{\mathrm{eff}} = \frac{\partial T_{\mathrm{ext}}}{\partial \alpha} = S - \frac{U^2}{2}\frac{\partial^2 C}{\partial^2 \alpha}. \qquad (3)$$

This implies that the effective spring stiffness can be lowered by increasing the DC-bias voltage. Hence, resonance frequency and sensitivity of the hairs may be adaptively changed to accommodate optimal signal reception.

Since the capacitive structures are amenable to electrostatic actuation via the electrodes, one may use additional AC signals at frequencies chosen at will (figure 10). Voltage-controlled actuation implies nonlinearity, since the

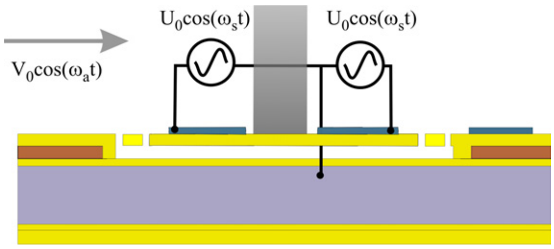

Figure 10. AC biased hair-sensor.

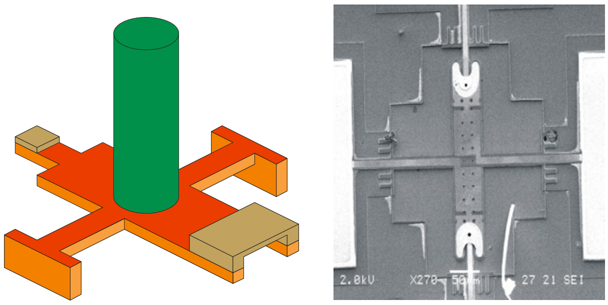

Figure 11. A hair sensor based on a bistable switch (left) and a partly finished bistable hair sensor (right).

electrostatic torque depends on the voltage as well as on the angle:

$$T_0^{\mathrm{air}} \cos \omega_a t = S\alpha - \frac{U_0^2}{4}[1 + \cos 2\omega_u t]\frac{\partial C}{\partial \alpha}. \quad (4)$$

Mixing of the electrostatic and acoustic signals may be utilized for parametric mixing in order to perform filtering and obtain selective gain [18].

Using available thermal and acoustic noise, or by adding mechanical noise through electrostatic actuation, one may investigate stochastic concepts (stochastic resonance) on the scale of hundreds of hairs. This can be performed on the capacitively probed sensors but alternatively it is also possible to make e.g. bistable switches (figure 11). The latter have the advantage of relative easy resistive read-out [21].

Exploiting charge generation from piezo-electric material in future devices, hair sensors may be directly integrated with living neuronal networks.

Apart from the various aspects of perception studies, the sensor structures provide interesting possibilities for distributed sensing. This allows for determination of fields (rather than single-valued average quantities), e.g. the observation of micro-turbulence. Likewise, comparable arrays may be used for tactile sensing.

5. Conclusion

We have shown functional acoustic flow sensor arrays based on the mechano-hair sensors found on crickets. The arrays with hundreds of hairs allow for investigation of various sensing and perception schemes like stochastic resonance, parametric amplification, mechanical filtering, etc.

Acknowledgments

We thank Erwin Berenschot and Meint de Boer for their processing advice, our colleagues in the EU project CICADA for stimulating discussions and input to this work and the EU for financial support through project IST 2001 34718 (CICADA) [19] in the Lifelike Perception Programme.

References

[1] Snyder K *et al* 2003 The outer hair cell: a mechanoelectrical and electromechanical sensor/actuator *Sensors and Sensing in Biology and Engineering* ed Barth, Humphry and Secomb (Vienna: Springer) chapter 6
White R D and Grosh K 2005 Microengineered hydromechanical cochlear model *Proc. Natl Acad. Sci. USA* **102** 1296–1301

[2] Wellens T, Shatokhin V and Buchleitner A 2004 Stochastic resonance *Rep. Prog. Phys.* **67** 45–105

[3] Levin J and Miller J 1996 Broadband neural encoding in the cricket cercal sensory system enhanced by stochastic resonance *Nature* **380** 165–8

[4] Bahar S and Moss F 2004 Stochastic resonance and synchronization in the crayfish caudal photoreceptor *Math. Biosci.* **188** 81–97

[5] Shimozawa T, Murakami J and Kumagai T 2003 Cricket and wind receptors: thermal noise for the highest sensitivity known *Sensors and Sensing in Biology and Engineering* ed Barth, Humphry and Secomb (Vienna: Springer) chapter 10

[6] Barth F G 2004 Spider mechanoreceptors *Curr. Opin. Neurobiol.* **14** 415–22

[7] Coombs S 2001 Smart skins: information processing by lateral line flow sensors *Auton. Robots* **11** 255–61

[8] Dangles O and Casas J 2003 private communication, Institut de Recherche en Biologie de l' Insecte
Dangles O, Magal C, Pierre D, Olivier A and Casas J 2005 Variation in morphology and performance of predator-sensing system in wild cricket populations *J. Exp. Biol.* **208** 461–8

[9] Landolfa M A and Jacobs G A 1995 Direction sensitivity of the filiform hair receptors *J. Comparitive Physiol.* A **177** 759–66

[10] Shimozawa T, Kumagai T and Baba Y 1998 Structural scaling and functional design of the cercal wind-receptor hair of cricket *J. Comparative Physiol.* A **183** 171–86

[11] Humphrey J A C *et al* 1993 Dynamics of arthropod filiform hairs. I. Mathematical modeling of the hair and air motions *Phil. Trans.: Biol. Sci.* **340** 423–44

[12] Ozaki Y, Ohyama T, Yasuda T and Shimoyama I 2000 An air flow sensor modeled on wind receptor hairs of insects *Proc. MEMS (Miyazaki, Japan)* pp 531–7

[13] Chen J, Fan Z, Zou J, Engel J and Liu C 2003 Two dimensional micromachined flow sensor array for fluid mechanics studies *J. Aerospace Eng.* **16** 85–97

[14] Li J, Chen J and Liu C 2000 Micromachined biomimetic sensor using modular artificial hair cells *Nanospace 2000* (Houston)

[15] Zou J, Chen J and Liu C 2001 Plastic deformation magnetic assembly (PDMA) of out-of-plane microstructures: technology and application *J. Microelectromech. Syst.* **10** 302–9

[16] Fan Z, Chen J, Zou J, Bullen D, Liu C and Delcomyn F 2002 Design and fabrication of artificial lateral line flow sensors *J. Micromech. Microeng.* **12** 655–61

[17] de Bree H-E *et al* 1996 The microflown: a novel device measuring acoustical flows *Sensors Actuators* A **54** 552–7

[18] Carr D W, Evoy S, Sekaric L, Craighead H G and Parpia J M 2000 Parametric amplification in a torsional microresonator *Appl. Phys. Lett.* **77** 1545–7

[19] http://www.bionics-cicada.org/

[20] Tautz J 1979 Reception of particle oscillation in a medium—an unorthodox sensory capacity *Naturwissenschaften* **66** 452–61

[21] Kuipers W J 2005 Drag force actuated microswitch *MSc Thesis* Univeristy of Twente