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Topical Review

Grasshopper-inspired air flow sensors: design and sensing research review

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Topical Review

Cricket-inspired air flow sensors: design and sensing research review

ABSTRACT The cricket has incredibly sensitive hairs on its cerci capable of low frequency/ low flow velocity sensing as well as angular sensing for both intraspecies communication and predator location. A review of the existing literature of designs based on the biological structure of these hairs showed high promise, the most sensitive device producing air flow sensitivity of up to 0.4 mm/s compared to the cricket's 0.3mm/s. The designs fell into two categories, capacitive and resistive sensing. The capacitive devices showed superior capabilities for equivalent hair lengths based on comparative analysis undertaken in this report. None of the devices showed high levels of angular sensitivity and many focused purely on single directional sensitivity (highest achieved angular resolution is 13 degrees), falling far short of the cricket's capabilities, however much of the research is at least twelve years out of date as of the time of this report. This opens up the potential that with modern fabrication capabilities and new design techniques, there could be far higher performance devices capable of production. Overall, the design's high performance in flow sensitivity but lacking performance in angular sensitivity is evidence for use in some MEMS applications but needs further development to become more widespread.

KEYWORDS Cricket; biomimetic; review; sensor; airflow

I. INTRODUCTION

Nature has developed a wide variety of incredibly sensitive solutions to detecting a creature's surroundings and often show much higher accuracy with far 'simpler' implementations than modern engineered sensors. The structure of these biological sensors is vastly different to the majority of modern engineered audio sensing, using parallel filiform hairs connected in an array via neurons and are consistent across a vast range of creatures, including insects [1], fish [2] and even in the cochlea of mammals [3].

The effectiveness of nature's auditory sensing has led to great interest from the engineering community and caused the development of a range of new sensing devices. This review will focus on those that draw from the cerci of the common cricket which have an incredibly sensitive auditory system developed in for detection of predators as well as intraspecies communication. These insects have a large number (500-750) of filiform sensors ranging in length from 50µm to 2mm on its rear abdomen that act as airflow sensors [6]. Fig. 1 shows how these filaments are connected to the neurons in the abdomen of the cricket. The system of the dendrite and neuron acts a second order dynamic system (an inverted pendulum) and have resonant frequencies in the range of 85-500hz [4][5]. This biological system shows incredible sensitivity, a minimum detectable threshold air flow velocity of 0.3mm/s [7][8].

Modern low flow rate air sensors focus on a very different structure, using a separate filtering and amplification system. The three conventional solutions are ultrasonic and magnetic sensors and hot wire anemometry. Ultrasonic and magnetic flow meters can be used to detect low flow cases but are constrained to uses within piping.

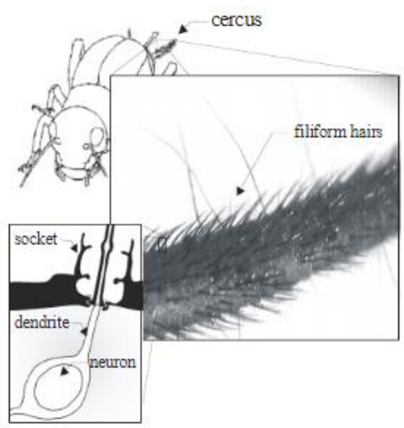

Figure 1. The structure surrounding and of an individual hair [9]

Ultrasonic flow meters begin to struggle with sensitivity and accuracy problems below 60 cm/s, while magnetic flow meters are far more sensitive with limits as low as 0.1m/s [21][22]. The magnetic flow meter relies on the fluid having magnetic properties which constrains the use case even further from just within a pipe. Hot wire anemometers have a similar use case to the filiform hairs, capable of being placed on an external surface, and offer the most comparable performance to the mechanical filiform sensors with flow sensitivity as high as 0.01 m/s [21].

Engineers have developed a variety of solutions that mimic the dendrite neuron setup using modern micromanufacturing techniques and only became feasible recently because of this, with early designs being published in the early 2000s.

II. REVIEW OF ENGINEERING SOLUTIONS

The research that has been published tends to fall into two taxa, capacitive and resistive sensing of the hair movement. This split will be used for the purpose of comparative analysis.

A. RESISTIVE SENSING

The resistance sensing designs all used similar design approaches. Using short artificial hairs synthesised from various materials attached to multiple strain gauges at the base. Each design uses a variation of the Wheatstone bridge for strain measurements in order to detect how much the hair is moving and therefore estimate the air flow conditions

Ozaki *et al* produced some of the earliest work in the area, releasing two designs in 2000 [11]. Both use a Wheatstone bridge to perform the deflection measurement, but they vary in degrees of freedom (DOF) of the hairs. The first uses a rectangular 'hair' arranged as a vertical cantilever with only 1 DOF. By placing strain gauges on the faces of the rectangular hairs, the deflection of the tip can be estimated using the mechanical properties and the air flow predicted. This setup can be seen in Fig.3A. The second device uses a four-beam suspension of a hair each with a strain gauge attached shown in Fig.3B. The four-point connection gives the device two degrees of freedom allowing it to theoretically measure flow direction. This design uses a four active Wheatstone bridge to compensate for temperature variation and boost the output signal for more a sensitive device. Arrays of both devices were tested using an air tunnel

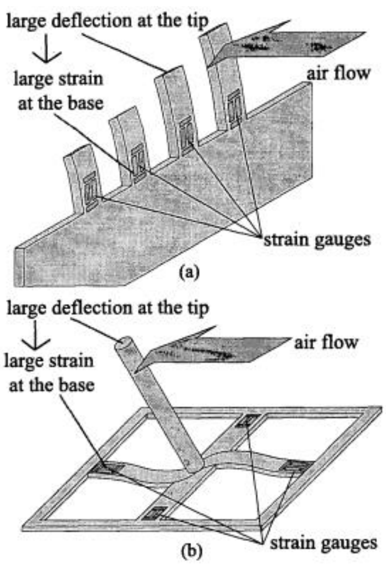

Figure 3. Diagram of sensor function proposed by Ozaki *et al*. A. 1-DOF hair design B. 2-DOF hair design.

and showed sensitivity limits of tens of cm/s to 2 m/s with the 2-DOF sensor achieving some directional sensitivity. No final value of sensitivity is provided and based on estimates from provided graphs, the device would struggle to achieve angular resolution greater than 45 degrees.

Engel *et al* used a half bridge setup, detecting the bending at the base of the artificial hair in two axes perpendicular to each other [10]. The focus of this research is the use of polyurethane elastomer for the fabrication of much longer (up to 300 µm) artificial hairs. This method achieved a sensitivity of 245 ppm resistance change for every micron deflection at the tip of the artificial hair. The device did achieve isotropic behaviour and showed an estimated sensitivity in the off axis of one fifth of the on axis. The paper provided no data directly comparable with the other designs, however, based on comparisons of strain sensitivities with other papers such as the one provided by Chen *et al*, the device could be capable flow sensitivities of above 0.1 m/s.

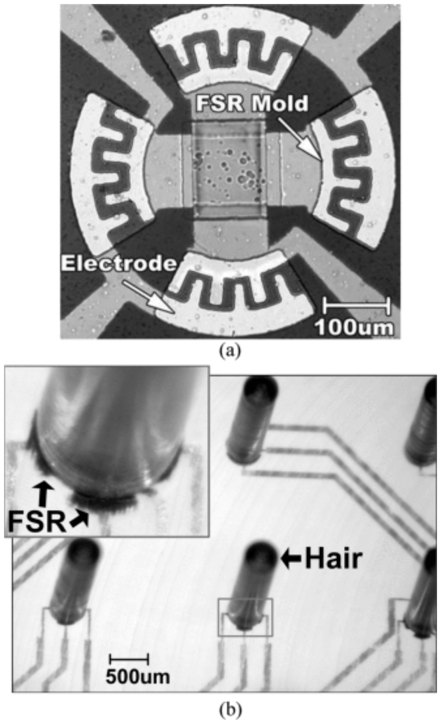

Figure 2. Images of design proposed by Engel *et al*. [10]

Chen *et al* developed a more complex 1-DOF design [12]. In this design the hair is synthesised from SU-8 epoxy and are cylindrical. This hair is then suspended on a cantilever beam with a piezoresistive strain gauge to measure the beam deflection and, by proxy, the hair deflection (shown in Fig.4). The measurements from the piezoresistor, arranged in a quarter bridge arrangement, can then be combined with some numerical analysis to produce an estimate for the flow rate experienced by the hair.

The resonant frequency of the hair was tested and found to be 3.07 kHz, much higher than the cricket hair's range of 85 – 500 Hz [4][5]. Further testing showed an average sensitivity of 0.145% change in resistance per micron of tip deflection resulting in a maximum achieved accuracy of 0.7mm/s (in water), sensing frequencies as low as 50Hz despite the noise from the test setup. This device was developed and tested for aquatic use while using the biological concepts found in the cricket which limits the relevance of any measurements provided, as measurements of fluid flow rate are far more sensitive. This is dues to the increase in drag force experienced by the hairs generating larger readouts on the sensing element. The difference renders the sensitives and any other measurements incomparable to the rest of the devices reviewed in this report.

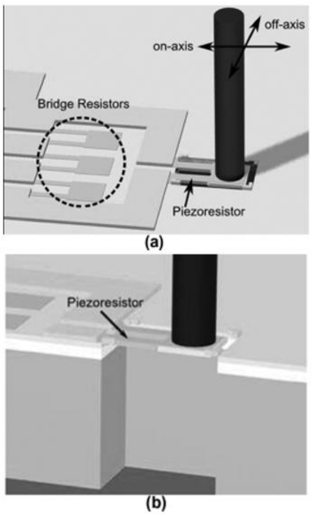

Figure 4. Cantilever hair designed by Chen et al. A. Wheatstone bridge and artificial hair cell B. Cross section showing the cantilever beam

Table 1 shows a comparison of the key parameters provided in the research into the different types of resistance based artificial hair cells.

Table 1: Summary of resistance-based devices

Design	Hair Width (μm)	Hair Length (μm)	Hair Material	Air Flow Sensitivity	Sensing
Cricket	-	50 - 2000	Biological	300 μm/s	Neuron
Engel *et al* [10]	500	3000	high aspect ratio polyurethane	3 ppm/spl (estimated 1 mm/s)	Half bridge
Ozaki *et al* [11]	1 DOF: 230, 230	1 DOF: 800, 400	-	0.1 – 1 m/s	Full bridge
Chen *et al* [12]	0.1-0.3	2-8	SU-8 Photoresist	0.7mm/s (in water)	Quarter bridge

B. CAPACITIVE SENSING

While the concept of using torque generated by drag acting on a hair remains the same, capacitive devices use the displacement between capacitor plates and the resulting change in capacitance to measure the tip deflection of the hairs. These devices can be split based on the method of hair fabrication, providing two taxa for comparison and analysis. Earlier designs and those that do not use SU-8 photoresist for the artificial hair failed to reliably produce hairs above 500 μm in height. Later developments used a two-stage method of superimposing hair fabrication on top of a premade array of hairs. This produced two-tiered hairs up to 1mm in height, improving performance due to the increased drag these hairs can experience.

1) SINGLE TIERED HAIRS

Dijkstra *et al* used three electrodes orthogonal to the hair, two in plane with the base of the hair and one directly beneath it (Fig.5). The upper electrode is given slight freedom to rotate to allow the hair to deflect. A third contact is added in plane with the upper electrode to detect translation. This system produces an airflow sensitivity estimated between 0.1 – 1 m/s. Its effectiveness should be put in the context that it is one of the earliest designs for a capacitance-based solution that has acted as a foundation for new approaches and improvements by a significant portion of published research in the field.

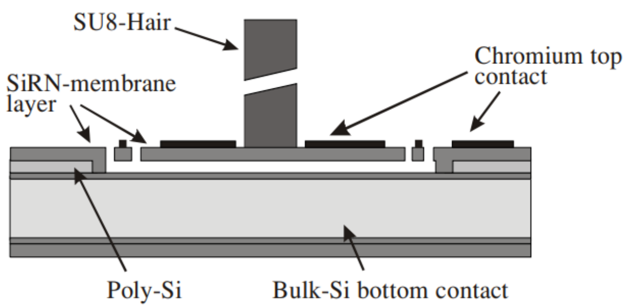

Figure 4. Cross section of the base of the transducer, showing the three electrodes, designed by Dijkstra *et al*

Sadeghi *et al* produced an alternative design that uses hydraulic pressure generated from an artificial hair with an attached boss to deform a capacitor electrode, changing the hair cells capacitance and providing a way of measuring air flow (Fig.5) [14]. This device's method for detecting hair deflection strays further from the original biological solution, however, the reliance on the artificial hair and similarity of the overall function of the sensor is a large reason for the device's success. By arranging four of these artificial hair cells facing four directions 90 degrees apart, the array achieves a level of directional measurement based on comparison across the hairs. These design choices led to a device with an operating range of up to 15 m/s with a sensitively of 1.7 mm/s as well as an angular resolution of 13 degrees.

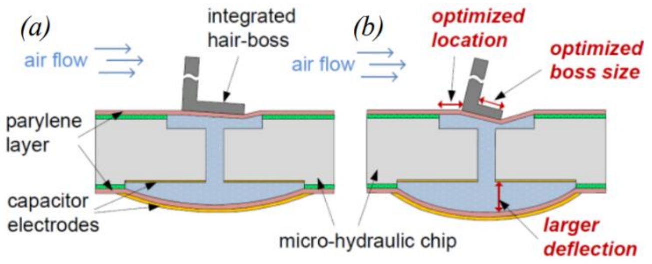

Figure 5. Cross section showing the pump action of the artificial hair and boss producing a change in capacitance. A. No/low air flow B. Increased air flow Final design

2) *TWO TIERED HAIRS*

All of the subsequent papers used the fabrication of two tiered hairs to boost hair length and therefore increase sensitivity. The hair length of the device is increased past previous limits by a second deposition of SU-8 photoresist on a pre-synthesised lattice of hairs, increasing the maximum hair length to 1000 μm and inducing a step reduction in hair radius at half the hair's height

Bruinink *et al* and later Jaganatharaja *et al* utilised this advancement to develop, and then improve the design of capacitive hair deflection measurements [15] [16]. The most recent iteration laid out in the paper by Jaganatharaja *et al* can be seen in Fig.6B. A new fabrication method and a different capacitor layout is shown in Fig. 6A. which, combined with the new hair design, improves the sensitivity of the device to 0.85 mm/s. Improving on the original sensitivity of the device shown by Bruinink *et al* of 1 mm/s.

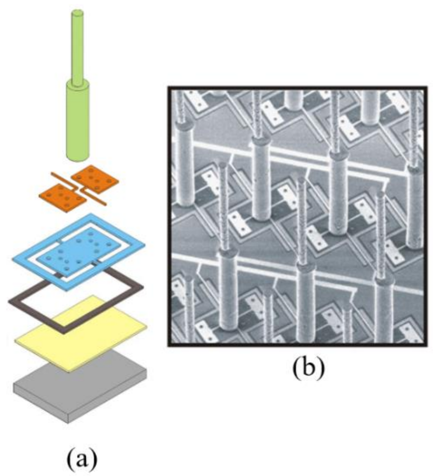

Figure 6. High performance capacitance design by Jaganatharaja *et al* A. Exploded view of each layer of the artificial hair cell B. Final design

Krijnen *et al* also proposed a design based off the development of the two-tiered hair design [17]. This time the hair synthesis was able to produces hairs as tall as 1mm with radii of 25 μm and 12.5 μm for the first and second tier. The paper fails to go into significant detail about the manufacturing techniques used for the capacitance measurements, keeping large portions of the design very similar to the design by M. Dijkstra et al. Through improvements to signal processing and using large arrays of hairs managed via frequency division multiplexing, the system achieves an incredible sensitivity of ~0.4 mm/s with 300Hz bandwidth.

Another design that built on the work put forward by Dijkstra *et al* is the work of Droogendijk *et al* [18]. Similar to Krijnen *et al*, the new artificial hair design was taken advantage of. Again, much of the core design of the capacitance measurement was kept similar, however this research focused on a technique known as electrostatic spring softening (ESS) to increase the sensitivity by enhancing the mechanical response of the system to airflow. It achieves this by applying a bias voltage to the electrodes in at the base of the hair, reducing the torsional stiffness of the hair via ESS [23]. This produces greater change in capacitance for the same air flow. Thanks to this, the device can claim a limit of detection as low as 85 μm/s which is approaching natures accuracy of 30 μm/s [19].

Table 2 shows a comparison of all the devices that use capacitance in order to detect hair tip deflection with both tiered and non-tiered hairs.

Table 2 Summary of capacitance-based devices

Design	Hair Width (μm)	Hair Length (μm)	Hair Material	Air Flow Sensitivity (mm/s)
Cricket	-	50 - 2000	Biological	0.3
Dijkstra *et al* [13]	-	470	SU-8 Photoresist	100-1000
Sadeghi *et al* [14]	100	400	Accura S10 polymer	1.7
Jaganatharaja *et al* [15]	Reduces by ~1/2 at 450μm	900	SU-8 Photoresist	0.85
Bruinink *et al* [16]	50,25	900	SU-8 Photoresist	1
Krijnen *et al* [17]	50,25	1000	SU-8 Photoresist	0.4
Droogendijk *et al* [18]	50,25	800	SU-8 Photoresist	1

III. DISCUSSION

There are clear trends shown across the various devices laid out in this report. First, is the difference in performance in angular sensitivity. While the resistive devices lack in flow sensitivity, the simplicity of a strain gauge allows for more complex mechanical design, exemplified by both of the resistive designs providing individual hair strand angular measurement. While the capacitive devices can utilize arrays of artificial hair cells in a variety of orientations, such as in the design by Sadeghi *et al*, these require more resources to produce and take up more surface area. Surface area is especially key when designing for microelectronic systems and estimation based off images provided shows that the area of the device by Sadeghi *et al* has a surface area of 64 μm^2 compared to just 16 μm^2 and 12 μm^2 for the resistive devices. In practice, however, the lack of sensitivity in the resistive devices neuters any accuracy in directional measurement (Ozaki *et al*) shown in Fig.8A, or in order to increase sensitivity, directionality is sacrificed, and the device becomes more anisotropic (Engel *et al*), as shown in Fig.8B. On balance, this failure to find high angular accuracy puts the resistive devices at a disadvantage to the devices that use capacitive measurement.

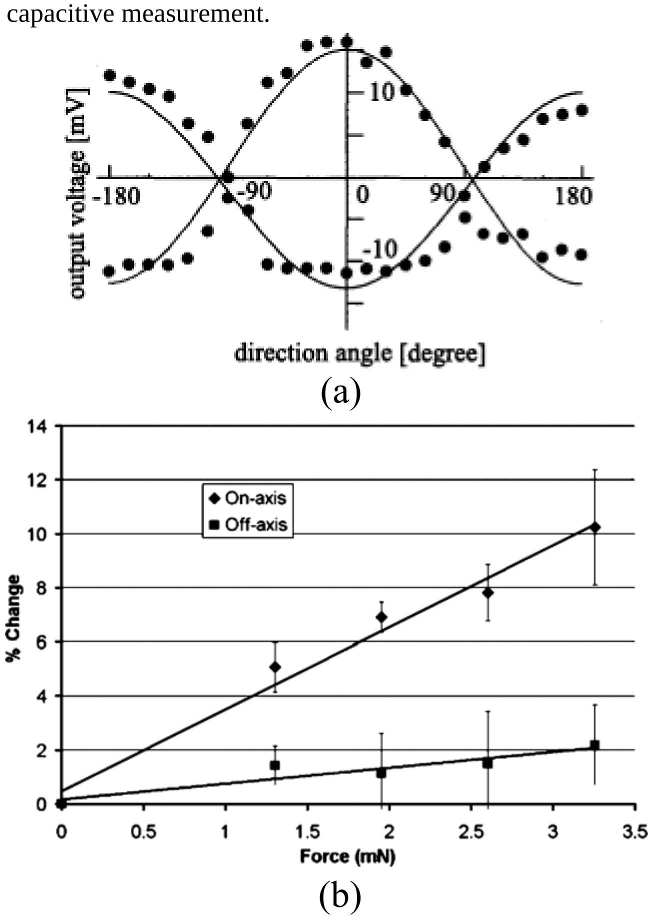

Figure 8. Directional sensitivity of the two resistive devices. A. Directional sensitivity of Ozaki *et al* design B. Directional sensitivity of Engel *et al* design

The second trend, shown across all taxa, is the effect of artificial hair length. This parameter has a large impact on device performance as shown in Fig.7, where the sensitivity of the capacitance devices is plotted against their hair length. This exponential relationship is backed up by the literature where estimations are made that the drag torque produced is proportional to the square of the hair length, or cube depending on the boundary layer conditions [17] [13]. (For all following analysis the design proposed by Chen et al has been excluded due to specificity to liquid measurements)

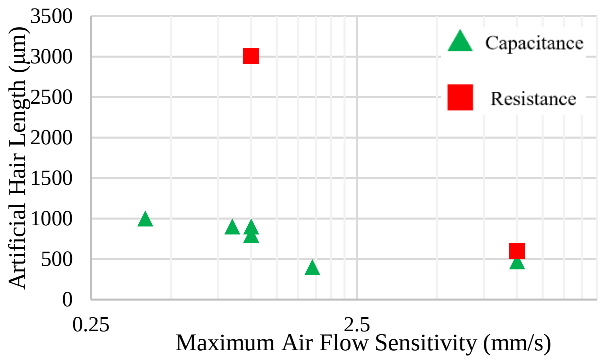

Figure 7. Sensitivity and hair length comparison of resistance and capacitance devices. *Sensitivity data estimated based on comparison of strain sensitivity to other resistive devices

The small sample size inhibits the ability to draw clear conclusions, however qualitative trends are visible and reinforce the decision to group the devices into the previously mentioned taxa. The devices using capacitance achieved much higher sensitivities for the same hair length, and also achieved much higher sensitivity overall. Even within the capacitive group, the split based on hair length unearths a clear difference in sensitivity.

If the development of the polyurethane hairs is transferrable to capacitive devices, which has yet to be proven, it could make for a large leap forward in sensitivity. Through doing some rough estimates, and using a squared proportionality of hair length and sensitivity as discussed previously, it could be argued that capacitive devices with artificial hairs as long as 3000 μm could reach a theoretical maximum sensitivity of 0.1-0.2 mm/s.

1) *APPRAISAL OF PUBLISHED WORK*

The quality of the sources themselves brings into question the reliability of the analysis performed in this report. The most recent published source available was found to be by Sadeghi *et al* and was released in 2013. Micromanufacturing capabilities have improved dramatically since then, and if any current attempts at developing a device took place, the fabrication and performance of a method of either taxon is likely to be improved.

Furthermore, a large number of the sources failed to provide critical information, such as number of artificial hairs in each array, when claiming device sensitivity. This could drastically affect performance as the parallel performance is a key aspect of both the engineered solutions, and the biological solution.

Despite this the published work shows a high level of detail and provides a good faith in the devices and their capabilities.

IV. CONCLUSIONS

The devices laid out in this review show a variety of capabilities, with the highest performance device showing a flow velocity sensitivity of 0.4 mm/s. Devices that used a form of capacitive measurement showed far greater sensitivity given the same artificial hair length, showing both that the hair length itself and the choice of capacitive or resistive measurement has a large impact on device performance.

Comparing these devices to the natural solutions that they mimic, studies on crickets showed that the insects are capable of air flow sensitivities of up to 0.3 mm/s [7][8]. This is 0.1 mm/s greater than the most sensitive man-made device. The crickets also have incredible locational accuracy, achieving an angular resolution of 1º-1.5º after just 1 ms of exposure, unlike all the majority of man-made devices which achieved, at best, 13º of angular resolution, showing that development still has some way to go before nature is matched in performance [24].

Compared to conventional devices, such as hot wire anemometers, the biomimetic counterparts excel. Rated sensitivities on a variety of sources of anemometers show that the devices very rarely achieve sensitivities of above 0.1 m/s with the maximum accuracy found of 0.01m/s, still well below the maximum of 0.4 mm/s of the best biomimetic device and well within the capability of all the capacitive devices with hair lengths of greater than 400 µm [21].

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