Optimization Of Bio-inspired Hair Sensor Arrays

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Crickets use a pair of hairy appendages on their abdomen called cerci, each of which contains numerous mechano-receptive filiform hairs (Fig. 1). These sensitive hairs can respond even to the slightest air movements, down to 0.03 mm/s, generated by the approaching predators and initiating an escape mechanism in the crickets [1]. Bio-mimicking the cricket cerci, arrays of artificial hair sensors have been successfully fabricated using advanced MEMS techniques [2] (Fig. 2). Each artificial sensor consists of a SU-8 hair mounted on a suspended nitride membrane with two chromium electrodes on top, which form differential capacitors with the conductive silicon substrate (Fig. 3). Air flows on the sensors induce a hair deflection resulting in a membrane-tilt which is capacitively measured.

Despite its appreciable performance (Fig 4), the actual cricket filiform hairs outperform artificial hair sensors by several orders in sensitivity (Fig. 5). Nevertheless, more careful look at the anatomy and physiology of the cricket cerci provides new directions to be explored with MEMS technologies to realize higher sensitivities on a par with crickets'. This paper aims to provide an overview of comparisons between the actual and artificial hair sensors in terms of sensitivity, structural functionalities and robustness and draws out constructive insights to optimize sensor performance.

Crickets employ thin (~ 1 to 9 µm diameter) and long (~150 to 1500 µm) hairs which results in small moment of inertia, necessary to operate in the required frequency range of 200 Hz. With MEMS technology, we are only able to fabricate SU-8 hairs of length 1 mm with 50 µm diameter, resulting in a moment of inertia which is approximately 150 times larger than the crickets. Further, the torsional stiffness of the silicon nitride springs is approximately 360 times larger when compared to that of cricket hairs. It is possible to fabricate springs with small torsional stiffness either by using soft polymers or by modifying the spring cross-sections.

Crickets' filiform hairs are arranged radially on cerci, whose unique structure facilitates 3D flow sensing. The present artificial hair sensors are arranged uniformly on a flat substrate, restricting its sensitivity only to longitudinal flows [3]. Though functionally untested yet, an attempt to structurally mimic the cerci is made by assembling three flat substrates containing artificial hair sensor arrays (Fig 6). Such an assembly enables the flow to have a transversal component, resulting in increased sensitivity.

While the cricket hairs are robust enough to withstand in real-life, drastic environments involving airflows of 1 m/s, artificial hairs could very well stop working even at low flow rates of few mm/s. Alternative sensor design and technique, which is free of weak mechanical parts could help to achieve the required robustness. With the help of advanced MEMS technology, it is a challenge to achieve the overall performance range of the actual cricket hair sensors and this work seeks to find the basic guidelines in pursuing it.

References
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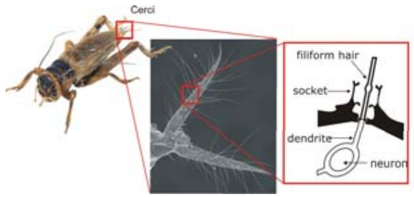

Figure 1. Mechano-receptive hairs found on cerci of crickets [SEM image courtesy: G. Jeronimides, Univesity of Reading, UK.]

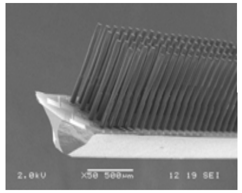

Figure 2. MEMS-based, biomimetic artificial hair sensor arrays

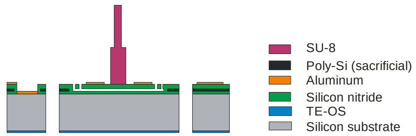

Figure 3. Schematic of the MEMS-based, artificial hair sensor

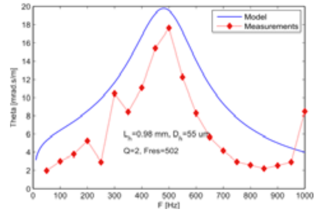

Figure 4. Measured (optically) and modeled normalized sensitivity of realized artificial hair sensors vs. frequency

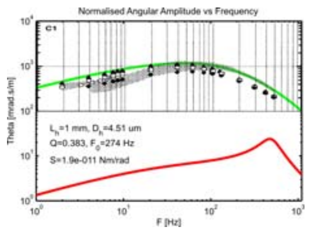

Figure 5. Comparison of model predicted response for cricket hairs (green line) and model predicted response for artificial hair-sensor design (red line)

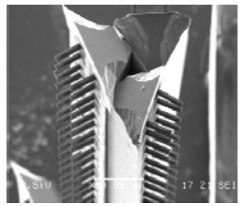

Figure 6. Structurally mimicked artificial cerci.