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Current Opinion in
Insect Science

Insect-inspired acoustic micro-sensors

Y Zhang, A Reid and JFC Windmill

Micro-Electro Mechanical System (MEMS) microphones inspired by the remarkable phonotactic capability of *Ormia ochracea* offer the promise of microscale directional microphones with a greatly reduced need for post-processing of signals. Gravid *O. ochracea* females can locate their host cricket's 5 kHz mating calls to an accuracy of less than 2° despite having a distance of approximately 500 μm between the ears. MEMS devices base on the principles of operation of *O. ochracea's* hearing system have been well studied, however commercial implementation has proven challenging due to the system's reliance on carefully tailored ratios of stiffness and damping, which are difficult to realize in standard MEMS fabrication processes, necessitating a trade-off between wide-band operation and sensitivity. A survey of the variety of strategies that have been followed to address these inherent challenges is presented.

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Introduction

The traditional method of sound source localization is to build a microphone array which combines at least two independent omnidirectional microphones [1]. Calculating the incident angle of sound waves then depends on the separating distance (i.e. time delay) between the microphones receiving the plane waves [2–4]. Similar to microphone arrays, many large animals including human beings have two ears with sufficient separation that the nervous system is able to resolve the interaural time difference (ITD) and interaural intensity difference (IID) to determine the source location. The requirement for spatial separation poses a fundamental problem for sound localization in small animals [5] and in micro-scale devices (i.e. Micro-Electro-Mechanic-System (MEMS) devices) smaller than the wavelength of interest.

In the 1990's, *O. ochracea* was found to have a great capability for detecting sound source [6,7••,8]. The parasitic female *Ormia* uses auditory cues to localize the mating call of a host *Gryllus*, a genus of cricket, and then deposits its predaceous larvae on the host [9]. The cricket's mating call has a fundamental frequency around 5 kHz and wavelength at approximately 70 mm, compared to the interaural distance of *Ormia* that is only around 520 μm [10,11]. Despite the extremely small distance that gives the original maximum ITD and IID as approximately 1.5 μs and 1 dB [12], respectively, experimental investigations show that it can localize the mating call with a resolution less than 2° [13]. This high accuracy is attributed to the mechanical coupling structure of *Ormia*'s ear, as shown in Figure 1(a) and (b), which enhances both ITD and IID by up to 40 times greater than the original values at 5 kHz [14••]. The first resonance is a rocking mode about the bridge centre point, and the second is a translational mode with each end of the bridge moving in-phase while the bridge bends in the middle as shown in Figure 1(c). The response of the Ormia ear at any frequency is then described by a linear combination of these resonance modes [15••].

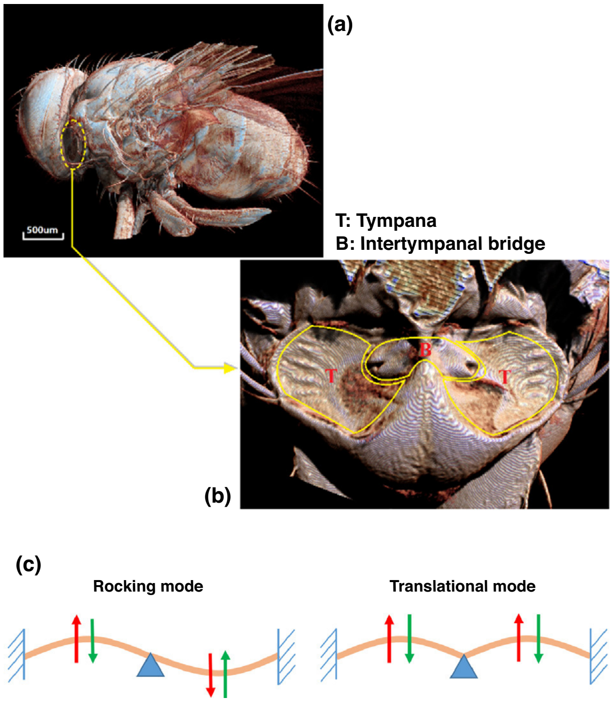
Ormia-inspired MEMS microphone designs can be broadly separated into two main categories in terms of their directivity: the first-order and the second-order. The response of the first-order microphones is proportional to the pressure gradient combined with the integral of pressure across the surface [16,17] while second-order microphones have directional responses that are proportional to the difference between the gradients [18].

First order Ormia inspired microphones

First-order *Ormia*-inspired microphone designs include the see-saw model [19–22] and the clamped diaphragms model [23–27] as shown in Figure 2. See-saw models' defining characteristic is a pivot between two unclamped diaphragms. An early iteration of this design from Miles *et al.* [19,28,29] used a polysilicon diaphragm supported with well-distributed crossed stiffeners [30•,31,32] to tailor the relative sensitivities of the rocking and translational modes of the device while lowering the overall mass. As with most of the designs, amplification of directional cues occurs only in a single narrow working frequency band [33–35].

The transduction method plays a key role in the sensitivity and the amplification of directional cues. Three transduction methods have been attempted by Miles *et al.*, paralleled-plate capacitive sensing [20,36], optical sensing [31,37,38•], and comb-finger capacitive sensing

Figure 1



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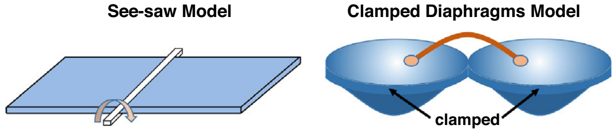
MicroCT scanned images of Ormia ochracea: **(a)** The side view of Ormia's body. **(b)** The frontal face of the hearing organ. **(c)** A sketch of the two main resonance modes: rocking mode and translational mode.

[17,39•]. For parallel-plate sensing, the SNR is negatively influenced by electronic noise, and the viscous damping caused by the air between the diaphragm and the back-plate leads to thermal noise [40]. Optical sensing based on a phase-sensitive diffraction grating structure can lower noise and power requirements compared to capacitive sensing. This method is achieved by incorporating inter-digitated comb fingers at the ends of the diaphragm. However, optical sensing is a comparably high-cost transduction method, which is generally considered not suitable for commercial use. Capacitive combs, in contrast, can be fabricated in a single layer MEMS device and offers the benefits of extremely low noise [41••,42] at the trade-off of electrical sensitivity. In recent years PZT [43–45] or Aluminium Nitride [46] thin film layers have been used in combination with cantilevers connecting to the diaphragms to provide an alternative method of transduction.

Figure 2



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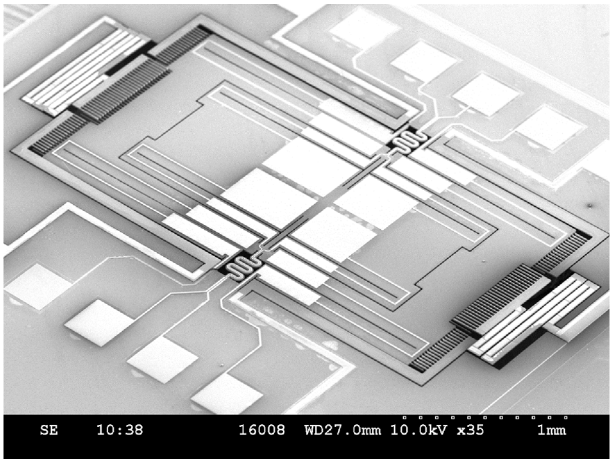
Schematic diaphragms of see-saw and clamped diaphragms Ormia inspired microphone models.

The method of transduction has a particular impact for *Ormia*-inspired microphones due to the sensitivity of the desired amplification of ITD to damping. High damping ratios from capacitive back-plates and thin film damping broaden the frequency range of the increase in directional cues at the expense of the gain of amplification [47•], while lower damping ratios benefit from increased sensitivity but produce only a single narrow working band [48•]. Obtaining a flat amplification of ITD or IID across a usable frequency range, a critical element of hearing-aid applications, may be achieved by sacrificing significant gain in the amplification as demonstrated in two designs from Miles *et al.* — one using a capacitive comb sensing scheme [40] and the other an optical diffraction grating [49] — which nevertheless show the same mechanical characteristics. The resonance frequencies for these devices places the lower, rocking mode at 735 Hz with the higher, translational mode at 15 427 Hz. The estimated damping remains low, given the absence of a back-plate in either design, at 0.16 for the rocking mode and 0.25 for the translational mode with the result that the devices provide a flat gain of approximately 1.5 times the ITD. An alternative strategy was developed by Zhang *et al.* [50–53,54•,55•] where multiple working frequency bands extend the useable working range of the device. This extends the see-saw design pattern through the use of asymmetric diaphragms and an inner and outer diaphragm configuration, with each providing two frequency bands. The design used a piezoelectric sensing system, and produced directional responses at frequency bands below 10 kHz. Figure 3 shows the latest published development of the device.

Measuring amplifications in intensity difference poses additional challenges. Since the amplitude of response will be proportional to the local sound pressure a direct comparison would require the use of a reference, omnidirectional microphone. This enlarges the entire package size and brings errors caused by the offset between the *Ormia* inspired microphone and the omnidirectional one. Yu *et al.* circumvented this problem by taking the ratio of amplitudes of the two diaphragms [24,56,57] and their phase difference which were termed the mechanical Interaural Intensity Difference (mIID) and mechanical Interaural Phase Difference (mIPD) respectively. These measures obviate the need for a reference microphone, however as the motion of the diaphragm on the contralateral side to the source is ideally greatly suppressed the denominator of these equations is often near zero leading to a high Cauchy-like noise error in the measurement of sound angle. The devices developed by Yu *et al.* are intended to directly mimic the *Ormiine* ear's single

Figure 3



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Ormia-inspired MEMS microphone with multiple working frequency bands operation, developed by Zhang *et al.* [62].
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frequency operation [47•]. The device has its best performance at 8 kHz, which is slightly below the first resonance and very similar to *Ormia's* hearing organ (i.e. the best performance of Ormia's ear occurs at 5 kHz, however the first resonance frequency is slightly higher than that value, which is around 7 kHz). At 8 kHz the slope of the mIPD versus the azimuth sound incident angle of this device is about 1.69 deg/deg.

The microphones presented here only permit the localization of sound on one axis, either the azimuth measured around the axis normal to the plane of the device, or the pitch, measured around the axis normal to the line between the two diaphragms. In any situation where either the azimuth or the pitch cannot be assumed to be zero there will be some ambiguity in the results, with the directional reading of the sensor describing a paraboloid surface in space. The problem could be potentially solved with an array of directional microphones [58,59]; however several teams have attempted to create sensors which extend the principles of *Ormia*-inspired hearing to two dimensions. The simplest of these consists of three mechanically linked diaphragms in a triangle formation around a central pivot [60•]. Comparing the phase difference between any two diaphragms will yield a set of azimuth and pitch angles, which can then be correlated to the set produced by another pair of diaphragms to localize the sound source [61]. Although this sensor is capable of resolving the ambiguity in pitch and azimuth angle it does so by triangulation and offers little improvement over a similarly spaced array of *Ormia*-inspired microphones. In 2018 Zhang *et al.* introduced a further new microphone design. The design has two pairs of orthogonal diaphragms, utilising the *Ormia* paradigm [62]. Each pair has independent directionality responses, leading to the potential for 3D sound localization. This single device can be regarded as two individual bi-directional microphones. It is also notable that this device combines both piezoelectric and capacitive sensing. Ono *et al.* [63,64] and Chen *et al.* [65] have proposed centrally supported gimbals to achieve the same goal, however, all these designs are either on the meso-scale or are proposed models only.

Second order Ormia inspired microphones

A second-order directional microphone has better ability to reject off-axis noise since it detects the sound location through estimating the second spatial derivative of the pressure gradient. The first model of second-order *Ormia*-inspired MEMS microphone was designed by Liu *et al.* [18,66], which joins two single *Ormia*-inspired first-order polysilicon microphones built by Miles *et al.* mentioned above with an S-type beam in the middle. Developing Liu's work, Albahri [67•] optimized the model and replaced the S-type connection with a simple rectangular beam and added extra mass to the sides of the rotating plates to reduce the influence of any mismatch between the two single microphones. Meanwhile, Huo [68] changed the two diaphragms into a structure constructed with comb fingers, and removed the hinge. In theory, this gives the microphone a wide bandwidth of operation as the relative motion of the two diaphragms is not dependent on the frequency, however the sensitivity of the second order microphone increases with the square of the surface area, rather than being directly proportional, leading to significant miniaturisation challenges.

Conclusions

Biomimetic microphones, originally inspired by the mechanical structure of *O. ochracea*'s hearing organ, have higher directionality and are more suitable for microfabrication sensitivity than any conventional directional microphone array. They amplify the time delay and intensity difference efficiently between two membranes despite their tiny dimensions. Relying on different design concepts, such microphones can be made more complex in order to achieve higher mechanical sensitivity, or be simplified to decrease difficulties in fabrication. Designs can be divided into various groups, including first-order see-saw model and clamped diaphragms models, and second-order models. However, this model does require an omnidirectional microphone to get the sound pressure variation and bring full function to a system that requires accurate sound incident angle definition. The clamped-diaphragm model uses mIPD to locate sound and solve the omnidirectional microphone problem. But the fixed ends boundary of the diaphragm in this model generates a reaction force and so degrades the effective force driving vibration. The small displacement of the membranes can only be measured using optical (fibre) techniques so far. Despite patents relating to *O. ochracea* inspired microphones now numbering in double figures and stretching back nearly 20 years, there is still research ongoing to solve the various issues to implementing these microphones in commercial, real-world applications. The growing market for miniature microphones, and need for technical improvements, across industries including mobile telecommunications, hearing prostheses and computing, suggests that such research efforts will continue into the future.

Conflict of interest statement

Nothing declared.

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