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MEMS Directional Sound Sensor with Simultaneous Detection of Two Frequency Bands

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Abstract—Conventional directional sound sensing systems use an array of spatially separated microphones to achieve directional sensing by monitoring the arrival times and amplitudes at each microphone. The directional accuracy is then determined by the spatial separation of the microphones. In contrast, the *Ormia ochracea* fly’s ears are separated by merely 500 μm yet have remarkable sensitivity to the direction of sound even at wavelengths two orders of magnitude greater than the size of the fly’s hearing structure. The fly uses a unique system which consists of two identical wings hinged at the center to determine the direction of sound. Recently, our group demonstrated a MEMS-based directional sound sensor modeled on the hearing system of the fly. The sensor response has two resonant modes (rocking and bending) and a strong response was only achieved at the bending frequency since the amplitude of the rocking mode depends on the tiny pressure difference between the two wings. In this paper, we report achievement of dual-band sensing using asymmetric wings to enhance the response at the rocking frequency. The fabricated sensor showed nearly equal responses at the rocking and bending frequencies.

I. INTRODUCTION

In the process of human hearing, the direction of incident low frequency sound is primarily determined by sensing the interaural phase difference (IPD) [1] or, equivalently, the difference in arrival times between two spatially separated receivers (ears). In extremely small animals like insects, the minimal separation between their ears makes the IPD virtually imperceptible. The *Ormia ochracea* fly, however, with an interaural separation of less than 500 μm, is able to determine the direction of incoming sound with a theoretical accuracy of 1°-2° given adequate signal to noise ratio (SNR). [2] This exceptional acoustic direction-finding capability allows the fly to rapidly locate chirping crickets upon which the fly deposits parasitic larvae.

A number of micro-electromechanical systems (MEMS) based devices have since been developed that emulate the fly’s hearing system. For example, Miles, *et al.*, [4] employed interdigitated diffracting gratings combined with a vertical cavity surface emitting laser (VCSEL) and photodiode array for measuring vibration amplitudes interferometrically. Other approaches include the use of a capacitive diaphragm and backplate scheme, similar to that used in conventional electrostatic microphones, [5] and creating a Fabry-Perot interferometer using a superluminescent diode and a Mylar diaphragm that acts as the tympanum. [6] Instead of using the optical readout schemes above, we have developed a sensor with electronic readout using interdigitated comb fingers attached to the ends of these wings as illustrated in Figure 1). [7] This approach can lead to monolithic integration of signal processing electronics with the MEMS sensor for miniaturization.

The *Ormine* hearing structure is uniquely adapted for directional hearing due to the mechanical coupling of its two tympana. Instead of two isolated receivers, the two tympana are connected by a semi-rigid cuticular structure. Modeling the combined structure as two coupled, damped harmonic oscillators, Miles, *et al.*, [3] showed that the motion is a combination of two fundamental modes. One mode, in which the two sides oscillate 180° out-of-phase, can be envisioned as a rocking motion similar to a see-saw. In the second mode, the coupling structure bends in the middle and the two sides oscillate in-phase, generating a bending-like motion. The rocking motion is the result of a difference in acoustic pressure between the two sides; namely the total effective rocking pressure, $P_r(t)$, is given by $P_r(t) = P_i(t) + P_c(t)$, where $P_i$ is the pressure on the ipsilateral or near side and $P_c$ is the contralateral pressure on the side further from the sound source. The bending motion is driven, instead, by the sum of the two pressures: $P_b(t) = P_i(t) + P_c(t)$. This results in a bending amplitude which is much larger than that of the rocking mode.

The interaural time difference ($\tau$) of a plane wave incident...
on the two wings is given by $d \sin \theta / v_s$ (where $d$ is the lateral separation of the two tympana, $\theta$ is the angle of incidence from normal, and $v_s$ is the speed of sound). If the angular frequency of the incident sound wave is $\omega$ then the corresponding phase difference is given by $\phi \equiv \pm \omega \tau / 2$. Because the dimensions of the device are small compared to the wavelength at resonance, the pressure amplitude is nearly constant across the device which means the rocking mode is almost entirely driven by the phase difference, $\tau$. [3] The amplitude of the rocking, $A_r$, and bending, $A_b$, modes as a function of the phase difference can be written as

$$A_r \propto s P_0 \sin \phi$$

$$A_b \propto s P_0 \cos \phi$$

(1)

where $s$ is the area of each wing, and $P_0$ is the incident acoustic pressure amplitude. In the long-wavelength limit, however, the phase difference between the two sides becomes only a few degrees, and Eqs 1 can be simplified to obtain the directional dependence of the rocking and bending amplitudes, given as

$$A_r \propto (\omega d/v_s)s P_0 \sin \theta \cos \theta$$

$$A_b \propto s P_0 \cos \theta$$

(2)

Note that the bending mode amplitude is independent of the incident direction of sound.

Figure 2 shows the measured frequency response of the sensor in Fig. 1 at a set of incident angles using a laser vibrometer. As expected, the response at the rocking frequency was found to be relatively weak compared to that of at the bending frequency. In addition, the amplitude at the bending motion showed a strong dependence on the direction of sound as opposed to a nearly constant amplitude as expected (Eq. 2) when sound was assumed to interact with only the front surface of the wings. Since the backside of the device is open, the system becomes equivalent to a pressure-gradient microphone. In this case, the net pressure amplitude has a cosine dependence and the angular dependence of the two amplitudes are now given by [7]

$$A_r \propto (\omega d/v_s)s P_0 \sin \theta \cos \theta$$

$$A_b \propto s P_0 \cos \theta$$

(3)

which explains the difference between earlier prediction (Eq 2) and the experimental results shown in Figure 3.

The directional dependence of the sensor response was electronically measured using an Irvine Sensors MS3110 capacitive readout IC with a sensitivity to $4$ aF/$\sqrt{\text{Hz}}$, with which the changing capacitance is compared to an on-chip reference capacitor and forms a balanced bridge with the trim capacitors in the IC. The measurement was done in an anechoic chamber and the sensor was driven by a pure sine wave at the bending mode frequency. Figure 3 shows the measured directional response as the sensor was rotated relative to a fixed sound source. The response has the expected cosine dependence at the bending frequency. The amplitude at the rocking frequency is too small to be measured electronically due to limitations of the present electronic readout system. In the following, an approach to enhance the response at the rocking frequency will be described.

II. DESIGN

With a lateral separation between the two wings of roughly one millimeter (versus a wavelength of approximately 25 cm), the phase difference between the two sides is approximately $1.4^\circ$ in the rocking mode. This means that the pressure at the two wings is essentially in phase and causes the difference in pressure to be very small. Because the rocking mode amplitude is governed by this difference in pressure, the rocking mode is barely detectable above the noise floor as seen in the frequency response in Fig. 2. If the areas of the two wings ($s$ in Eqs 3) are not identical, however, the difference in area can cause a much greater difference in the effective force on each side and the amplitude at the rocking frequency is greatly increased. A finite element model was developed with asymmetric wings in COMSOL MULTIPHYSICS software and extensive simulation was conducted to optimize the design for...
fabrication by the SOIMUMPS process available through the MEMSCAP foundry service. The new sensor consists of two wings with dimensions $1 \times 1 \text{mm}^2$ and $1 \times 0.75 \text{mm}^2$ which are connected to the substrate via two $100 \mu\text{m}$ long and $40 \mu\text{m}$ wide legs (see Fig. 4). The substrate is $400 \mu\text{m}$ of n-type Si with $1 \mu\text{m}$ SiO$_2$ which are etched away beneath the device to eliminate squeeze film damping.

### III. RESULTS

The frequency response of the sensor in Fig. 4 was simulated using COMSOL and treating the incident sound as a plane wave to properly take into account the diffraction effects. This involves simultaneously solving structural and wave equations. The damping effects due to air drag was taken into account using the approach described in Reference [7]. Figure 5 shows the simulated frequency response of the sensor with asymmetric wings assuming the sound pressure at each frequency to be 1 Pa. The rocking and bending resonances were at 2.79 kHz and 5.3 kHz, respectively. It can be easily seen that the use of the asymmetric wings greatly enhanced the amplitude at the rocking frequency.

In addition to the frequency response, the amplitude at the rocking and bending frequencies as a function of incident angle of sound was also simulated as shown in Fig. 6. The data shows that at both frequencies the amplitudes have the expected cosine dependence since the driving force is determined by $(s_1 - s_2)P_0\cos\theta$, where $s_1$ and $s_2$ are the areas of the wings.

The optimized sensors were fabricated on SOI substrate with a 10 $\mu\text{m}$ device layer; the details of the fabrication can be found in Ref. [7]. The device was mounted on an open-backed dual in-line package (DIP) socket to minimize the interaction of the sound with the packaging. Using a Polytec OFV-534 laser vibrometer and driven with a swept sine wave from 1 - 10 kHz, the mechanical frequency response was measured for a set of incident angles as shown in Fig. 7. It can be seen that the amplitude of the measured frequency response is small compared to the simulation in Fig. 5. This is primarily due to the fast frequency sweep used in the measurement compared to the time constant of the sensor ($\approx$5 ms). The measured rocking and bending frequencies of the sensor were found to have nearly the same amplitudes with frequencies around 2.78 kHz and 5.29 kHz, respectively, and a bandwidth of about 100 Hz, primarily due to viscous air damping (Fig. 7). The measured frequencies are in good agreement with that obtained from COMSOL simulation results. In addition, amplitudes at the two frequencies decrease rapidly as the incident angle is increased. The detailed comparison with the expected cosine behavior requires measurements to be carried out in an anechoic chamber using electronic readout which is
IV. CONCLUSION

The device presented in this paper expands the potential for sensors modeled after the *Ormia ochracea* hearing system to allow acoustic direction finding with exceptional accuracy. In earlier designs, the response was limited to a single, narrow frequency band and the present work shows the possibility of extending response into two bands while maintaining the directional sensitivity. The sensor provided spectral response in two bands with nearly the same amplitude. The simulated and measured frequency responses are found to be in close agreement which validates the approach used for simulation. By adding a second frequency to earlier designs, the work presented here allows us to compare multiple frequencies to improve accuracy in finding the direction of wideband sources, or it could add the ability to distinguish between two specific sources.

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