

Fly-ear inspired micro-sensor for sound source localization in two dimensions

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Abstract: Inspired by the hearing organ of the fly *Ormia ochracea*, a miniature sound localization sensor is developed, which can be used to pinpoint a sound source in two dimensions described by the azimuth and elevation angles. The sensor device employs an equilateral triangle configuration consisting of three mechanically coupled circular membranes whose oscillations are detected by a fiber-optic system. The experimental results indicate that significant amplification of the directional cues and directional sensitivity can be achieved with the fly-ear inspired sensor design. This work can provide a basis for the development of miniature sound localization sensors in two dimensions.

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1. Introduction

Microphone arrays deployed over a broad spatial range have been widely used in conventional sound source localization systems.^{1,2} To determine the sound direction, the most popular method is based on estimation of the time deference of arrival (TDOA) between a microphone pair in an array. For a far-field sound source, the TDOA can be obtained as $\tau = d \sin \theta / c$, where c is the sound speed, d is the distance between the two microphones, and θ is the incident angle of the sound source. By using TDOA information from multiple microphone pairs along with the triangulation method,³ the incident sound source can be pinpointed in a three-dimensional space. Clearly, if the distance between the microphone pair becomes much smaller than the sound wavelength, the TDOA will become indiscernible for detecting the sound direction. This poses a fundamental challenge for the miniaturization of microphone arrays.

A biological solution to the size constraint predicament has been found after studying the directional hearing ability of the parasitoid fly *Ormia ochracea*. Although the interaural distance of the fly ears is only 520 μm , the fly can localize its cricket host with a resolution of as small as 2°. The key to this remarkable directional hearing capability has been linked to the mechanical coupling mechanism of the fly ear; the two eardrums are coupled by an intertympanal bridge.⁵⁻⁷ As a result, the directional cues at the mechanical response level [i.e., mechanical interaural time difference (mITD) and mechanical interaural intensity difference (mIID)] can be greatly amplified.

Inspired by the fly ear, several research groups have developed miniature directional microphones based on various configurations. For example, micro-electro-mechanical system (MEMS) based microphones, which utilize a rigid rectangular plate rotated about a compliant pivot, have been demonstrated for the detection of small pressure gradients.⁸⁻¹⁰ More recently, a device based on a similar design has been reported with a capacitive method integrated into the device for measuring the

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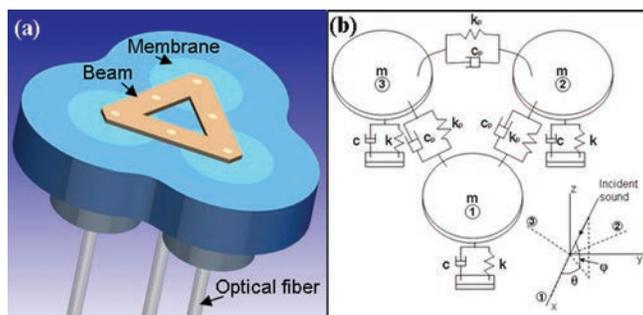


Fig. 1. (Color online) (a) Schematic of the fly ear inspired sound localization sensor and (b) illustration of the reduced order model of the sensor device.

diaphragm response.¹¹ In our previous study, it has been found that the fly-ear structure has a “medium” coupling characteristic and optical directional microphones with two structurally coupled circular diaphragms have been demonstrated at the large-scale as well as the micro-scale for the amplification of directional cues.^{12,13} While the previous work had been focused on mimicking the fly’s hearing system, the aforementioned devices can only be used for localizing sound in one dimension. In another effort, a circular diaphragm with its center supported by a gimbal has been implemented in a microphone device, which can potentially be used for two-dimensional sound localization.^{14,15}

In this letter, we extend the understanding of fly ear’s coupling physics from one dimension to two dimensions and use this enhanced understanding to facilitate the design and development of a novel fly-ear inspired miniature sound localization sensor, which can be used to localize a sound source in two dimensions (azimuth and elevation). Endowed with the bio-inspired mechanical coupling mechanism, great amplification in both the directional cues and directional sensitivity can be obtained with such a sensor device. As a result, this sensor can achieve a performance comparable to that of a conventional large-scale microphone array, while being designed on a much smaller scale.

2. Sensor design and reduced-order model

A sensing structure resembling a two-dimensional mechanical coupling mechanism is proposed here, as shown in Fig. 1(a). Three boundary-clamped circular membranes are arranged to form an equilateral triangular configuration, with a membrane located at each corner of the triangle. A beam pivoted about its center is employed to couple two adjacent membranes at their centers. A reduced-order model of the system is developed to achieve a fundamental understanding of the two-dimensional coupling physics. As shown in Fig. 1(b), the sensor device with three membranes (membranes 1, 2, and 3) is considered as a system consisting of three mass-spring-damper sub-systems. Each of the masses (m), springs (k), and dampers (c) represents a diaphragm which can oscillate when subjected to an incident sound wave. Each of the coupling beams is considered as a combination of a rotational spring (k_p) and a damper (c_p). From the governing equations, the natural frequencies of the system are found to be $f_1 = f_2 = \sqrt{(k + k_p)/m}$ and $f_3 = \sqrt{(k + 4k_p)/m}$. The first two natural frequencies correspond to the rocking mode of the device, in which one membrane oscillates 180° out of phase with respect to the other two membranes. The third natural frequency corresponds to the bending mode of the device, in which all three membranes oscillate in phase.

In our previous study,¹² it has been pointed out that the fly ear makes use of a combination of the rocking and bending modes to obtain appropriate amplification of the directional cues without sacrificing directional sensitivity (i.e., the derivative of directional cues with respect to the sound incident angle). In this sense, the ratio of the

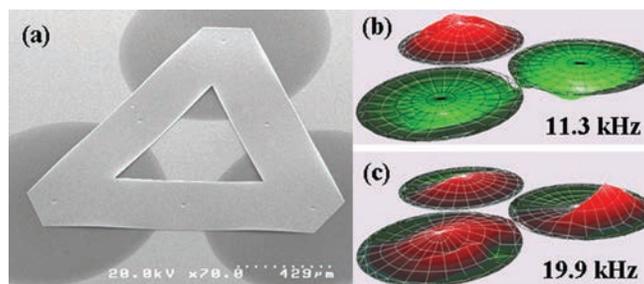


Fig. 2. (Color online) (a) SEM image of the microfabricated sensor device and mode shapes of the sensor device with (b) rocking mode at 11.3 kHz and (c) bending mode at 19.9 kHz.

bending mode to rocking mode natural frequencies, which is referred to as the resonance ratio η , plays an important role in achieving the appropriate mechanical coupling between the two membranes. For a fly-ear sized structure with two coupled membranes, if η is too small (close to 1), the mechanical coupling becomes too weak to render enough amplification of the directional cues. On the other hand, if η is too large (>10), the rocking mode dominates the performance, resulting in a directional sensitivity close to zero at relatively large sound incident angles. For the fly ear, the resonance ratio is found to be medium ($\eta=4$), which ensures an appropriate combination of the rocking and bending modes. Here, for a sensor device with three coupled membranes, it can be determined that $\eta = \sqrt{(k + 4k_p)/(k + k_p)}$. Note that when the resonance of the beam (k_p) is much larger than the stiffness of the membrane (k), the maximum resonance ratio is found to be $\eta=2$, which is a medium value. Such a medium valued resonance ratio is expected to help realize appropriate use of both the rocking and bending modes, and thus, effectively facilitate the amplification of both the directional cues and directional sensitivity.

Based on the reduced-order model, the transfer functions of the system can be obtained, which can be further used to determine the directional cues. Here, the mechanical interaural phase difference (mIPD) (equivalent to mITD or TDOA) is chosen as the directional cue for investigation, which describes the phase difference in oscillations between a pair of coupled membranes. By obtaining the mIPDs between two different pairs of coupled membranes as a function of the azimuth angle (θ) and the elevation angle (φ), sound source localization can be achieved in two dimensions. Owing to the bio-inspired two-dimensional coupling principle, the mIPDs and associated directional sensitivities ($\partial\text{mIPD}/\partial\theta$ and $\partial\text{mIPD}/\partial\varphi$) between the two different pairs can be amplified simultaneously.

3. Fabrication, experimental testing, and results

The sensor device, shown in Fig. 2(a), is fabricated by using MEMS fabrication technique. The membrane is made of silicon with a thickness of $0.5\ \mu\text{m}$ and a radius of $590\ \mu\text{m}$. The beam structure employs alternating layers of silicon nitride and silicon oxide with dimensions of $1200\ \mu\text{m} \times 300\ \mu\text{m} \times 3\ \mu\text{m}$. The selection of materials and dimensions is made to ensure the maximum resonance ratio of 2 can be achieved. An experimental study was carried out to characterize the performance of the sensor device. The natural frequencies and mode shapes of the sensor were determined by using a scanning vibrometer (PSV-400, Polytec Waldbronn, Germany). The rocking mode [see Fig. 2(b)] and bending mode [see Fig. 2(c)] natural frequencies were found at 11.3 and 19.9 kHz, respectively, rendering a resonance ratio of 1.76 (close to 2).

To detect the acoustic pressure induced membrane oscillations, a low-coherence fiber-optic interferometric system¹⁶ was employed. The sensor device was integrated with another silicon wafer with three through holes to support three optical fibers positioned to face the centers of the three membranes, facilitating the detection of the membrane oscillations. This optical detection technique has been proven to provide a significantly

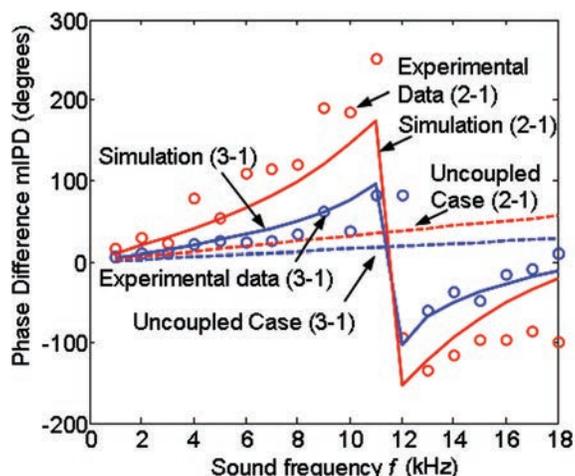


Fig. 3. (Color online) Phase differences between membranes 3 and 1 [denoted as (3 1)] and membranes 2 and 1 [denoted as (2 1)] as a function of sound frequency for $\theta = 150^\circ$ and $\varphi = 90^\circ$. Uncoupled phase differences are analytical results obtained for three uncoupled microphones that are arranged to have the same equilateral triangle configuration.

improved performance over a widely used capacitive sensing method.¹⁶ The fully integrated sensor was mounted on a platform that can be rotated over the azimuth and elevation angles. A speaker was used to play pure-tonal sounds with frequencies ranging from 1 to 18 kHz for obtaining the frequency-response characteristics of the device. The frequency-response curves of the phase differences obtained for a specific azimuth and elevation angle ($\theta = 150^\circ$ and $\varphi = 90^\circ$) are shown in Fig. 3. Significant amplification of the phase differences can be observed at frequencies slightly below or above the rocking mode natural frequency ($f_1 = 11.3$ kHz), when compared with an uncoupled system with three separated membranes of the same dimensions. Furthermore, the phase differences change signs (e.g., 180° phase difference) at a frequency close to the rocking mode natural frequency, which are indicative of the low values of the system damping factors. Above the rocking mode natural frequency, the amplification of the phase differences begins to trail off and becomes greatly reduced around the bending mode resonance location. These results compare well with those obtained through simulations with the reduced-order model. Since the phase differences can be amplified over a large frequency

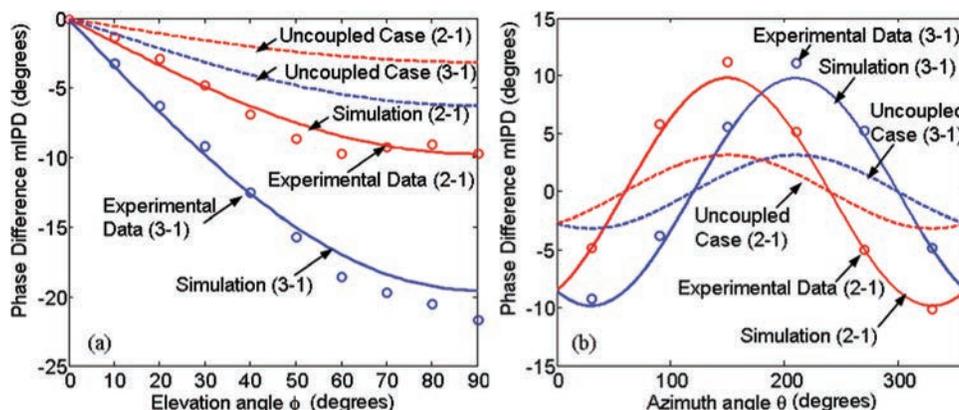


Fig. 4. (Color online) (a) Phase differences [(3 1) and (2 1)] as a function of the elevation angle φ for $\theta = 30^\circ$ at 2 kHz and (b) phase differences [(3 1) and (2 1)] as a function of the azimuth angle θ for $\varphi = 30^\circ$ at 2 kHz.

range, the working frequency of the sensor can be chosen to be either below (e.g., 2–9 kHz) or slightly higher (e.g., 13–16 kHz) than the rocking mode natural frequency.

For proof-of-concept, at a chosen working frequency of 2 kHz, the phase differences are plotted as a function of the elevation angle and azimuth angle, as shown in Figs. 4(a) and 4(b), respectively. When comparing the relative phase differences between the coupled and uncoupled cases at 2 kHz, amplification by a factor of three for both the phase differences and the directional sensitivities ($\partial \text{mIPD} / \partial \theta$ and $\partial \text{mIPD} / \partial \varphi$) is apparent across the entire range of the azimuth and elevation angles. Such a performance is equivalent to that of an uncoupled microphone array with a three times separation (5.2 mm) between the microphones. These results again compare well with the simulation results.

4. Concluding remarks

In conclusion, inspired by the superacute ear of the parasitoid fly *Ormia ochracea*, the mechanical coupling principle has been successfully extended to two dimensions. Our study on a two-dimensional coupling structure shows that it has an inherently medium maximum resonance ratio, which ensures an appropriate use of both the rocking and bending modes, and thus, effectively facilitating the amplification of both the directional cues and directional sensitivity. Based on the two-dimensional coupling mechanics, for the first time, a micro-scale two-dimensional sound localization sensor has been developed. Both modeling and experimental studies with the sensor device have indicated that an amplification of phase differences can be obtained in two dimensions at the working frequency of the sensor, which can be chosen over a wide range. At a selected working frequency of 2 kHz, it has been found that both the phase difference and the directional sensitivity can be amplified by three times, which is equivalent to that obtainable from a conventional microphone array that is three times larger in size. This work can serve as a foundation for the development of miniature fly-ear inspired multi-dimensional sound localization devices, which can impact many fronts that require acoustic localization sensors in a confined space.

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