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Biomimetic optical directional microphone with structurally coupled diaphragms

H. J. Liu, M. Yu,[a] and X. M. Zhang[b]
Department of Mechanical Engineering, University of Maryland, College Park, Maryland 20742, USA

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A biomimetic directional microphone based on structurally coupled diaphragms and a fiber-optic detection system is presented. The microphone design aims to mimic the fly *Ormia Ochracea's* ear structure and capture its performance. Experiments show that the designed microphone amplifies the interaural time difference (ITD) by 4.4 times and has a directional sensitivity of 6.5 μs/deg. An important finding is that one needs to utilize both the rocking and translational vibration modes to obtain the appropriate ITD amplification without sacrifice of directional sensitivity. This work can serve as a foundation for realizing fly-ear inspired miniature directional microphones. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3043724]

Directional microphones have been widely used in applications including hearing aid devices, robot navigation, and underwater sensor networks.[1] A directional microphone is usually constructed from two or more individual microphones, which are arranged in a specific manner to obtain signal differences and create a directional response pattern.[1] Currently, the time delay is widely used to determine the azimuth angle of a sound source.[2] In order to detect the time delay in a discernible manner, the separation between microphones needs to be greater than a critical distance. This poses a fundamental challenge for miniaturization of directional microphones.

In nature, directional hearing usually relies on acoustic cues such as the interaural time difference (ITD) and interaural intensity difference (IID). In some small insects, the auditory receptors are forcibly set close to each other. A striking example can be found in the parasitoid fly *Ormia Ochracea*, which shows a remarkable ability to locate the calling sound (at ~5 kHz) of its host cricket even though its ears are separated by only 520 μm (the best possible ITD of 1.5 μs and IID of less than 1 dB).[3–6] Studies show that the fly possesses a unique mechanical structure called the intertympanal bridge to couple the motions of the two tympanal membranes.[7] With such a structure, both the ITD and IID can be amplified significantly.[8]

Inspired by the fly ear, Miles and co-workers[8–11] presented pioneering work in developing miniature directional microphones. Guided by a two-degree-of-freedom model,[8] these microphones typically consist of two micromachined rigid plates that are joined to a compliant rotational hinge.[9,10] In a sound field, the pressure difference causes the two plates to rotate in opposite directions (rocking mode) while the average pressure causes them to move in the same direction (translational mode). It is aimed to primarily utilize the rocking mode while suppressing the contribution of the translational mode. The natural frequency of the translational mode is intentionally chosen to be far higher than that of the rocking mode and the working frequency range. This is accomplished by using two reinforced plates, which do not experience substantial elastic deformations when subjected to sound pressure fields.[8–11]

Since the fly eardrums are thin cuticular membranes and respond to sound waves like elastic membranes rather than rigid structures,[8] we have developed a continuum mechanics model based on structurally coupled diaphragms to study the fly-ear structure.[12] Our goal is to unravel the underlying science of the fly's hearing mechanism that helps the fly achieve its remarkable performance at its working frequency of 5 kHz and to apply this mechanism to develop directional microphones. After extensive parametrical studies, it has been determined that the fly ear may have to use a combination of the rocking mode and the translational mode to achieve such a performance.[12] Based on this understanding, here, a biomimetic directional microphone is presented, which not only mimics the fly ear with structurally coupled diaphragms but also captures its performance characteristics.

The biomimetic microphone consists of a microphone structure and a fiber-optic detection system, as shown in Fig. 1(a). To mimic the fly's tympanal membranes and intertympanal bridge, the microphone structure is designed to have two identical circular diaphragms, each of which is clamped to a housing block. An interconnecting bridge is used to connect the diaphragm centers and is pivoted about its midpoint. The housing block has two through holes from the backside to facilitate the insertion of optical fibers. To detect the vibrations of each of the diaphragms, a low-coherence fiber-optic interferometric system[13] is used, in which a superluminescent light emitting diode is used as the light source and a tunable Fabry–Pérot filter is used to provide the reference cavity for the two sensing cavities formed by the fiber ends

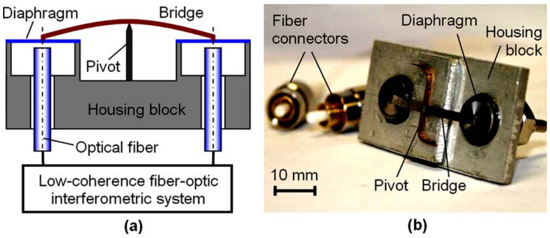

FIG. 1. (Color online) (a) Schematic of the biomimetic directional microphone with structurally coupled diaphragms (cross-sectional view) and a fiber-optic detection system. (b) Photography of the integrated device.

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[a] Author to whom correspondence should be addressed. Electronic mail: mmyu@umd.edu.
[b] Electronic mail: exmzhang@umd.edu.

and the diaphragms. Compared with the widely used capacitive sensing method, this optical detection technique is highly sensitive but immune to the squeeze film damping effect and thermal noise.[14]

An integrated microphone device is shown in Fig. 1(b). The diaphragms are made from Mylar material with 3.5 mm radius and 22 μm thickness. The bridge is a steel beam with dimensions of $25.4\times1.9\times0.1$ mm^3 and its pivot is provided by a brass beam (1.9 mm width and 0.1 mm thickness). Although the size of this device is about 20 times larger than that of the fly ear, it captures the essential dynamics of the fly-ear structure while facilitating a proof-of-concept implementation. This biomimetic directional microphone can be fabricated by using traditional machining and assembly tools. By contrast, the fabrication of a microphone at the scale of the fly ear requires a complicated microfabrication process with the challenges including fabrication of well-clamped thin diaphragms with enough pressure sensitivity and construction of a bridge that is well pivoted at its center and has well characterized material properties.

Through nondimensionalization of the continuum mechanics model, the performance of the biomimetic microphone can be studied by using the five following nondimensional parameters: stiffness ratio, mass ratio, two damping factors, and ratio of diaphragm separation to sound wavelength. For brevity, the detailed mechanics model is not presented and only the influence of the stiffness ratio $\chi_k = k_b/k_d$ is studied here, where the stiffness of the bridge and the diaphragm is defined as $k_b=48E_bI_b/L^3$ and $k_d = 16\pi E_d h_d^3/12a^2(1-\upsilon_d^2)$; I_b and E_b are the bridge area moment of inertia and Young's modulus of the bridge; the variables a, h_d, υ_d, and E_d are the thickness, Poisson's ratio, and Young's modulus of the diaphragm, respectively; and L represents the diaphragm center separation. The microphone design parameters have been carefully chosen to capture the fly-ear performance. Due to the different sizes and materials, the design differs from the fly-ear structure in terms of the natural frequencies and the working frequencies. However, in both cases, the first translational mode natural frequency (31 kHz for the fly and 2 kHz for the microphone) is not too far above the first rocking mode natural frequency (7.1 kHz for the fly and 1.2 kHz for the microphone). Such a frequency separation ensures contributions of both the translational and rocking modes to the response. It is noted that the biomimetic design does not just simply scale up the fly-ear parameters; instead, it aims to capture the essential mode coupling mechanism of the fly-ear structure.

As the designed microphone and the fly ear work at different frequencies (5 kHz for the fly and 1.1 kHz for the microphone), in order to make a meaningful comparison of their performance, interaural phase difference (IPD) is chosen as the first performance parameter. The IPD is defined as the phase difference between the two responses of the ears (or diaphragms). Independent of the sound-source frequency f, the IPD always ranges from $-180°$ to $180°$ and the corresponding ITD can be determined from $\mathrm{ITD}=\mathrm{IPD}/2\pi f$. Another chosen performance parameter is the directional sensitivity (DS), which is defined as $\mathrm{DS}=\partial(\mathrm{IPD})/\partial\theta$ (or equivalent $\mathrm{DS}=\partial(\mathrm{ITD})/\partial\theta$). DS can be used to evaluate the ability to discern a particular azimuth angle.

Based on the parametric studies, the structural coupling in the fly-ear structure is a key to the amplification of IPD (or ITD). The coupling strength is mainly determined by the stiffness ratio χ_k; the larger the stiffness ratio, the stronger the coupling. For the designed microphone and fly-ear structure, the simulation results for IPD versus sound azimuth angle θ are compared in Fig. 2. With a "strong" coupling ($\chi_k=100$), a high amplification of the IPD can be achieved. However, the fly-ear structure does not show this characteristic. Instead, it resembles the performance obtained with a "medium" coupling ($\chi_k=9$). This coupling ensures that the fly ear has not only a good IPD amplification (~12 times at $\theta=90°$) but also a good ability to distinguish between different sound azimuth angles (i.e., a good DS even at large azimuth angles). For the designed microphone, a medium coupling ($\chi_k=6.4$) is chosen to resemble such fly-ear characteristic. It is noted that the diaphragms are commercially available microphone diaphragms, whose stiffness is known. To realize the design stiffness ratio of 6.4, an appropriate selection of bridge material (steel) and bridge geometry ($25.4\times1.9\times0.1$ mm^3) is made. The IPD for the uncoupled cases corresponds to two separate microphones (or the fly-ear membranes) with the same separation. When compared with the uncoupled case, the designed microphone exhibits an IPD amplification of about 3.3 times at the 90° azimuth.

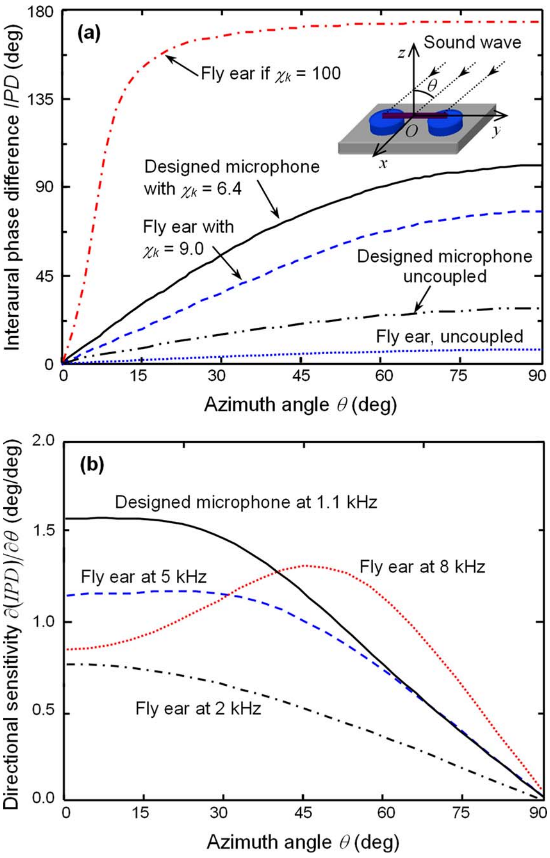

FIG. 2. (Color online) Comparison of model predictions for the biomimetic microphone design and the fly ear. (a) IPD vs the sound azimuth angle. The inset shows the definition of the azimuth angle. (b) DS vs azimuth angle at different frequencies.

It is well known that the fly ear has exceptional localization ability at 5 kHz, which is slightly below the first rocking mode natural frequency (7.1 kHz). However, a basis for explaining such a narrow band localization capability has not been explored. In Fig. 2(b), the DS for the fly-ear structure is plotted as a function of azimuth angle at different sound

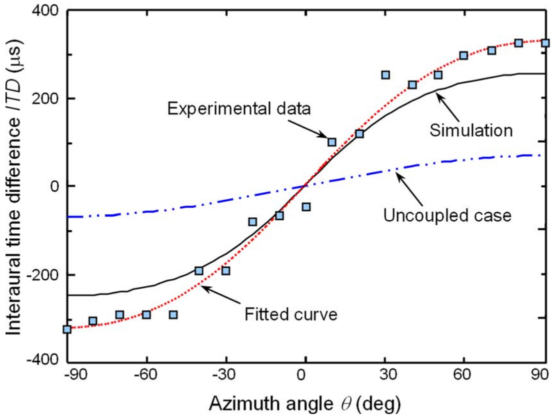

FIG. 3. (Color online) Experimental results of the biomimetic microphone: ITD vs the azimuth angle at the designed working frequency of 1.1 kHz.

frequencies. It is noted that at 5 kHz, the fly ear cannot only achieve a constant DS for azimuth angles in the range of 0° to 30° but can also obtain a maximum DS compared to those obtained at other frequencies (e.g., 2 kHz and 8 kHz). This indicates that the fly-ear structure has been tailored to achieve the best DS at 5 kHz to fulfill the localization task within a 30° azimuth. This is consistent with the phenomena observed in an experimental study.[6] To capture this fly-ear characteristic, the working frequency of the microphone is chosen to be 1.1 kHz, which is slightly below the first rocking mode natural frequency (1.2 kHz).

Experimental studies were carried out with the designed microphone. Based on the frequency response of the device, the first two natural frequencies were determined to be 1.3 and 2.2 kHz, which are close to the design values. At the designed working frequency of 1.1 kHz, the ITD is obtained for different azimuth angles. According to Fig. 3, the ITD is amplified more than 4.4 times at the 90° azimuth and the experimental data compare well with the simulation. The DS reaches a peak of 6.5 μs/deg and stays almost constant within ±30° azimuth.

In conclusion, a directional microphone that captures the essential design of the fly *Ormia Ochracea's* ear structure and performance characteristics has been discussed. The microphone structure consists of two individual diaphragms, structurally coupled by a bridge. It has been demonstrated that the microphone exhibits an ITD amplification larger than 4.4 and a maximum DS of 6.5 μs/deg. This work provides physical insights into the fly-ear mechanism and an experimental proof-of-concept of a directional microphone that mimics the fly-ear structure. As the nondimensional model that is used to guide the design is independent of the physical size, the understanding gained through this work can be extended to the microscale and thus form a basis for the development of biomimetic miniature directional microphones.

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