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Response of a biologically inspired MEMS differential microphone diaphragm

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ABSTRACT

The development of a novel, biologically inspired acoustic sensor is presented. The primary goal of this effort is to construct a miniature device that is capable of detecting the orientation of an incident sound source with an accuracy of 2°. The design approach follows from our investigation of the mechanics of directional hearing in the parasitoid fly, *Ormia ochracea*. This animal has been shown to be able to detect changes in the line of bearing of an incident sound that are as small as 2° [1]. The tympanal structures of the ears of this animal suggest a novel approach to designing very small directionally sensitive microphones. A microphone diaphragm design is presented that has been fabricated using silicon microfabrication technology. Measurements of the static deflection due to intrinsic stress and of the response to sound are shown to be in excellent agreement with predictions. Predicted results indicate that this microphone concept could lead to a practical differential microphone with self-noise as low as 20 dBA.

Keywords: Microphone, acoustic sensor, biomimetic, MEMS

1. INTRODUCTION

Any acoustic sensor that responds preferentially to sound from a specific direction must detect the spatial gradient of the sound that is incident on it. In current microphone technology, this is typically achieved either by constructing a pressure sensitive diaphragm driven on either side by sound sampled at different locations in the sound field, or by using two isolated microphones and processing the signals electronically. The distance between the locations at which the sound is sampled is normally smaller than the sound wavelength. It is well known that as the overall dimensions of the sensor are reduced, with a corresponding reduction in the spatial separation in the sensed pressures, the detected pressure difference will also be reduced. This loss of sensitivity poses numerous engineering challenges in the design of very small directional microphones. In the present study, we describe an improved design approach inspired by the auditory systems of small animals that are adept at localizing sounds.

Our approach to designing miniature directional microphones follows from our previous study of the auditory system of the parasitoid fly *Ormia ochracea* [2]. This animal has shown exemplary ability to localize sounds even though its ears span only about 1mm. The fly can detect changes in the angle of incidence of the sound that are as small as 2°[1]. In this fly, the detection of the pressure gradient is achieved by mechanically coupling the motions of the two ears. As a result, a difference in pressure at the exterior of the two ears causes them to move out-of-phase. The combination of this motion with an in-phase motion excited by the average pressure leads to a directionally sensitive response [2]. If one wishes to detect the pressure gradient using a very small device, this system suggests that an effective way to accomplish this is to design a sensor that rocks about a fulcrum due to differences in pressure at two points on its exterior. This differs from the usual approach of sampling the sound pressure at two points and arranging the device so that these pressures drive either the exterior or interior side of a single microphone diaphragm.

The aim of this paper is to describe our current results in fabricating this biologically inspired directional microphone concept. A model for the response of a conventional differential microphone is first described in which sound drives both the internal and external surfaces of the microphone diaphragm. Results from this model are then compared to those of a simplified model of the response of a microphone diaphragm based on Ormia's ears. The use of this approach opens up numerous design possibilities that have not previously been available. Because our current interest is in developing very small differential microphones, an appropriate means of constructing the devices is to use silicon microfabrication techniques. Detailed designs have been developed with consideration given to a wide range of design parameters. Results are presented that show that our predictions of the deformation of the diaphragm due to intrinsic stress along with the vibration response due to sound are in excellent agreement with measurements.

2. BIOLOGICAL INSPIRATION

In a previous study, we discovered that the mechanical structure of the ears of the parasitoid fly *Ormia ochracea* endows the fly with a remarkable ability to sense the direction of an incident sound wave [2]. The fly's auditory system has evolved in such a way that it is ideally suited to hearing and localizing a cricket's mating call. Measurements of the mechanical response of the ears of this fly indicate that when sound arrives from one side, the ear that is closer to the sound source responds with significantly greater amplitude than the ear that is further from the source. The interaural difference in mechanical response is due to the coupling of the ears' motion by a cuticular structure that joins the two tympana, which we have named the intertympanal bridge. This is the first report of the use of a mechanical link between a pair of ears to achieve directionally sensitive hearing [2].

An examination of the analytical model for the acoustic response of the tympana of *Ormia ochracea* shows that the system can be represented in terms of two, uncoupled resonant modes of vibration that are excited by a sound wave as shown in figure 1 below. A primary goal of the present investigation is to apply our understanding of the mechanics of this and similar auditory systems and mimic the operating principles used in order to construct an acoustic microsensor that is insensitive to unwanted noise disturbances. The ears of *Ormia ochracea* serve to demonstrate that such a small directional microphone, or "ormiaphone," can be developed.

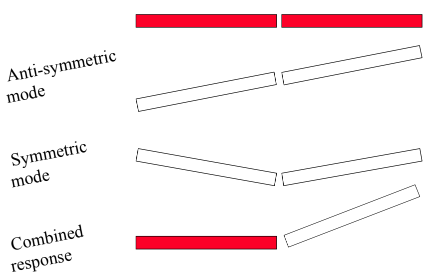
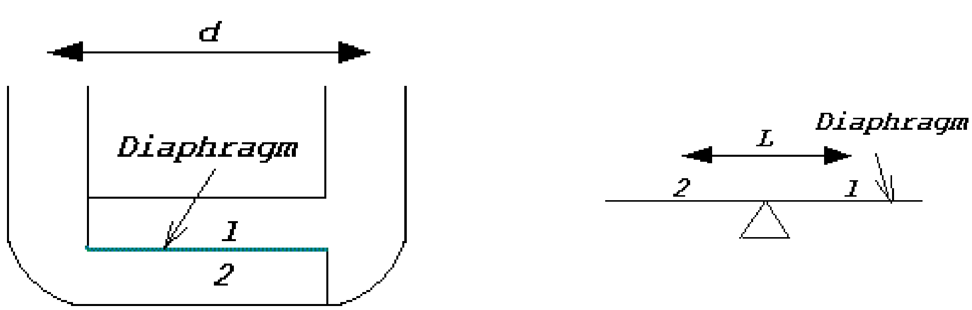


Figure 1. Modes of vibration of the intertympanal bridge. The anti-symmetric mode involves rocking of the bridge about the fulcrum and responds to the pressure gradient. The symmetric mode is a translational bending motion in which the two sides move in-phase and responds to the average pressure on the two sides. When the mechanical properties of the system are appropriate, the general response consists of a combination of the two modes where their contributions cancel on one side and add on the other.

3. DIFFERENTIAL MICROPHONE CONCEPT

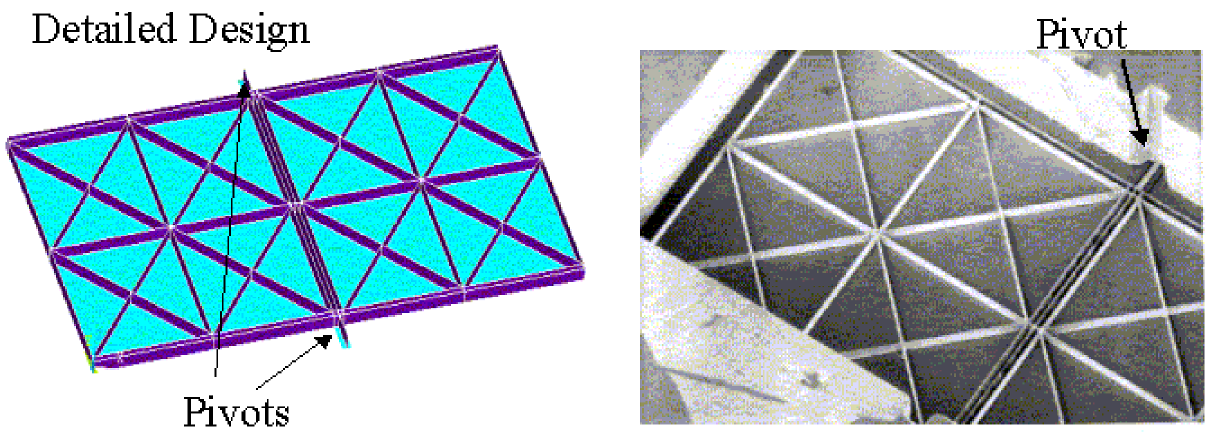
A simplified representation of a conventional differential microphone is depicted in figure 2(a) in which a diaphragm is driven on both the top and bottom sides by sound that travels through two ducts having openings that are separated by a distance *d*. Our alternative approach, inspired by the ears of the fly, is depicted schematically in figure 2(b). In this case, sound drives only the top surface of the diaphragm. The difference in pressure at points *1* and *2* on the top surface produce a rocking motion about the pivot point. The right and left sides of the diaphragm thus move in opposite phase in response to a spatial pressure gradient. This construction introduces entirely new design possibilities for sensing pressure gradients.



(a) Conventional Differential Microphone (b) Ormia-Inspired Microphone

Figure 2. Constructions of the differential microphone

To develop a microphone diaphragm based on the concept shown in figure 2(b), a detailed finite element model was created for a 1×2 mm diaphragm made of polycrystalline silicon as shown in figure 3(a). This design consists of a stiffened plate that is supported on flexible pivots. The diaphragm was designed in order to minimize the mass while preventing unwanted structural resonances. Figure 3(b) shows a polysilicon device that we have fabricated.



(a) FEA Model (b) Fabricated Polysilicon Device

Figure 3. Diaphragm Structure of the Ormia Differential Micrphone

4. PREDICTIONS OF ACOUSTIC PERFORMANCE

In this section, predicted results for the sensitivity and noise performance of the Ormia microphone (depicted in figure 3) are compared with a conventional design (depicted in figure 2a). The performances of specific designs are compared to illustrate some of the advantages of the present approach. Since our current interest is in the development of very small acoustic sensors, it is assumed that each design will be fabricated using silicon microfabrication techniques. The diaphragm shown in figure 3(a) is designed using a detailed finite element model so that it responds as a rigid plate that is supported on torsional springs at the pivots.

The sensitivity of the differential microphone concepts shown in figures 2(a) and 3(a) may be computed from:

$$S_c = \frac{V_b}{h} \frac{s\alpha^2 i\omega \frac{d}{c}\cos(\phi)/m_c}{\omega_c^2 - \omega^2 + i\omega 2\omega_c \zeta_c}$$

and

$$S_o = \frac{V_b 2si\omega(L/2)^3 \cos(\phi)/(cIh)}{\omega_o^2 - \omega^2 + i\omega 2\zeta_o \omega_o}$$

Where, $i=\sqrt{-1}$, c is the sound speed, ϕ is the angle of incident sound, ω_c and ω_o are the resonant frequencies of the conventional and ormia directional microphone respectively, $\omega_c = \sqrt{\frac{k}{m_c}}$, $\omega_o = \sqrt{\frac{k_t}{I}}$, and ω is the driving frequency.

The dimensions of the microphones are both 1×2 mm, and the structures are constructed out of 1μm thick polysilicon. Both microphones thus have the same area s. For the Ormia microphone, the total mass is $m = 0.975\times10^{-8}\ kg$, the mass moment of inertia about the axis through the supports is $I = 3.299\times10^{-15}\ kgm^2$, The resonant frequency of the rotational mode ω_o is predicted to be 1409*Hz*. For the conventional microphone, the mass is $m_c = 0.46 \times 10^{-8}\ kg$, the resonant frequency of the diaphragm ω_c is found to be about *10kHz*. The bias voltage $V_b = 1$ *volts* and the backplate gap $h = 3\mu m$. The damping constants in each design are selected to achieve critical damping, i.e. $\zeta_c=\zeta_o = 1$.

Predicted acoustic responses for the two microphone diaphragm designs are shown in figure 4 below. It is apparent that the *Ormia* microphone has substantially higher sensitivity than the conventional approach over the audible frequency range of interest here.

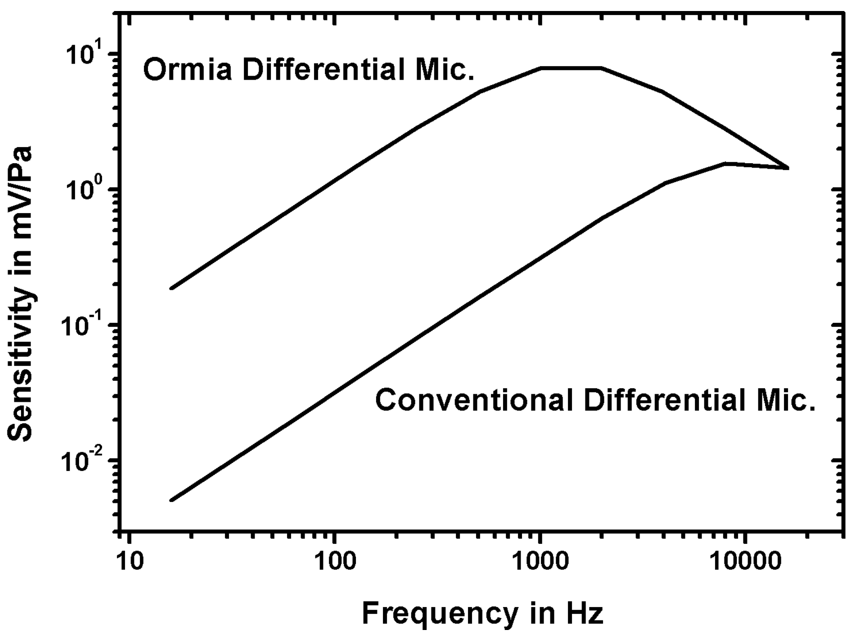


Figure 4. Predicted Frequency Responses of the Differential Microphones

Along with the acoustic sensitivity, it is also very important to examine the lowest sound levels that can be measured with a given microphone. This is limited by the self-noise of the microphone as described in [3]. Noise performance of microphones is usually characterized by using the A-weighted overall equivalent sound pressure due to the noise. In order to construct a fair comparison of the noise performance of candidate designs, a compensation filter is developed so that the signals from the microphones are adjusted to have identical frequency responses. The compensation filter for each microphone signal was applied to achieve the flat frequency response from 250Hz to 8kHz. The noise of the microphone results from energy dissipation in the system that can be thought of as being due to equivalent dashpots that are distributed over the diaphragm surface. The microphone noise was computed from

$$N = SPL_{ob} + 10\log_{10} P_{sd} ,$$

where, SPL_{ob} is the octave band sound pressure level, P_{sd} is the white noise power spectrum due to thermal noise, $P_{sd} = 4k_bTR/s^2$ [3]. k_b is Boltzmann's constant, $k_b = 1.38\times10^{-23}\ J/K$, T is the absolute temperature, s is the area over which the dashpot act, R is the equivalent dashpot constant.

The predicted noise performances of the two microphones are shown in figure 5 below.

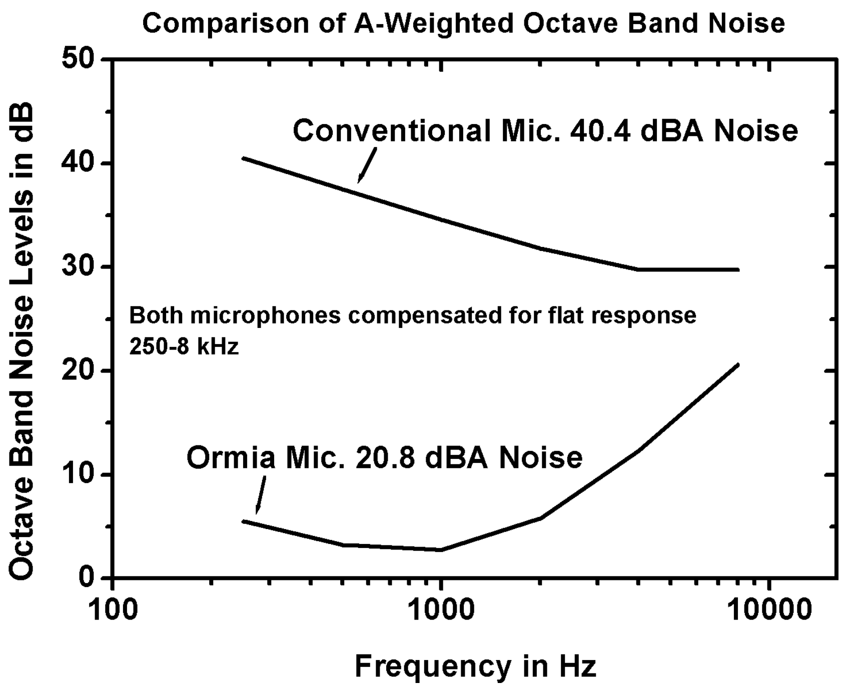
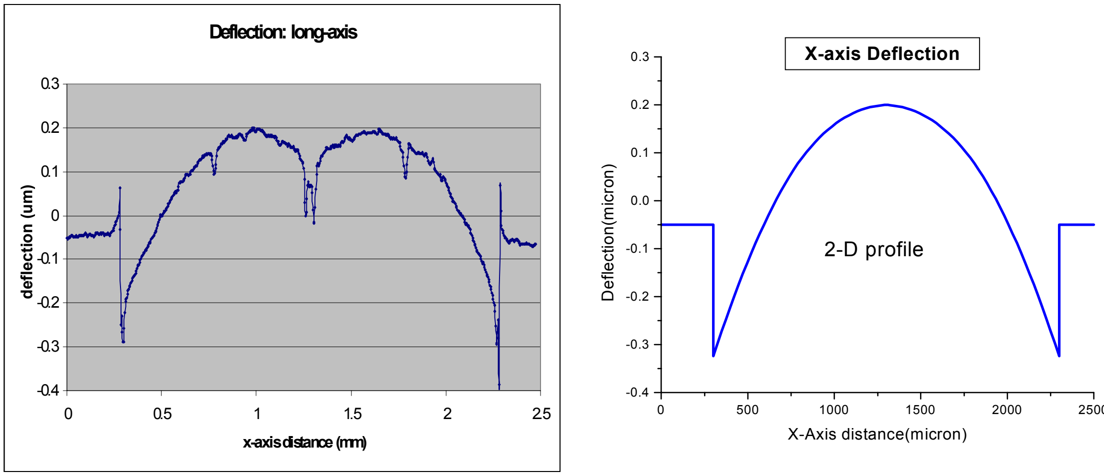


Figure 5. Predicted Output Noise Spectra of the Differential Microphones

As shown in figure 4, the peak of the sensitivities always appear near the resonant frequency of the system, thus the compensation filters and noise levels are lowest near this point. The sensitivities of the *Ormia* microphone are over one order of magnitude higher than conventional microphone over most of the frequency range of interest here. The low signal level of the conventional microphone at low frequencies causes it to require about 40 dB of gain in order for it to output the same signal level as the *Ormia* microphone. It can be seen in figures 4 and 5 that because the use of the particular mechanical structure in the *Ormia* microphone, the frequency response and the noise performance are considerably improved in the miniature design. The noise level predicted for the *Ormia* design is only about 20 dBA. This is a remarkably low noise level and rivals that of high performance *non-directional* microphones.

5. EVALUATION OF FABRICATED DEVICES

Results of fabrication of the design shown in figure 3(a) are shown in figure 3(b). Characterization of the devices included the measurement of the flatness and dimensional accuracy along with the response to sound. As shown in figure 6 below, measurements and analysis of the static deformation of the microphone were completed to verify that the design prediction matched the experimental data. The results shown in the figure indicate the deflection along the 2 mm long axis of the diaphragm at its midline. The static deformation of the diaphragm resulted from the intrinsic stress in the polysilicon that is created during the fabrication process. Measurements of the curvature of uniform wafers with polysilicon films indicated that the polysilicon was subjected to approximately 20 MPa of compressive stress. Despite this significant compressive stress, the results shown in the figure indicate that the diaphragm is remarkably flat with a maximum deflection of only 0.3 μm. The results based on our analysis are extremely close to the measured data.



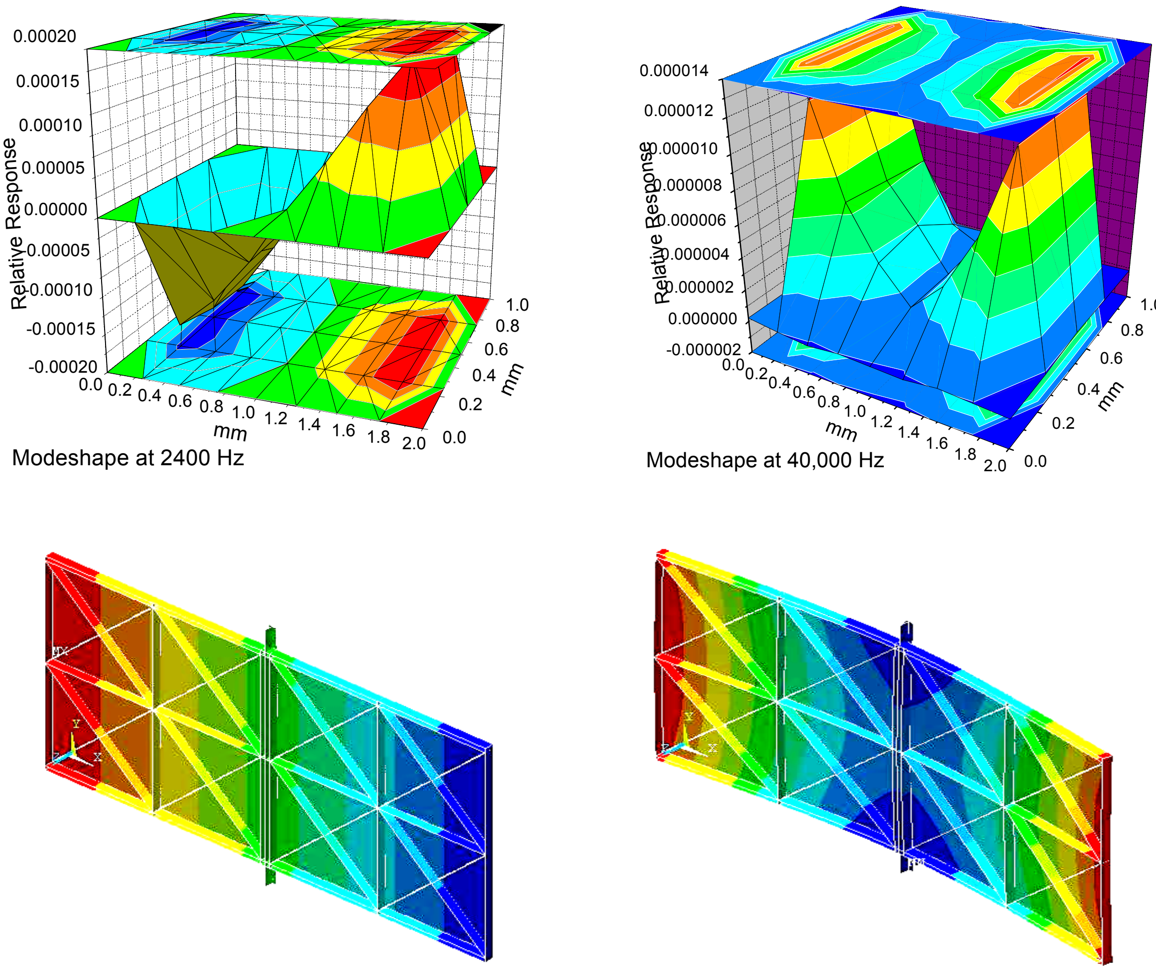
(a) Measured X-axis2-D profile from WYCO (b) Predicted X-axis 2-D profile from ANSYS

Figure 6. Static Deformation Along the 2 mm Long Axis

Along with a characterization of the static deflection of the devices, measurements were performed to examine the dynamic performance. The structures are designed to have a rocking mode and a translational mode of vibration. The measured modes of vibration are processed from frequency response measurements of points on the test structure. The sound-induced vibration of the diaphragm was measured using a Polytec laser vibrometer. A rectangular measurement grid over the surface of the diaphragm is used. The imaginary part of the complex transfer function is plotted over the rectangular grid for a particular frequency band. The data was processed and viewed using a custom written Matlab GUI.

Measured results are shown in figure 7 below along with predictions based on our detailed finite element model. The figure shows that the measured results are in excellent agreement with predictions.

Along with predicting the resonant frequencies and mode shapes, it is crucial that we are able to accurately predict and measure the response of the microphones to an incident sound field. Figure 8 shows a comparison of the measured and predicted response relative to the sound pressure incident on the center of the diaphragm. This figure shows the magnitude and phase of the response versus frequency on the side of the diaphragm that is closest to the sound source (ipsilateral). The predicted results were obtained using a Matlab program (written by us) that post-processes the output from our detailed ANSYS FEM model. This Matlab program calculates the vibration of the structure to a distributed, traveling acoustic field. The results shown here indicate the displacement at a point one-quarter of the way along the length of the diaphragm and half-way across the width, where the length is 2mm and the width is 1mm.



Predicted 2663 Hz
(a). The rocking mode

Predicted 40,895 Hz
(b). The translational mode

Figure 7. Measured and predicted mode shapes

The data in figure 8 show that the diaphragm response contains two resonant peaks. The peak that occurs at relatively low frequencies, approximately 2400 Hz, corresponds to the mode in which pure rocking occurs about the central supports as shown in the left panels of figure 7. The next mode of vibration, at a frequency of about 40 kHz, consists of in-phase motion of the two sides of the diaphragm as shown in the panels at the right of figure 7. This mode is well above the frequency range of normal human hearing and will have negligible influence on the performance of the diaphragm. The fact that only one resonant frequency (corresponding to the rocking mode) occurs in the frequency range of interest causes this design to perform with excellent fidelity. Many microphone designs suffer from unwanted resonances that adversely impact the frequency and phase response.

It is apparent from figure 8 that the resonance at 2400 Hz is rather lightly damped and has a higher Q value than is desirable. A procedure we have developed for identifying the damping parameters for vibrating systems indicates the damping ratio of this mode is $\zeta \approx 0.00512$ so that $Q = 1/(2/\zeta) \approx 97.7$. It is important to note that the devices we have fabricated thus far do not include backplates and hence lack an important source of damping. It is well known that viscous forces due to air flow in the gap between the backplate and the diaphragm results in significant damping of the diaphragm modes.

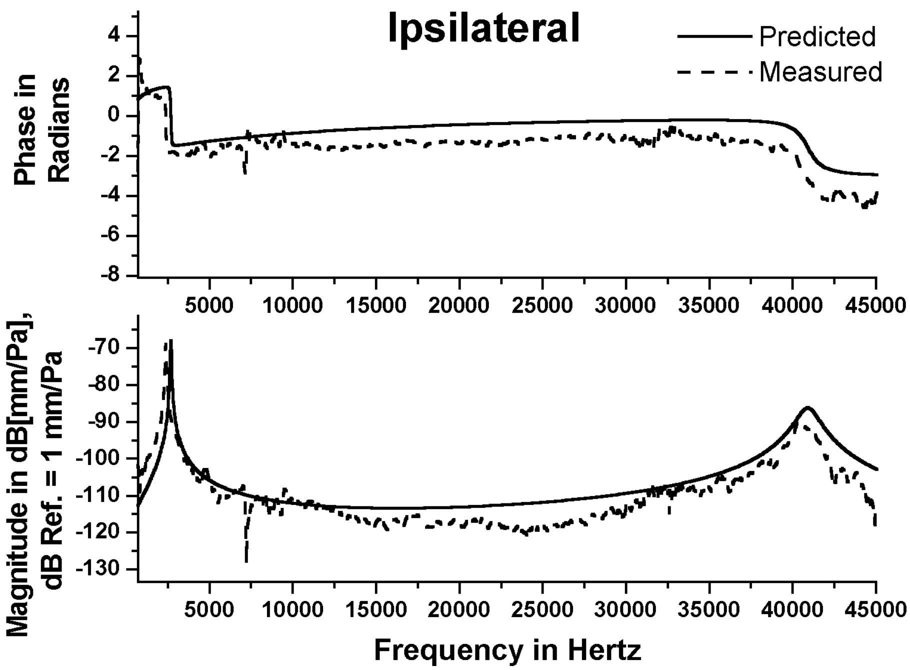


Figure 8. Comparison of measured and predicted response of our differential microphone diaphragm (with no backplate) due to an incident sound. Data are normalized relative to the incident sound pressure.

6. CONCLUSIONS

A biologically inspired concept for a differential microphone is presented that has the potential of allowing the development of higher performance microphone designs. Fabricated results are presented that show excellent agreement with predictions.

7. ACKNOWLEDGEMENTS

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