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The Development of a Biologically-Inspired Directional Microphone for Hearing Aids

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Directional microphone · Silicon microfabrication technology · *Ormia ochracea*

Abstract
The development of novel microfabrication techniques for producing a directional microphone for hearing aids is here described. The mechanisms underlying both the structure and function of these unusual microphones were originally inspired by the ears of an inconspicuous insect, the parasitoid fly *Ormia ochracea.* The structure of Ormia's ears inspired new approaches to design directional microphones that are more sensitive and have lower thermal noise than that typical of those using traditional approaches. The mechanisms for directional hearing in this animal are discussed along with the engineering design concepts that they have inspired, because they illustrate how basic research can inspire technology development–translational research. However, to realize the potential of bioexploitation this microphone diaphragm concept would have been very difficult to realize without the availability of new silicon microfabrication technologies. Thus, this report can be viewed as an example of what may be possible with the application of new fabrication methods to microphones. Challenges and opportunities provided by the use of silicon microfabrication technology for microphones are discussed.

Introduction

An extremely common complaint of hearing aid users is that they have great difficulty understanding speech in noisy environments. The use of directional microphones has shown considerable promise for addressing this problem. A number of clinical studies of the hearing impaired have demonstrated improvements in speech intelligibility in noise from the use of directional microphones [see for example Bilsen et al., 1993; Ricketts, 2000a, b]. While advances in directional microphone technology are of great interest, the most recent revolutionary change in microphone construction was the advent of the commercially viable electret over 30 years ago [Sessler and West, 1964]; the sensor still consists of a metalized pressure-sensitive membrane placed near an electrode. In contrast to the modest advances in microphone technology, our ability to process signals has exploded through the advent of low-power digital signal processors and Sigma-Delta analog-to-digital conversion. Our processing technology has outpaced our acoustic transducer technology. The development of improved directional microphone technologies coupled with improved signal processing algorithms will result in a demonstrable improvement in the lives of the hearing impaired.

The directional microphone concept described in the following is inspired by the discovery of the ears of the parasitoid fly, *Ormia ochracea.* The mechanical structure of the ears of *O. ochracea* endows the fly with a remark-

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able ability to sense the direction of an incident sound wave [Miles et al., 1995; Mason et al., 2001]. 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 [Robert et al., 1992]. The parasitic female must find a specific host cricket on which to deposit her predaceous maggots. Hence, gravid female *O. ochracea* locate calling male crickets using auditory cues. The offspring are deposited on or near a cricket and ultimately consume it. Our initial efforts to study the fly's ears were on determining the mechanism by which these small animals localize the sounds from the cricket. It seemed surprising that such a small animal, roughly the size of a housefly, possessing auditory organs with eardrums separated by a few hundred microns, could be so adept at localizing sounds. Over the past decade, we have conducted a thorough mechanical and anatomical investigation of the ears of this animal [Robert et al., 1994, 1996; Miles et al., 1995, 1997].

In the following, we describe the mechanism for directional hearing in this animal. As will be apparent, these flies have evolved a unique mechanism for directional hearing, based on mechanical coupling of its eardrums. This 'invention' of nature has inspired a useful exercise in biomimicry, in which the physical acoustics of fly's ears serve as a basis for novel microphone design. The principles used for developing conventional directional microphones will be described along with a discussion of the evolution and performance possibilities of the current Ormia-inspired microphones. Because these new microphone designs are made possible by the use of new fabrication technologies, some of the challenges and opportunities for future advances in microphone constructions are discussed.

The Unusual Ears of *O. ochracea*

Laser vibrometric measurements of the mechanical response of the ears of *O. ochracea* indicate that when sound arrives from one side, the tympanum that is closer to the sound source responds with significantly greater amplitude than that which is further from the source. This occurs even though the two eardrums are very close together, both fitting in a space about 1 mm across. Because of the minute separation between the eardrums, the interaural differences in incident pressure are extremely small. 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, as shown in figure 1 [Miles et al., 1995]. This was the first report of the use of a mechanical link between a pair of ears to achieve directionally sensitive hearing, which had not been previously reported in any other animal.

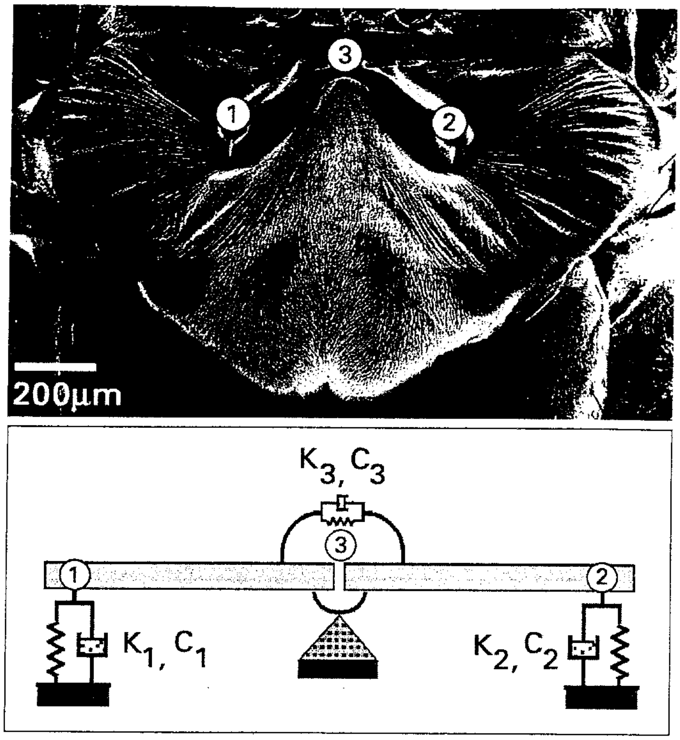

Fig. 1. The ears of *O. ochracea* and a mechanical model used to describe the directional sensitivity. The two tympana are the corrugated membranes that are mechanically connected through the intertympanal bridge, shown here with the numbers 1, 2, and 3. The central point (3) acts as a hinge. The sensory cells are connected to the tympanal pits (1 and 2). The mechanical model includes equivalent stiffnesses, K_1, K_2, and K_3 and equivalent viscous dashpots, C_1, C_2, and C_3 [Miles et al., 1995].

We developed an analytical model of the ears of *O. ochracea* that accurately predicts the mechanical response of the eardrums when stimulated by sound from any incident direction [Miles et al., 1995]. An examination of this model shows that the system can be represented in terms of two independent resonant modes of vibration that are excited by a sound wave as shown in figure 2. This consists of a rocking mode, in which the two eardrums move in opposite directions, and a translational mode, in which the ears move in the same direction. The rocking mode is driven by the difference, or gradient, in pressure between the two exterior surfaces of the ears. The translational mode is driven by the average pressure

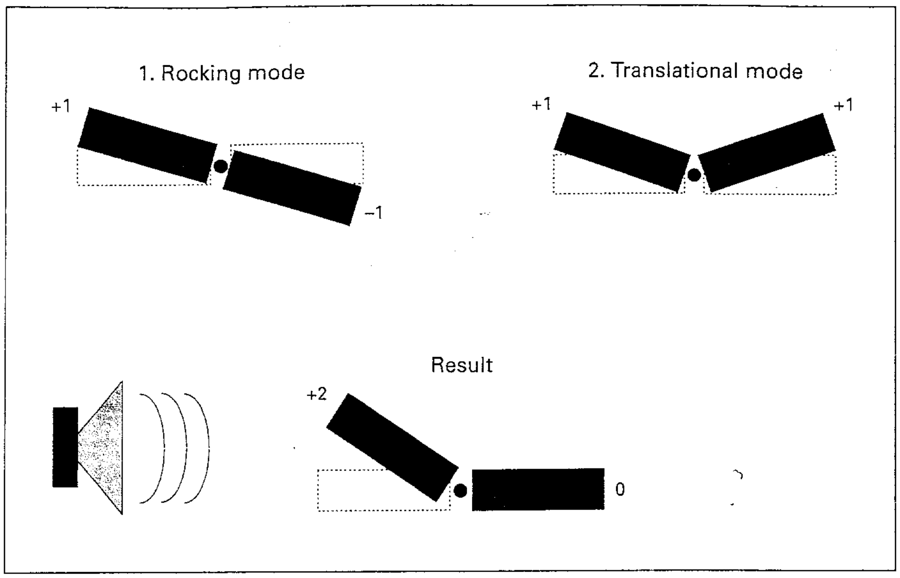

Fig. 2. The combination of a rocking mode and translational mode leads to directional sensitivity.

on the two ears. Operating under an appropriate set of mechanical properties for the ears, these two modes combine such that they add on the ear that is closer to the sound source and cancel on the ear that is further from the source. With the right choice of mechanical properties, this effect produces a directionally sensitive response in the fly's ears over a frequency range of about 5 kHz to over 25 kHz [Miles et al., 1995]. As shown in the lower schematic in figure 2, this mechanical coupling can generate a significant interaural difference in tympanal response, in the face of minute interaural difference cues in the sound field at the location of the ears. This difference in the amplitude of the motion at the two ears is due to very small differences in the phase of the incoming wave at the external surfaces of the tympana. One can view this system as a simple mechanical signal processor that combines the pressure gradient with the average pressure to achieve a directionally sensitive response [Miles et al., 1997].

This approach to sound source localization differs from what is used in most large vertebrate animals, like ourselves, in which two independent ears detect the sound and interaural differences in amplitude and time of arrival are processed by the central nervous system to determine the orientation of the sound source. Very little or no interaural processing takes place at auditory periphery, which is the 'secret' of the fly's ears. We exploit this mechanistic difference in device design below.

Comparison with Conventional Directional Acoustic Sensing

Any system that responds to sound pressure in a manner that depends on the direction of propagation of the wave must detect the spatial gradient in the pressure. The straightforward methods of creating a conventional pressure gradient sensor use either the difference in the response of two independent microphones (where the subtraction is accomplished by electronic circuitry or signal processing) or a pressure-sensitive membrane that responds due to the net (i.e. difference) pressure on its two sides.

The essence of what is special about the ears of *O. ochracea* is that miniscule pressure gradients in the sound field cause the pair of eardrums to rotate about a central anatomical pivot point in the rocking mode shown in figure 2. Essentially, the pressure gradient creates a net moment, producing rotation of the entire assembly about the pivot. Figure 3 shows a schematic of an Ormia-inspired pressure gradient diaphragm on the left and a conventional gradient diaphragm on the right. In the conventional diaphragm, the two pressures act on the top and bottom surface of a simple membrane. The membrane responds to the net force produced by these pressures, which is equal to the pressure difference because they act on opposite sides of the diaphragm. The use of an acoustic pressure gradient to produce a moment and hence a rotation of a diaphragm suggests a significant departure from previous approaches to directional acoustic sensing.

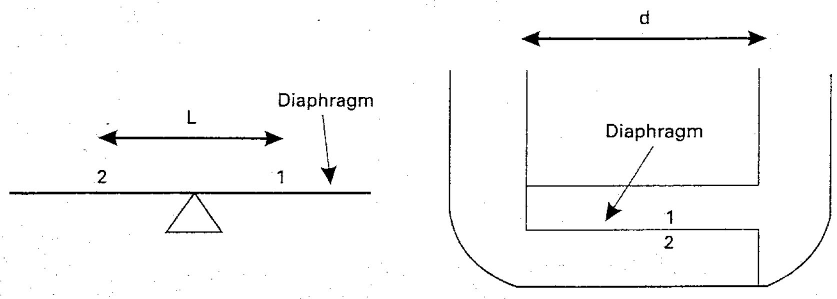

Fig. 3. Schematic of an Ormia-inspired pressure gradient diaphragm on the left and a conventional gradient diaphragm on the right. In the Ormia-inspired microphone diaphragm, the difference in sound pressure applied at points 1 and 2 produces a net moment, and hence a rotation of the entire assembly about a pivot. In the conventional diaphragm, the two pressures are sensed at the openings of two ports separated by the distance d as shown in the figure on the right. The microphone package then directs these pressures such that they act on the top and bottom surface (denoted by points 1 and 2) of a simple membrane. The membrane responds to the net force produced by these pressures, which is equal to the pressure difference because they act on opposite sides of the diaphragm.

This approach offers a host of design possibilities and the potential of radically improved performance.

Because nature conferred upon the small Ormia fly an unusual technique to detect pressure gradients, i.e. an auditory system that is severely constrained by size, it seemed appropriate that engineers interested in small, sensitive, and robust directional microphones should also examine the merits of this approach.

The Evolution of the Engineering Design – Biomimetic Directional Microphone

Because the materials and fabrication processes that are available preclude simply 'copying' of the design of Ormia's ear, our approach has been to mimic, or borrow, the essential ideas rather than create a high fidelity replica. This becomes the starting point of an extensive engineering design process. The analysis and design of the mechanical diaphragm structure involved engineering evolution. The earliest design consisted of a membrane, or thin plate, supported along its perimeter and stiffened and tuned with masses in order to emphasize the response to the difference in pressure [Gibbons and Miles, 2000; Miles et al., 2001; Yoo et al., 2002]. Lessons learned from the analysis and fabrication of this structure led to the realization that a considerably more compliant (and hence more responsive to sound) diaphragm could be constructed if it was fashioned out of a stiffened plate and supported by carefully designed hinges as shown in figure 4 [Miles et al., 2001; Tan et al., 2002]. In this design, rather than attempt to construct a diaphragm that possesses both the rocking and translational modes of Ormia's ear (as shown in figure 2), we sought the more modest goal of constructing a pressure gradient microphone that responds primarily with the rocking mode; the stiffness of the structure was designed so that the natural frequency of the translational mode of figure 2 was above the frequency range of interest (approximately 40 kHz). The materials and fabrication constraints thus led to a significant departure from the morphology of the fly's ear but the essential principle of differential sensing is still employed. In order to achieve the effect of the in-phase mode, one can add another nondirectional microphone and combine the signals to obtain any of the directivity patterns that are possible with a first-order directional sensor.

Differential Microphone Acoustic Performance

In this section, predicted results for the sensitivity and noise performance of the Ormia differential microphone (fig. 4) are compared with that of a conventional design (such as depicted in the right panel of figure 3). The performance of several specific designs are compared to illustrate some of the advantages of the present approach. Since our goal is to develop very small acoustic sensors, we deliberately used silicon microfabrication techniques.

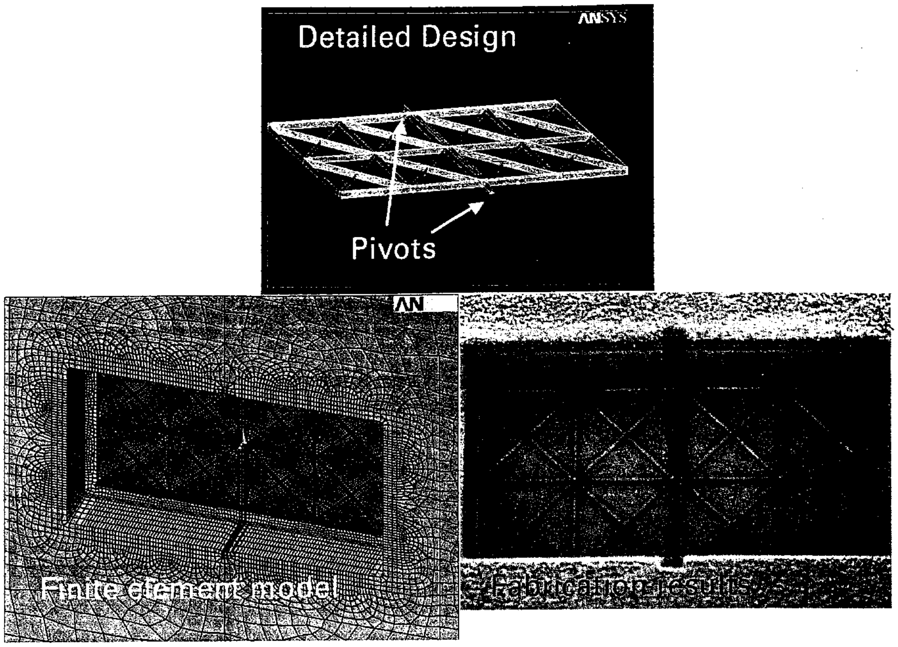

Fig. 4. Ormia-inspired differential microphone diaphragm. This diaphragm is supported only on carefully designed pivots. A slit separates the diaphragm from the surrounding substrate everywhere except at the pivots. A finite element model of the diaphragm is shown at the top, and a mesh of a model used to examine stresses is shown in the lower left. A scanning electron micrograph of a diaphragm fabricated out of polycrystalline silicon is shown on the lower right. The rectangular diaphragm has dimensions 1 × 2 mm.

In order to facilitate the design process, it is important to use a computationally efficient means of estimating the acoustic sensitivity of the diaphragm. Because of the complexity of the diaphragm structures that can be fabricated in silicon, it is appropriate to use the finite element method to model the dynamic response. Based on the detailed finite element models, we have established that the design behaves much like a rigid body that rotates about the pivots shown in figure 4. This is determined by predicting the resonant mode shapes and natural frequencies of the structure. In our typical design, the rocking mode (as illustrated in the upper left of fig. 2) has a resonant frequency between 1 and 2 kHz, while the translational mode has a resonant frequency between 30 and 40 kHz. The translational mode is thus above the frequency range of human hearing in these designs.

With the assumption that the diaphragm structure behaves like an ideal rigid body, with a response that is dominated by the rocking mode, we can estimate the response to sound by calculating the moment applied to the diaphragm by a plane acoustic wave that is incident at an angle Φ relative to the direction normal to the plane of the diaphragm. The analysis of this simplified lumped-parameter representation of the diaphragm requires knowledge of the equivalent stiffness of the pivots and of the mass moment of inertia about the pivots. These quantities may be readily determined by using the detailed finite element model. We have shown that this lumped-parameter model, where the parameters are identified by the finite element method, yields accurate predictions of the response of the diaphragms to sound [Tan et al., 2002].

A similar approach can be taken to estimate the sensitivity of a differential microphone that is fashioned out of a conventional diaphragm as in the right panel of figure 3. The diaphragm can be modeled as a flexible plate with fixed boundaries. In this comparison, the sound field is assumed to enter the microphone through the two openings separated by the distance d in the right side of figure 3. The difference in the pressures on the top and bottom sides of the diaphragm (labeled 1 and 2 in the figure) produce a net force on the diaphragm. In both of these microphones, it is assumed that the wavelength of sound is significantly longer than the distances L or d in figure 3. We will assume that capacitive sensing is used to obtain an electronic signal from the microphones.

The sensitivities of the differential microphone concepts shown in figure 3 may be estimated from:

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

and

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

where the subscripts o and c denote the Ormia and conventional concepts shown on the left and right of figure 3, respectively. S_o and S_c are the sensitivities of the microphones in volts/Pascal, $i = \sqrt{-1}$, 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,

$$\omega_c = \sqrt{\frac{k}{m_c}}, \quad \omega_o = \sqrt{\frac{k_t}{I}},$$

and ω is the driving frequency.

The dimensions of the microphones are assumed to both be 1 × 2 mm, and the structures are constructed out of 1-μm-thick polysilicon. Both microphones thus have the same area s. For the Ormia microphone, the total mass, obtained from our finite element model is $m = 0.975 \times 10^{-8}$ kg, the mass moment of inertia about the axis through the supports is $I = 3.299 \times 10^{-15}$ 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 10 kHz. The bias voltage $V_b = 1$ V and the distance between the diaphragm and the backplate electrode is $h = 3$ μm. The damping constants in each design are selected to achieve critical damping, i.e. $\zeta_c = \zeta_o = 1$. The parameter α is equal to 0.69. This parameter is computed by taking the inner product of the first vibrational mode shape of the clamped plate with the uniformly distributed acoustic pressure.

Predicted acoustic responses for the two microphone diaphragm designs show that the Ormia microphone has approximately 20 dB greater sensitivity of the conventional microphone over the audible frequency range [Tan et al., 2002].

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 [Gabrielson, 1993]. 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 utilized 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 a flat frequency response from 250 Hz to 8 kHz. 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 self, or thermal noise in dBA may be estimated from

$$N = 135.2 + 10 \log_{10} P_{sd},$$

where P_{sd} is the white noise power spectrum due to thermal noise, $P_{sd} = 4\ k_bTR/s^2$ [Gabrielson, 1993]. k_b is Boltzmann's constant, $k_b = 1.38 \times 10^{-23}\ J/K$, T is the absolute temperature, s is the area over which the dashpots act, R is the equivalent dashpot constant. In this comparison the value of R has been taken such that each design is critically damped so that the damping ratio is unity, i.e. $\zeta_c = \zeta_o = 1$. It is found that the predicted thermal noise floor of the conventional microphone is 40.4 dBA while that of the Ormia differential microphone is 20.8 dBA [Tan et al., 2002].

The significant reduction in thermal noise of the Ormia differential microphone results from the fact that the compliance of the diaphragm can be made to be very high. This high compliance is achieved by careful design of the pivot supports.

Our approach enables us to create almost any desired stiffness (or compliance) of the diaphragm through the proper design of the support at the pivot. The only ways to adjust the stiffness of a conventional diaphragm, being essentially a plate or membrane, are to adjust its thickness, or change its initial tension. The reduction of the diaphragm thickness introduces a host of fabrication difficulties and raises concerns over the device's durability. The frequency response of the diaphragm will also suffer as its thickness is reduced because unwanted resonances will appear in the frequency range of interest. Because our design consists of a stiffened plate supported on a carefully designed hinge, we are able to design it so that any unwanted resonances are well above the frequencies of interest.

Current Challenges and Future Opportunities

Based on the predicted results described above, there are significant benefits to the use of a rather unconventional microphone diaphragm that would be very difficult to realize without the precision that is available through silicon microfabrication. Silicon microfabrication enables the use of novel diaphragm constructions that are likely to lead to significant performance benefits as this technology matures.

Fabrication Issues

In order for any promising microphone concept to have an impact on the hearing impaired, it is essential that great care be taken at the outset to ensure it ultimately can be fabricated in a cost-effective way. Silicon microfabrication has great potential to provide devices that can be manufactured using a minimum of human labor and, subsequently, low cost. The promise of low-cost devices has been a primary motivation in nearly all research on silicon microphones and it has proven an intoxicating lure for a number of microphone manufacturers. Despite these efforts, however, much more needs to be done to develop microphone designs that can be fabricated with a sufficiently high yield to make this approach cost-effective.

It is widely accepted that by far the biggest challenge in fabricating microphones out of silicon (or other materials used in microfabrication) is the reduction of the influence of stress on the structural integrity and dynamic properties of the microphone diaphragm [Pedersen, 2001; Loeppert, 2001]. Unfortunately, due to the micromechanical properties of the materials, the fabrication process typically results in a significant amount of stress in the diaphragm that can be sufficient to result in fracture of a significant percentage of the devices before the fabrication is complete. In addition, the stress is strongly dependent on fine details of the fabrication process that are almost impossible to control sufficiently. Since the typical microphone diaphragm consists of a very thin plate, stress (either tensile or compressive) can have a marked influence on the dynamic response. Stress nearly always has significant detrimental effects on microphone performance.

Myriad approaches have been developed to reduce the effects of stress on silicon microphones including the use of corrugations and stress relieving supports [see for example Scheeper et al., 1994; Bergqvist and Rudolf, 1994; Zhang and Wise, 1994; Jennan, 1990; Cunningham and Bernstein, 1997; Spiering et al., 1993].

By incorporating a diaphragm as shown in figure 4 that, by design, has significant bending stiffness, in-plane stresses due to fabrication have substantially less impact. It is also important to note that the overall compliance of the diaphragm is determined by the design of the pivot supports, not the thickness or stress in the diaphragm as in conventional approaches. As a result, our design approach avoids many of the difficulties caused by stress in silicon microphones.

Performance Limitations due to Capacitive Sensing

Capacitive sensing, either through the use of a charged electret or a biased back-plate, is employed in the vast majority of miniature microphones that have sufficiently low noise and high sensitivity to be candidates for use in hearing aids. It is well known, however, that the use of capacitive sensing places significant design limitations on the microphone diaphragm that adversely impacts the electronic noise performance. In addition, due to the viscosity of air, the use of a biased electrode in close proximity to the diaphragm introduces a significant source of microphone self-noise. A major breakthrough in microphone performance may be achievable through the use of alternative sensing methods, such as optical sensing, by eliminating many of these design limitations.

To illustrate the limitations imposed on the noise performance of the read-out circuitry used in a capacitive sensing scheme, consider a simple model of a conventional (nondirectional) pressure-sensitive microphone. Suppose the buffer amplifier used to convert the change in microphone capacitance to an electronic signal has a white noise spectrum given by N volts/$\sqrt{\text{Hz}}$. If the effective sensitivity of the capacitive microphone is S volts/Pascal then the input-referred noise will be N/S Pascals/$\sqrt{\text{Hz}}$. In a conventional (nondirectional) capacitive microphone, the sensitivity may be approximated by $S = V_bA/(hk)$ where V_b is the bias voltage, A is the area, h is the air gap between the diaphragm and the back plate, and k is the mechanical stiffness of the diaphragm. Here we have assumed that the resonant frequency of the diaphragm is beyond the highest frequency of interest. The input referred noise of the buffer amplifier then becomes $N/S = Nhk/(V_bA)$ Pascals/$\sqrt{\text{Hz}}$. Based on this result, one is tempted to reduce this noise by increasing the bias voltage, V_b, or by reducing the diaphragm stiffness, k.

Unfortunately, one is not free to adjust these parameters at will because the forces that are created by the biasing electric field can cause the diaphragm to collapse against the back plate. In a constant-voltage (as opposed to constant charge) biasing scheme, the maximum voltage that can be applied between the diaphragm and the back plate is called the collapse voltage given by

$$V_{collapse} = \sqrt{\frac{8}{27}\frac{kh^3}{\varepsilon A}},$$

where ε is the permittivity of the air in the gap. Diaphragms that have low equivalent mechanical stiffness, k, will thus have low collapse voltages. To avoid collapse, one must have $V_b << V_{collapse}$. The above equation clearly shows that the collapse voltage can be increased by increasing the gap spacing, *h,* but this comes at the cost of reducing the microphone capacitance (and electrical sensitivity), which is inversely proportional to the nominal spacing, *h*. Since miniature microphones (and particularly silicon microphones) have very small diaphragm areas, *A*, the capacitance tends to be rather small, on the order of a pF. The small capacitance of the microphone challenges the designer of the buffer amplifier because of parasitic capacitances and the effective noise gain of the overall circuit. For these reasons, the gap, *h*, used in silicon microphone designs tends to be small, on the order of 5 μm.

The use of a gap that is as small as 5 μm introduces yet another limitation on the performance that is imposed by capacitive sensing. As the diaphragm moves in response to fluctuating acoustic pressures, the air in the narrow gap between the diaphragm and the back-plate is squeezed and forced to flow in the plane of the diaphragm. Because *h* is much smaller than the thickness of the viscous boundary layer (typically on the order of hundreds of μm), this flow produces viscous forces that damp the diaphragm motion [Skvor, 1967; Bergqvist, 1993; Homentcovschi and Miles, 2004, 2005]. It is well known that this squeeze film damping is a primary source of thermal noise in silicon microphones [Gabrielson, 1993]. By eliminating the constraints imposed by capacitive sensing along with the constraints of conventional diaphragm design approaches, microphone designs will be able to break through significant performance barriers.

In order to decouple the design of the diaphragm's compliance from the requirements of the sensing scheme, we are developing optical methods that do not require the use of significant bias voltages [Hall and Degertekin, 2002; Cui et al., 2006]. Preliminary calculations indicate that this sensing approach can achieve noise floors less than 20 dBA, rivaling those of large precision microphones.

Improvements in Fabrication Technology Will Lead to Improved Designs

While there have been numerous efforts to fabricate silicon microphones, thus far very few have led to successful commercial products. The technology of fabricating silicon sensors is still relatively immature, particularly compared to the very mature and highly successful electret microphones as currently used in hearing aids. Nonetheless, because silicon fabrication technology permits the creation of extremely precise and complex microstructures, it opens up a new world of possibilities in sensor design.

When a revolutionary technology arrives, its primary advantages may not be initially appreciated by designers. As an example, the earliest transistor circuits quite naturally bore a strong resemblance to vacuum tube circuits with the transistors replacing the function of the tubes. When designers learned more about the advantages of transistors, entirely new circuit topologies were created, making integrated circuits possible.

This effect has also occurred in the development of silicon accelerometers. While the initial designs resembled conventional accelerometers that were reduced in size, current silicon accelerometer designs utilize complex structures for their proof-mass and microscopic interdigitated comb fingers for capacitive sensing of the motion of the proof mass [see for example Xie et al., 2004]. These new sensor designs have evolved to take advantage of what can be accomplished with silicon microfabrication.

With very few exceptions, existing attempts to fabricate silicon microphones amount to a dramatic miniaturization of the same sorts of structures that are used in conventional microphones. They consist of a thin diaphragm supported around its perimeter, and a back plate a small distance away to permit capacitive sensing [see for example Bergqvist and Rudolf, 1995]. It is likely that the real advantages of silicon microfabrication for microphones have yet to be discovered. When they are, a revolution in microphone technology may occur.

We believe that one example of this technology 'coming of age' is the development of the differential microphone diaphragm we have developed. This structure takes advantage of what can be accomplished using silicon microfabrication and would be particularly difficult to realize using conventional fabrication methods.

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