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A SILICON DIRECTIONAL MICROPHONE WITH SECOND-ORDER DIRECTIVITY

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ABSTRACT
A miniature microphone is described that is capable of achieving second-order directional sensitivity to sound. Microphones that exhibit directionally sensitive response to acoustic pressures must detect differences in the pressure at a minimum of two spatial locations. First-order directional microphones detect the difference in pressure at two points, which for small separations between the measurement points, is proportional to the pressure gradient. Second-order directional microphones detect the difference between the gradients measured at two locations, yielding an estimate of the second spatial derivative of the pressure. While second-order directional microphones may be shown to provide a greater ability to reject off-axis unwanted sounds, they also suffer from significantly reduced sensitivity compared to that of first-order microphones, particularly at low frequencies. In addition, their performance is very strongly influenced by any inaccuracies in phase or amplitude in the detected pressures. The designs studied here have significant potential for overcoming these challenges. The diaphragms were inspired by our earlier studies of directional hearing in the fly *O. ochracea*. Measured results are shown for devices that have been fabricated out of polycrystalline silicon.

INTRODUCTION
There is a continuing need for the development of improved technology for acoustic sensing, particularly for portable electronic products. One market that poses significant technical challenges is the hearing aid industry. An extremely common complaint of hearing aid users continues to be that they have great difficulty understanding speech in noisy environments. Of all available technologies, the use of directional microphones has shown the most 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: [1]. Advances in directional microphone technology are of great interest to hearing aid dispensers and users [2]. Despite the ample evidence that directional microphones play a crucial role, we have seen very modest improvements in their performance, and many engineering challenges stand in the way of achieving their full potential. Along with producing greatly improved devices for the hearing impaired, the results presented here will also enable the development of advanced consumer products such as directional microphones for telephones, computers, portable digital devices, camcorders, and surveillance systems.

BACKGROUND: MICROPHONE DIRECTIONALITY AND FREQUENCY RESPONSE
The creation of an acoustic pressure sensor having an output that depends on the direction of the acoustic propagation requires the sensing of the acoustic pressure gradient. The straight-forward way to create a directional acoustic sensor consists of using a matched pair of omnidirectional microphones that sample the sound at two points separated by a distance, d, as shown in Figure 1. The signals from these microphones are processed electronically to achieve the desired directivity.

Unfortunately, as the size of any directional sound pressure sensor is reduced, the difference in the two sensed pressures will also diminish. This means that in approaches that employ two microphones, the difference in the signals becomes very small relative to the common mode, or average pressure. This small difference is also very sensitive to small differences in the response characteristics of the microphones. As a result, there is a requirement for careful matching.

Because the spacing between the sound ports in directional microphones is typically much smaller than the sound wavelength, the difference in the detected pressures also diminishes as the frequency goes down, or equivalently, as the wavelength increases. This loss of sensitivity at low frequencies is typically compensated using a 6 dB/octave low-pass filter along with gain to achieve a “flat” response. While this does achieve the desirable frequency response, the significant amount of gain needed at low frequencies dramatically amplifies the microphone noise. The increase in noise and loss of sensitivity in miniature directional microphones limits their applicability and often precludes their use in high-performance systems.

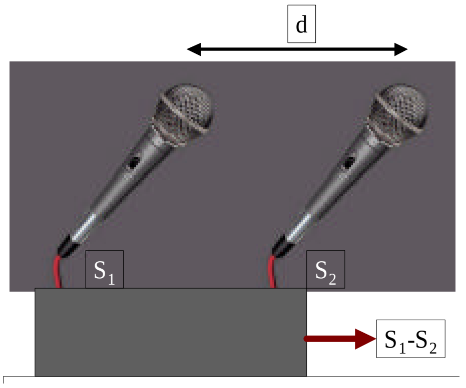

Figure 1. Create a directional output by subtracting the signals from two omnidirectional microphones

The directional acoustic sensing concept described above is considered a “first-order” differential sensor because it relies on an estimate of the pressure gradient through a measurement of the simple difference in pressure at two points. The directivity pattern of first-order differential microphones is the well-known figure eight pattern. The amplitude of the response is proportional to cos(θ), where θ is the propagation direction relative to the line that connects the pressure measurement points. If $\theta=\pi/2$, the response will be at a minimum, or a null.

While first order directional microphones have proven very beneficial in a large number of applications, there is great potential for dramatic improvements in performance through the use of second (and higher) order systems. A second-order directional hearing aid has been evaluated in reference [3]. It is reasonable to expect that the increased off-axis sound rejection of a second-order system would be beneficial to hearing aid wearers in noisy environments.

A second-order differential pressure sensing scheme can be represented schematically by the arrangement shown in Figure 2. This system consists of three omnidirectional microphones separated from each other by a distance, d. One can then construct two difference signals, S_1-S_2 and S_3-S_2. The difference between these signals will then be S_1-$2S_2$+S_3. It is shown below that while the output of a first-order pressure gradient sensor is proportional to cos(θ), the output of a second-order sensor is proportional to $\cos^2(\theta)$, giving a much stronger dependence on θ and, consequently, a much greater ability to reject unwanted sounds.

To illustrate the directivities and frequency responses of first and second-order differential pressure sensors, assume that a plane harmonic wave of amplitude P having a frequency ω is propagating with speed c at an angle θ relative to the line connecting the microphones. If we choose the location of S_2 in Figure 2 to be the origin, then the pressures measured by the three microphones in the figure may be written as $S_1=Pe^{i(\omega t+kd)}$, $S_2= Pe^{i(\omega t)}$, and $S_3=Pe^{i(\omega t-kd)}$, where $k=(\omega/c)\cos(\theta)$. The output of the second-order sensor is then

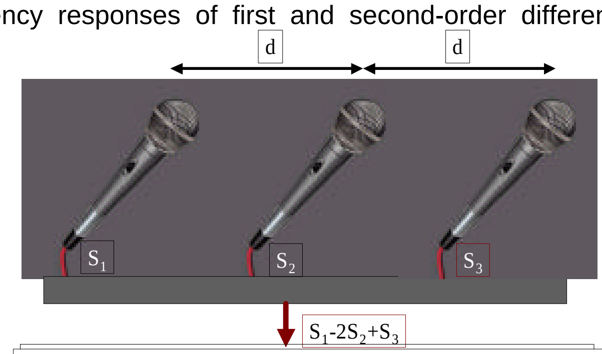

Figure 2. Second order pressure gradient sensing.

$$S_1 - 2S_2 + S_3 = Pe^{iwt}(e^{ikd} + e^{-ikd} - 2) = 2Pe^{iwt}(\cos(kd) - 1) \approx Pe^{iwt}(kd)^2 = Pe^{iwt}w^2\cos^2(q)(d/c)^2 \quad (1)$$

A first-order differential pressure sensor could be formed as in Figure 1 where we take only the difference between S_1 and S_2,

$$S_1 - S_2 = Pe^{iwt}(e^{ikd} - 1) \approx Pe^{iwt} ikd = Pe^{iwt} iw\cos(q)(d/c) \quad (2)$$

The results of equations (1) and (2) show the difference in the dependence on the angle of incidence, θ. Equation (1) shows that the second-order sensor has a dependence on angle of incidence given by $\cos^2(\theta)$, which gives it better rejection of off-axis sounds (i.e. for angles other than zero or 180^o) than the first order sensor, which depends on cos(θ). This substantially sharper directivity pattern results in enhanced rejection of unwanted signals.

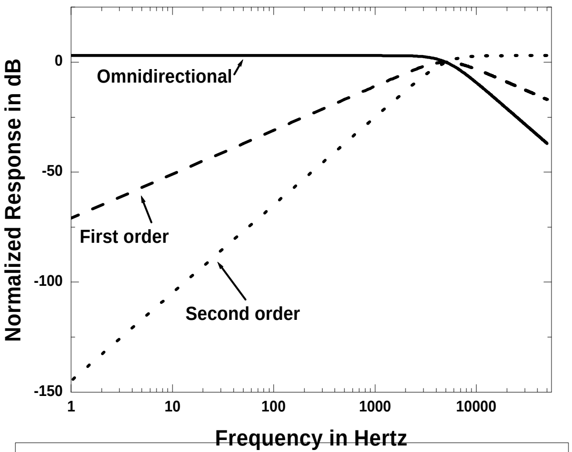

Figure 3. Normalized frequency responses of omnidirectional and first and second order directional microphones.

While the directionality of higher-order differencing schemes can be significantly superior to those of first order systems, several practical difficulties have hampered their application in commercial products [4]. Along with the dramatic difference in directionality illustrated in equations (1) and (2), it is also clear that the two sensors have markedly different dependencies on the sound frequency, ω. The frequency response of first-order directional microphones has a 6dB/octave high-pass filter characteristic with a corner frequency that is equal to the first resonant frequency of the microphone diaphragm. This filter shape is due to the linear dependence on ω shown in equation (2). The gain needed to compensate for the loss of low-frequency signals results in a substantial degradation in the noise performance of first-order microphones. Unfortunately, a second-order differential (or directional) microphone will have a high-pass frequency response with a 12 dB/octave slope in the stop band. This is because the second-order difference obtained in equation (1) depends on ω^2. The dramatic attenuation of low-frequency sounds often causes these signals to be lost in the noise of the system.

The predicted frequency responses of omnidirectional and first and second-order differential microphones are compared in Figure 3. These results assume that each microphone has a resonant frequency of 5kHz. The responses are normalized so that they are unity (or zero dB) at the microphone's resonant frequency. This figure illustrates the dramatic loss of sensitivity of the second-order microphone at frequencies that are much below resonance.

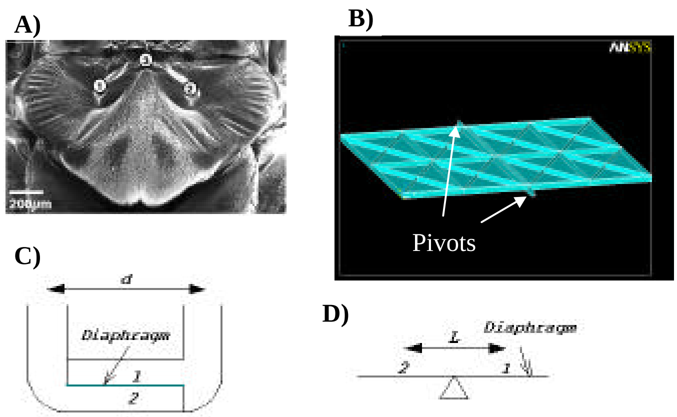

Figure 4. First-order differential microphone concept inspired by the ears of *Ormia ochracea*. A) The tympana of *O. ochracea* about the point 3. B) Design of a 1mm X 2mm differential microphone diaphragm. C) Conventional differential microphone diaphragm. D) Schematic of the diaphragm shown in B).

In addition to the differences in directivity and frequency response of the first and second-order pressure differences described in equations (1) and (2), it is also apparent that as the size of the sensor is diminished, i.e. as d is reduced, the sensitivity of the second-order sensor suffers more than does that of the first order sensor. This is because d is linear in equation (2) but is squared in equation (1). This loss in sensitivity with diminishing size, or aperture, adds a further challenge to the design of miniature directional acoustic sensors.

In spite of the extreme challenges of overcoming the low sensitivity and poor frequency response of second-order microphones, the improvement in directivity they can achieve gives a very substantial payoff if a practical design can be developed. The aim of this study is to provide a silicon diaphragm that achieves this.

FIRST-ORDER DIRECTIONAL MICROPHONE DIAPHRAGM

The second-order microphone diaphragm described here comprises an extension of a new approach we have developed to the design of differential microphones that is inspired by our previous discovery of a novel mechanism for directional hearing in the parasitoid fly, *Ormia ochracea* [5,6]. The design concept is illustrated in Figure 4, which shows *Ormia's* ear and a microphone diaphragm design that detects pressure gradients in essentially the same manner as the fly's ears. The essence of the idea is that in our design, pressure gradients cause the diaphragm to rotate about the pivots shown in the figure rather than cause a conventional diaphragm to deform like a piston. This is illustrated in panels C) and D) of the figure which show an *Ormia*-inspired pressure gradient diaphragm on the right and a conventional gradient diaphragm on the left. In the conventional diaphragm, the two pressures act on the top and bottom surface of a simple membrane while in our approach, the two pressures act on the top surface of either side and produce a rocking motion. This approach offers a host of design possibilities and, as will be described below, offers the potential of radically improved performance. The primary aim of the present study is to extend our first-order differential pressure-sensing concept illustrated in panels B) and D) of Figure 4 to create a microphone diaphragm that achieves second and higher-order differential pressure sensing.

SECOND-ORDER DIRECTIONAL MICROPHONE DIAPHRAGM

A second-order differential microphone concept that builds on the first-order microphone design described above is shown in figure 5 [7,8]. This device consists of two first-order differential diaphragms that are joined together with a flexible hinge. The central hinge must be designed so that it constrains the transverse deflections of the ends to be identical. The torsional stiffness of the hinge (along with that of each pivot point) must be designed so that the resonant frequency of the structure is below the desired frequency of operation. The design and fabrication of this structure are nearly identical to the highly successful approach we have developed for our first-order diaphragms discussed above. The acoustic response of the structure shown in Figure 5 is proportional to the second-order difference in the acoustic pressure, in a manner that is directly analogous to the system of Figure 2. This can be seen by considering a simplified model of the response of the system. An initial model of the system can be constructed by assuming that the diaphragm is comprised of two identical plates that move as rigid bodies about their hinges and that the hinge that joins them at the center constrains them to have the same displacement at that point, *w*, as shown in the figure. The motion of the system can be described by using either *w* or the rotation *f* as a generalized coordinate. The governing equation in terms of the rotation *f* is

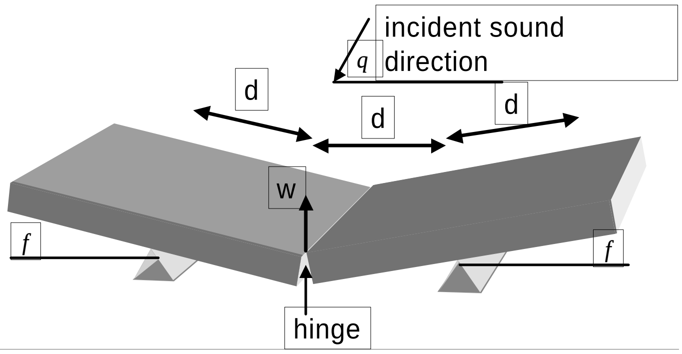

Figure 5. Second-order differential microphone concept

$$2I\ddot{f} + 2k_t f + C\dot{f} = Q \tag{3}$$

where *I* is the mass moment of inertia of each of the two rigid first-order diaphragms about their supporting pivots, $2k_t$ is the equivalent torsional stiffness, *C* is the equivalent viscous damping in the system, and *Q* is the moment due to the incident sound pressure. We will show that the moment that acts on the system has a second-order directivity. To express *Q* in terms of the applied sound pressure, note that the virtual work in the system is $dW=Qdf$. The virtual work done by the sound pressure, *p(x,t)* is

$$dW = \int_{-2d}^{2d} bp(x,t)dw(x,t)dx, \tag{4}$$

where *b* is the width of the diaphragm, *w(x,t)* is the deflection at any point. *x=0* is at the central hinge, and *d* is the variational operator. The sound pressure due to a traveling harmonic plane wave is $p(x,t) = Pe^{i(wt-kx)}$, where *k=(w/c)cos(q)*, $i = \sqrt{-1}$, *c* is the sound speed, and ω is the frequency. Because the coupled diaphragms are designed to behave as rigid bodies, the geometric constraint enables us to relate *w(x,t)* to *f* and *x* as

$$w(x,t) = -(x+d)f \text{ for } x<0 \text{ and } w(x,t) = (x-d)f \text{ for } x>0. \tag{5}$$

Substitution of equations (5) into (4) enables us to express the virtual work using *f* as a generalized coordinate,

$$\begin{aligned} dW &= bPe^{iwt}\left(-\int_{-2d}^{0} e^{-ikx}(x+d)df dx + \int_{0}^{2d} e^{-ikx}(x-d)df dx\right) \\ &= bPe^{iwt}2i\sin(kd)\left(\frac{(2d)\cos(kd)}{ik} + \frac{2i\sin(kd)}{k^2}\right) \approx -\frac{4}{3}k^2d^4bPe^{iwt}df \end{aligned} \tag{6}$$

We have assumed that the device is small so that *kd<<1*. Since *dW=Qdf* and *k=(w/c)cos(q)*, equations (6) give

$$Q \approx -4w^2/(3c^2)\cos^2(q)d^4bPe^{iwt} \tag{7}$$

Substitution of equation (7) into (3) enables us to solve for the rotation as

$$f = -\frac{2w^2/(3Ic^2)\cos^2(q)d^4bPe^{iwt}}{w_0^2 - w^2 + 2ww_0zi} \tag{8}$$

where the natural frequency is $w_0 = \sqrt{k_t/I}$ and ζ is the damping ratio. The response as predicted by equation (8) is thus proportional to $\cos^2(\theta)$ as in the three microphone system of figure 2 and equation (1). Note that equation (8) may also be used to compute the deflection at the central hinge, by using *w=w(0,t)=-df*. If the resonant frequency of the structure can be designed to be well below the frequencies of interest so that w_0<<*w*, then equation (8) becomes

$$f \approx \frac{2}{3Ic^2}\cos^2(q)d^4bPe^{iwt} \tag{9}$$

Equation (9) shows that for frequencies well above resonance, the response is independent of frequency. Preliminary results indicate that practical designs can be made having resonant frequencies as low as about 300 Hz.

EXPERIMENTAL RESULTS

Microphone diaphragms have been designed and fabricated out of polysilicon according to the concept shown in figure 5. The design of the diaphragms is described in reference [8]. Figure 6 shows a fabricated device along with an image of the design model. The diaphragm design incorporates stiffeners to ensure that the two coupled first-order diaphragms vibrate according to the desired shape depicted in figure 5.

The sound-induced vibration of the fabricated devices measured using a Polytec scanning laser vibrometer is shown in figure 7 along with the deflection that is predicted using a finite element model. The figure shows that the fabricated device vibrates in the essential mode shape in which the two differential microphone diaphragms vibrate in the manner shown in figure 5.

CONCLUSIONS

A microphone diaphragm concept has been described that can achieve a second-order directional response. This is accomplished by creating a diaphragm that consists of two first-order differential microphone diaphragms that are coupled together by a flexible hinge. The response to sound is shown to be proportional to the difference in the gradients detected by the two coupled diaphragms.

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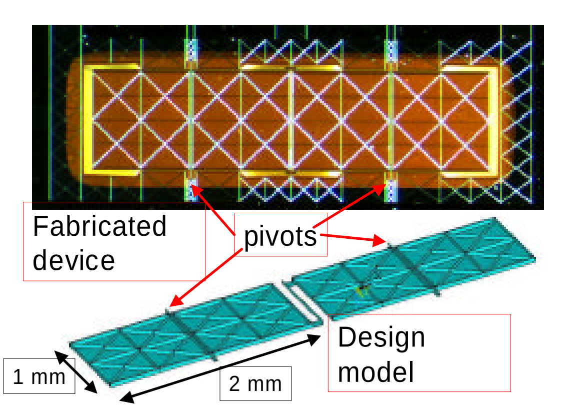

Figure 6. Design model (perspective view) and fabricated device (plan view). The second-order directional microphone diaphragm consists of two coupled first-order diaphragms that are each 1mm by 2 mm.

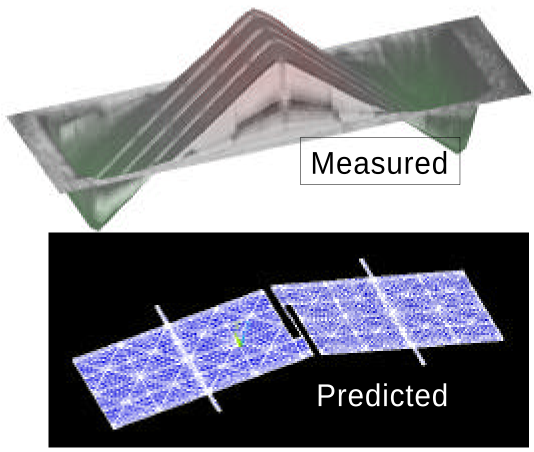

Figure 7. Comparison of measured and predicted sound-induced vibration of the second-order microphone diaphragm. The measurements were performed using a scanning laser vibrometer. The predicted mode shape was obtained using a finite element model [8].

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