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Bio-inspired sound localization sensor with high directional sensitivity

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Abstract

MEMS microphones inspired by *Ormia ochracea* are constrained by their reliance on the resonant behavior of the system, forcing designers to compromise the goal of high amplification of directional cues to operate across the audio range. Here we present an alternative approach, namely a system optimized for the maximum amplification of directional cues across a narrow bandwidth operating purely as a sound-localization sensor for wide-band noise. Directional sensitivity is enhanced by increasing the coupling strength beyond the 'dual optimization' point, which represents the collocation of a local maximum in directional sensitivity and a local minimum in non-linearity, compensating for the loss of the desirable linearity of the system by restricting the angular range of operation. Intensity gain achieved is 16.3 dB at 10° sound source azimuth with a linear directional sensitivity of 1.6 dB per degree, while linear directional sensitivity in phase difference gain shows a seven fold increase over the 'dual optimization' point of 8 degrees phase difference per degree change in azimuthal angle.

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Keywords: Sound localization; MEMS microphones; Bio-inspired; *Ormia ochracea*

1. Introduction

Micro-Electro Mechanical Systems (MEMS) microphones inspired by the auditory system of *Ormia ochracea* offer the promise of micro scale directional microphones. Despite a large body of literature on the principles of *O.*

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ochracea inspired design significant challenges persist limiting the application of these devices in commercial systems. The defining feature of *Ormia* inspired directional microphones is the apparent amplification of directional cues such as the interaural intensity difference (IID) and the interaural phase difference (IPD) in the phase and intensity difference between two coupled diaphragms, referred to as the mechanical interaural intensity difference (mIID) and mechanical interaural phase difference (mIPD). This amplification is the result of the linear superposition of the resonance modes of the device and as such the useful range in which a sound source can be amplified is constrained to be near one of these resonance modes. This presents a conflict with desirable properties for microphone design, where the flatness of the frequency response is ensured by designing resonance frequencies far from the operating range.

Current iterations of MEMS directional microphones resolve this problem by using relatively high Q systems and optimize their operation for a limited amplification of intensity and phase difference that is stable across a wide frequency range [1]. An alternative approach is to accept the sacrifice of bandwidth to achieve the maximum magnification of directional cues at a single frequency. This approach is intended for wide band noise, or for the localization of acoustic sources where the spectral signature is already well known. This can have particular applications for counter-sniper detection systems, as well as unmanned aerial vehicle (UAV) detection which, in their existing form, are large, vehicle-mounted or ground based systems [2][3]. As directional information at any frequency other than the design frequency is now negligible, and the system performs poorly at the transduction of non-directional time domain signals, the device may reasonably be considered no longer to be a microphone but a single purpose sound localization sensor. For these applications the accuracy with which the azimuthal angle to the sound source can be measured is paramount, the critical determinant of which is the rate of change of mIID and mIPD to sound source angle, known as the directional sensitivity. *Ormia ochracea's* hearing system is delicately tailored to this goal, the parameters of the system being balanced to achieve a linear directional sensitivity between -30° and 30° of the midline with the maximum rate of change of mIID and mIPD to the sound source angle – so called 'dual optimization' of the system [4].

In this study we investigate the dual optimization of *O. ochracea* in the low damping conditions available on a single layer silicon on insulator (SOI) MEMS device (Figure 1) in order to obtain a linear sound source angle measurement. While the directional sensitivity of a device at the point of dual optimization is consistent for most damping conditions, frequencies of operation and membrane sizes, it is demonstrated that restricting the angular range of the device allows a significant increase in directional sensitivity to that achieved without loss of non-linearity. The device presented here demonstrating a linear directional sensitivity in the mIID measure of 1.6 dB per degree, an increase of 45%, and in the mIPD measure of 8° per degree, a seven fold increase. The average error in returned sound source angle using the mIPD measure was 0.24° and using the mIID measure was 0.44°.

2. Theory

The principle feature of an *O. ochracea* inspired amplification of directional cues is a mechanism for energy transfer between two diaphragms. In *O. Ochracea* itself and in the examples of fixed periphery MEMS directional

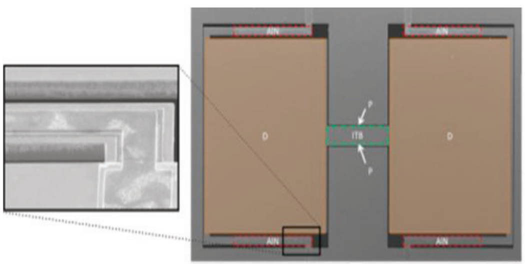

Figure 1: PiezoMUMPS fabricated sound localization device. D = Diaphragm, ITB = Inter Tympanal Bridge, P = Pivots, AlN = Aluminium Nitride piezoelectric sensing.

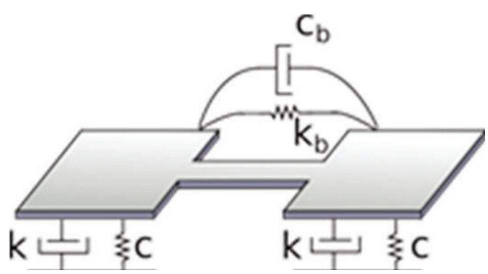

Figure 2: Lumped parameter model. The wings are assumed symmetrical and are linked by k_b, the stiffness of the bridge and torsional stiffness of the pivots, and the dashpot c_b.

microphones [4, 5] a bridge or lever arm is attached to the centre of each membrane, transferring the energy of each diaphragms displacement to the other via a pivot between the two membranes. More common in the literature is the 'rocking mode' microphone in which two cantilever wings are supported by a single, torsional central pivot [6][7][8]. The linked system can be viewed as a simple two degree of freedom system with two major resonance modes: the translational mode, in which the diaphragms move in phase, and the rocking mode, where they move in anti-phase. When these modes are of comparable strength the motion of the diaphragm on the contralateral side is repressed and that of the ipsilateral diaphragm is reinforced, creating a difference in power and phase of oscillation between the two diaphragms which is many times greater than that of the stimulating sound wave. The sensitivity of these differences to sound source angle is determined by the strength of coupling between the diaphragms, the stiffness of the intertympanal bridge. If the coupling is very strong the rate of change of mIPD and mIID with sound source angle is extremely high, but saturates quickly away from the midline. If the coupling is weak mIPD and mIID vary continually around the device, but with only a slight amplification over that which would be measured by two uncoupled diaphragms in the same configuration. Between these two extremes there exists a point of ‘dual optimization’, utilized by *O. ochracea* itself, where a high, linear rate of change of mIPD and mIID can be achieved between -30° and 30° from the midline.

Design is greatly facilitated by use of the lumped parameter model of the system, in which each diaphragm is treated as a mass-spring-damper system coupled by a spring and dashpot pair (Figure 2). The model has been shown to provide excellent agreement both for the behaviour of *O. ochracea*’s hearing system and for dual wing MEMS devices [9]. The approach used is that of Liu et al.[10] in which the equations of motion for the system are decomposed into their individual mode shapes, allowing the amplitude of displacement of each of the wings to be described as a superposition of the rocking and translation response.

$$x = \frac{p_0 s}{k}\left(\frac{\cos(\phi/2)}{\eta^2 - \Omega^2 + \imath 2\Omega\eta\xi_t} \pm \imath \frac{\sin(\phi/2)}{1-\Omega^2 + \imath 2\Omega\xi_r}\right) \tag{1}$$

Where:

$$\Gamma = \frac{1-\Omega^2 + \imath 2\Omega\xi_r}{\eta^2 - \Omega^2 + \imath 2\Omega\eta\xi_t} \tag{2}$$

Here s is the surface area of a wing, p_0 is the amplitude of the incident pressure wave, Ω is the frequency normalised to the resonance mode frequency, η is the ratio of the translational mode frequency to the rocking mode frequency and ξ_r and ξ_t are the damping coefficients associated with the resonance and translational modes respectively. The phase difference in the acoustic wave, ϕ, is given by $\phi = 2\pi f d \sin(\theta)/v$: where f is the frequency of the sound wave, v is the speed of sound and d is the distance between the measurement points and θ is the azimuthal angle of the sound source. The power difference, the mIID, and the phase difference, the mIPD can then be given as:

$$mIID = 20\log\frac{\Gamma + \imath\tan(\phi/2)}{\Gamma - \imath\tan(\phi/2)} \tag{3}$$

$$mIPD = \angle\frac{\Gamma + \imath\tan(\phi/2)}{\Gamma - \imath\tan(\phi/2)} \tag{4}$$

The directional sensitivity is calculated numerically using the limit definition of a derivative, with the measure of non-linearity (NL) the mean squared error of the actual mIID or mIPD to that predicted by the average directional sensitivity (ADS).

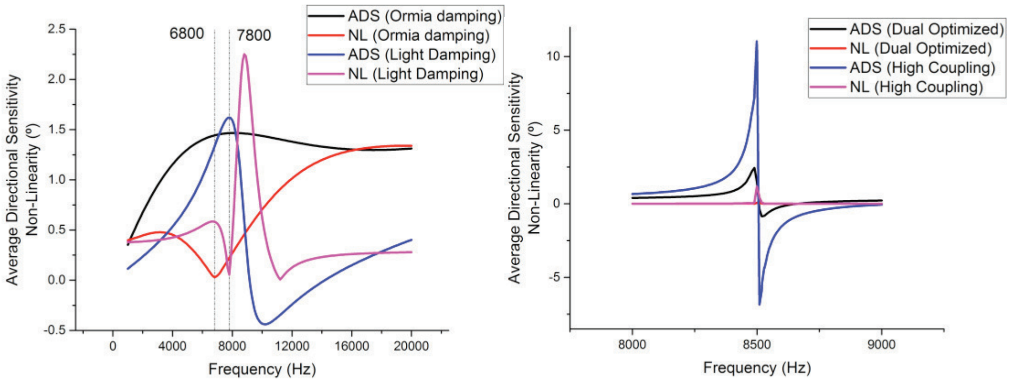

Figure 3: (Left) ADS and NL measures with comparable damping to *Ormia Ochracea* (ξ_t =1.23 and ξ_r =0.89) and moderate damping (ξ_t =0.25, ξ_r =0.16. (Right) Dual optimized single layer device at 10° range with dual optimization and overcoupled.

3. Design and modeling

For any given damping conditions the location of the point of dual optimization must be found parametrically. The response of the ADS and NL to the frequency is plotted for a range of coupling strengths. The point of dual optimization can be identified by a local maxima in ADS collocated in the frequency domain with a local minima in NL. When this dual optimization is achieved the directional sensitivity consistently falls within the range of 1 – 1.2 dB per degree and 1 – 1.2 degrees phase difference per degree while the NL falls in the range of 0.02 – 0.05 degrees within 30° of the midline [11].

If the angular range of operation is restricted to within 10° of the midline at the point of dual optimization the sensitivity remains the same, however the non-linearity decreases significantly. Increasing the coupling strength between the diaphragms can then allow large increases in directional sensitivity with comparable linearity to that of systems optimized to within 30° of the midline (Figure 3).

The device model was simulated using COMSOL Multiphysics to achieve the correct resonance frequencies and to verify the calculated directional sensitivity and range of the lumped parameter model. An acoustic-shell interaction model was used with the device simulated as a shell layer within a 5 mm radius air domain. The sound field was simulated as a harmonic sound wave, first swept between 1 kHz and 20 kHz to locate the resonance frequencies of the device and then held at the frequency of peak mIID and peak mIPD while the orientation of the sound wave was swept in 1° around the axis of the pivots of the device.

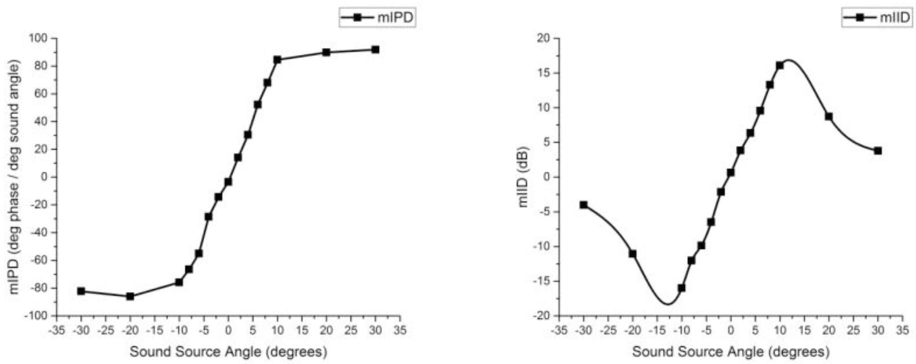

Figure 4: (Left) mIID swept over frequency range for fabricated device with comparison to lumped parameter estimates. (Middle) mIID response to sound source angle measured at intervals of 1° around the midline. (Right) mIPD response to sound source angle measured at intervals of 1° around the midline.

4. Results

The directional response of the device was measured using a scanning laser vibrometer (Polytec, PSV-300-F) using and OFV056 scanning head fitted with close up attachment. The sound source was a periodic chirp signal generated by an Agilent 33220A 20 MHz Function Waveform generator output through a Heil Air Motion Transformer. The chirp signal sweep ran between 4 kHz and 12 kHz over 500 ms measured at 80 dB (ref 20 uPa) at approximately 1 cm from the device by a 1/8" precision pressure microphone (Bruel and Kjaer, 4138) routed through a preamplifier (Bruel and Kjaer, Nexus 2690). Laser Doppler measurements were taken on the rear face with the sound source presented to the top layer of the device moving in 10° increments around the axis of the pivots from -90° to 90° with measurements at 1° intervals being taken within 10° of the midline.

The measured resonance frequencies were 8560 Hz for the rocking mode and 9281 Hz for the translational mode, with the peak mIID being found at 8572 Hz and the peak mIPD at 8565 Hz. The mIID and mIPD measurements at their respective peak frequencies were collated to produce the directional sensitivity plots (Figure 4). Peak values were attained at 10° for each with an average directional sensitivity of 1.6dB per degree in mIID and of 8° phase difference per degree sound source incidence angle in mIPD. Mean absolute error was 0.38 dB in mIID and 3.49° in mIPD for a sound source angle measurement error of 0.24° and 0.44° respectively.

4. Conclusion

Ormia inspired sound localization sensor design necessitates a tradeoff between angular range of operation, the directional sensitivity of the measures mIID and mIPD and the linearity of those measures. Higher directional sensitivities are achievable by increasing the coupling strength between the membranes beyond the point of dual optimization, but the angular range of operation must be compromised to prevent an increase in non-linearity of the measurement. Lumped parameter models and FEA simulation show good predictive value for the behavior of the manufactured sensor, allowing devices to be designed for a range of frequencies, angular ranges and sensitivities.

Acknowledgements

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References

[1] R.N. Miles, Q. Su, W. Cui, M. Shetye, F.L. Degertekin, B. Bicen, C. Garcia, S. Jones, N.A. Hall, Low-noise differential microphone inspired by the ears of the parasitoid fly Ormia ochracea, JASA, 125, (2009), 2013-2026.
[2] Jeffrey A. Mazurek, James E. Barger, Marshall Brinn, Richard J. Mullen, David Price, Scott E. Ritter, Dave Schmitt, Boomerang mobile counter shooter detection system. Proc. SPIE 5778, 264 (2005).
[3] G. Simon, M. Maróti, A. Lédeczi, G. Balogh, B. Kusy, A. Nádas, K. Frampton, Sensor network-based countersniper system. In Proceedings of the 2nd international conference on Embedded networked sensor systems (2004), 1-12).
[4] Liu, Haijun, Luke Currano, Danny Gee, Tristan Helms, and Miao Yu, Understanding and mimicking the dual optimality of the fly ear, Scientific reports 3 (2013).
[5] H. Liu, M. Yu, A new approach to tackle noise issue in miniature directional microphones: bio-inspired mechanical coupling, SPIE Smart Structures and Materials (2010).
[6] A.P. Lisiewski, H. Liu, M. Yu, Fly Ear Inspired Miniature Sound Source Localization Sensor: Localization in Two Dimensions, ASME 2010 International Mechanical Engineering Congress and Exposition (2010).
[7] W. Cui, B. Bicen, N. Hall, S. Jones, F. Degertekin, R.N. Miles, Optical sensing inadirectional memsmicrophone inspired by the ears of the parasitoid fly, *Ormia Ochracea,* MEMS 2006 Istanbul, (2006), 614-617.
[8] R.N. Miles, W. Cui, Q.Su, R. Wu, L.Tan, Y. Liu, Development of novel biologically inspired directional microphones, The Journal of the Acoustical Society of America 120.5 (2006): 3158-3158.
[9] Peng, A. N., Y. U. A. N. Weizheng, and R. E. N. Sen, Design and Microfabrication of Biomimetic Acoustic Pressure Gradient Sensitive Structure, Chinese Journal of Sensors and Actuators 6 (2010): 005.
[10] Robert, D., R. N. Miles, and R. R. Hoy. "Directional hearing by mechanical coupling in the parasitoid fly Ormia ochracea." Journal of Comparative Physiology A 179, no. 1 (1996): 29-44.
[11] Yu, Miao. Fly Ear Inspired Miniature Acoustic Sensors for Detection and Localization. Maryland University College Park Dept of Mechanical Engineering (2011).