Development of a Biologically Inspired MEMS Microphone

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***Abstract*—A multi-band operational MEMS microphone inspired by the hearing organ of *Ormia ochracea* is presented. The novel feature is that the device has both integrated capacitive and piezoelectric sensing capability. Similar to our previous designs, the new design works as a bi-directional microphone and has four separate resonance frequencies below 10 kHz, with intended application for human speech recognition scenarios. Since the capacitive sensing only depends on the displacement of the rotating plates, it provides 11.6 mV/Pa acoustic sensitivity at the first, rocking resonance mode, while the electric response produced by the piezoelectric actuators is almost zero around the same frequency. However, the piezoelectric readout supports a faster transient response and produces less noise at low frequencies than the capacitive sensing method. The complementary interaction between these two sensing methods in one device thus increases the overall electrical response and its accuracy.**

Keywords—MEMS directional microphone; biologically inspired; multi-band sensing; multi-sensing methods

I. INTRODUCTION

Over two decades have passed since researchers started designing MEMS microphones that take inspiration from the hearing system of a female parasitoid fly, *Ormia ochracea*. This type of biomimetic microphone possesses high resolution of sound localisation capability and a high sensitivity response due to the mechanical coupling between two vibrating plates of the microphone, just as in the behaviour of the *Ormia*'s tympana where the combination of rocking and bending resonance modes increases the inter-aural intensity difference (IID) and the inter-aural phase difference (IPD) between its two tympana. MEMS microphones based on *Ormia* can be categorized into single-plate models [1,2] and two-plate models [3], or symmetric models [4] and asymmetric models [5] depending in their geometries.

Similar to the performance of *Ormia*'s hearing organ which evolved to accurately localize the mating calls from its hosts at around 5 kHz, most *Ormia*-inspired MEMS microphones have low electrical response at frequencies off their main resonance frequencies. This shortcoming limits their applications in human speech recognition. In the process of investigating the solution for overcoming this constraint, we previously developed an AlN piezoelectric multi-band operational MEMS microphone design [6]. The earlier design has two plates placed in plane and rotating along the same axis, and therefore has two rocking and two bending modes. In detail, four resonance frequencies are evenly and closely distributed throughout the audio frequency band below 10 kHz. The main advantages of using AlN piezoelectric sensing films in the design is to accelerate the transient electrical response and reduce the overall chip size. However, as the greatest strain occurs on the central rotating beam when the devices are excited around the rocking modes, the piezoelectric pads attached on the bending cantilevers that sense the displacement of both the inner and outer plates produce much lower piezoelectric voltage outputs than possible in the bending modes. To compensate for this loss of sensitivity, capacitive comb fingers are introduced into the device design as a second, complementary sensing unit which also contributes to increasing the overall system damping. The original rectangular rotating beam is also substituted by an S-type beam. This moves the 4th resonance frequency closer to the 3rd resonance frequency to improve the sound localising performance between these two resonances.

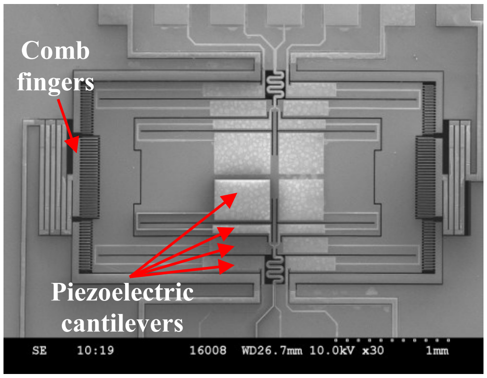

Fig. 1. SEM of fabricated MEMS device.

II. MICROPHONE DESIGN AND READOUT CIRCUIT

A. *Multi-sensing MEMS microphone operating in multiple frequency bands*

As shown in Fig. 1, the overall size of the silicon MEMS microphone is $3.76\,mm \times 1.8\,mm$, which includes the S-type cantilevers that connect to the fixed comb fingers that together with comb fingers distributed on the both sides of the outer plate form the device's capacitive readout. The comb fingers are 6μm in width, with a 6μm gap in between. The outer plate is $2.8\,mm \times 1.3\,mm$, while the inner plate is $2.06\,mm \times 0.76\,mm$. Each plate has four stress bending cantilevers connected to its two ends. The 500 nm thick AlN piezoelectric

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The work was supported by the Engineering and Physical Sciences Research Council (EPSRC) under grant EP/M026701/1, and by the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ ERC Grant Agreement n. [615030].

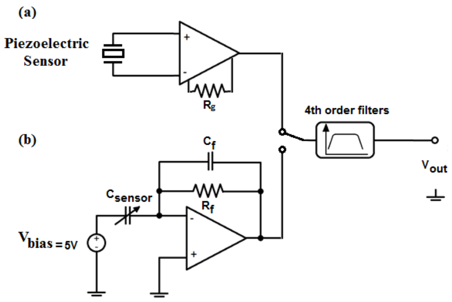

Fig. 2. Readout circuit designed for (a) Piezoelectric sensing (b) capacitive comb finger sensing.

sensing areas cover these cantilevers and the plate areas that are close to the torsion beam. The 30 µm width S-type torsion beam is 150 µm offset of the device centre to facilitate a bi-directional microphone performance over all frequency bands.

B. *Design of Readout Circuit*

There are a total of 8 piezoelectric sensing ports and 6 capacitive sensing ports on the device. In terms of measuring piezoelectric signals, a preamplifier is built using an instrumentation amplifier with a gain of 10 provided by gain resistor R_g. It is followed by a 4th order high pass filter and a 4th order low pass filter, cutting the frequencies off below 200 Hz and above 15 kHz.

The capacitive signal variation produced by the comb fingers is measured by a current sensing circuit as shown in Fig. 2. It is constructed with a charge amplifier followed by the same filters used in the piezoelectric sensing circuit. Considering the balance between the output gain at operating frequencies and the thermal noise as well as the static capacitance of comb fingers (~5 pF), the feedback capacitor $C_f = 1$ pF and the feedback resistor $R_f = 10$ MΩ were chosen. The close-loop gain A_v of the charge amplifier can be expressed as

$$A_V = \frac{V_{out}}{C_{sensor}} = \frac{V_{bias}}{C_f}. \qquad (1)$$

III. METHODOLOGY

A. *Finite Element Modelling Using COMSOL*

The finite element modelling is carried out using COMSOL Multiphysics software. The built-in solid-mechanical, solid-acoustic interaction, and piezoelectric-acoustic interaction modules are used to simulate the mechanical and electrical properties of the MEMS microphone. The microphone model is built with anisotropic single crystal silicon and fixed to a $5.5mm$ square substrate with open backside, surrounded by a spherical air domain. Both comb fingers and AlN layers are included in the simulated model. When simulating the output voltage generated by the AlN, the bottom side of the material was regarded as the ground while the top side was assumed to be connected to the output circuit.

B. *Measuring the Mechanical and Electrical Properties*

A desktop Polytec MSA-100-3D laser Doppler Vibrometer (LDV) was used to measure the mechanical resonance frequencies and frequency response of the microphone. The fabricated prototype was placed on a XY-transverse stage of the LDV. An 8-inch loudspeaker was positioned 20 cm beside the transverse stage to excite the microphone. It was tilted by 45 degrees relative to the MEMS membrane to avoid the LDV scanning head. The experimental setup for the electrical frequency response measurement and directivity characterization is similar to the description of previous work [6]. The charge amplifier used an OPA1611, which was chosen due to its extremely low noise and low power supply.

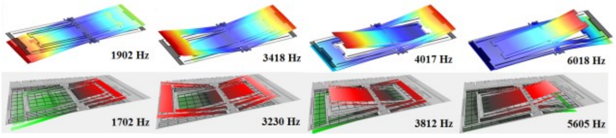

Fig. 3. Four main mode shapes below 10 kHz.

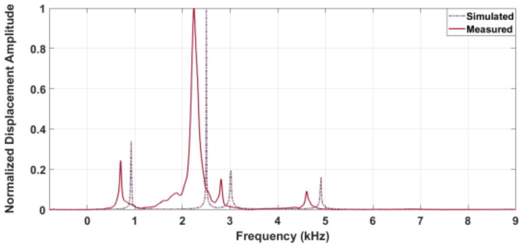

Fig. 4. Normalized simulated and experimental mechanical frequency response measured by 3D LDV.

IV. SIMULATED AND EXPERIMENTAL RESULTS AND ANALYSIS

A. *Mechanical Profile*

The new MEMS microphone has the same mode shapes as our previous designs, i.e. both inner and outer plates vibrate in phase or out of phase at four resonance frequencies as shown in Fig. 3. Figure 4 shows the normalized measured mechanical frequency response, which is closely matched with the finite element simulation. Since the backside of the die sits on the transverse stage of the LDV, it encloses an air cavity below the rotating plates and adds air damping into the system. In order to reduce the memory usage required for the COMSOL modelling, the metal layer deposited on the piezoelectric material was not included in the model. Thus, the measured resonance frequencies are approximately 200 Hz lower than those simulated, which are 1702 Hz, 3230 Hz, 3812 Hz, and 5605 Hz.

B. *Piezoelectric Sensing Readouts*

As shown in Fig. 5, the maximum measured average open-circuit acoustic sensitivity is about 12 mV/Pa at the second

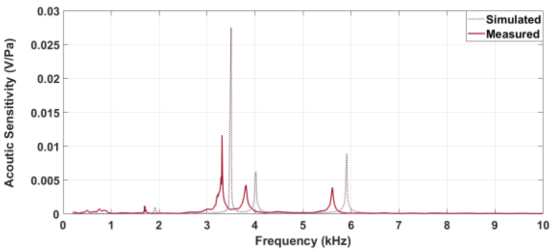

Fig. 5. The predicted and measured average open-circuit acoustic sensitivity obtained from the piezoelectric pads.

resonance frequency. It is seen that the simulated sensitivity value is around twice the experimentally obtained value because the air damping was not considered in the modelling. Furthermore, as expected, the electrical signal response at the first resonance frequency is comparably much lower than at the other resonance frequencies due to lower strain occurring in the bending cantilevers. As the third resonance frequency is less than 1kHz above the second resonance, the electrical frequency response between these two frequencies is broadened compared to the response between the other two adjacent resonance modes.

C. *Capacitive Sensing Readouts*

The intrinsic stress originating during fabrication in the silicon plates and the piezoelectric material is higher than expected, which leads to the larger wing of the outer plate being strongly curved in the fabricated device. Therefore, the initial vertical displacement of its comb fingers is much higher than the corresponding offset of the fixed comb fingers. This leads to no overlap being present between this set of comb fingers when the device is excited by the sound waves and thus a limited capacitance change. Therefore, only the comb fingers of the smaller wing were used for electrical signal measurement. The maximum acoustic sensitivity measured using the capacitive sensing units is 11.6 mV/Pa at the second resonance frequency as shown in Fig. 6. However, the electrical response at the first resonance frequencies is also increased in the capacitive sensing mode. The ratio of acoustic sensitivity measured using both the piezoelectric sensing and the capacitive sensing at the first resonance mode to the acoustic sensitivity measured at other resonance modes, γ, is shown in Table I. The subscript represents the order of the resonance frequency. In comparison to the piezoelectric sensing, the capacitive sensing method generates more noise at low frequencies (<100 Hz) despite the use of a high pass filter.

TABEL I. Ratio Of Acoustic Sensitivity Measured At The FIRST Resonance Frequency To The Rest Three Resonance Frequency

Sensing Methods	γ_{12}	γ_{13}	γ_{14}
Piezoelectric	10 %	29 %	32 %
Capacitive	25 %	74 %	72 %

D. *Directivity*

The directivity characterization was measured using the piezoelectric sensors. As shown in Fig. 7, the new MEMS device performs as a bi-directional microphone not only at the four resonance frequencies, but also at frequencies off the main resonance modes, i.e. the MEMS microphone has the same bi-directional properties across the whole frequency band of interest. It acquires most sound energy when the sound waves are incident from the axis normal to the surface of the rotating plates.

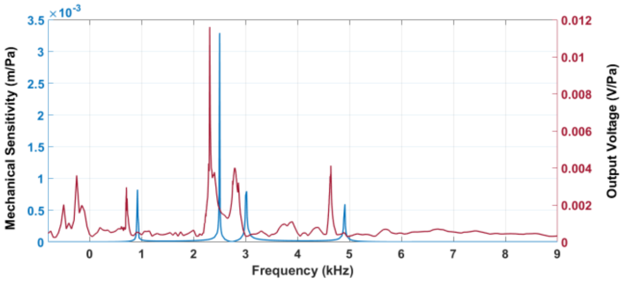

Fig. 6. Predicted mechanical sensitivity of outer smaller wing and its acoustic sensitivity measured from charge sensing circuit.

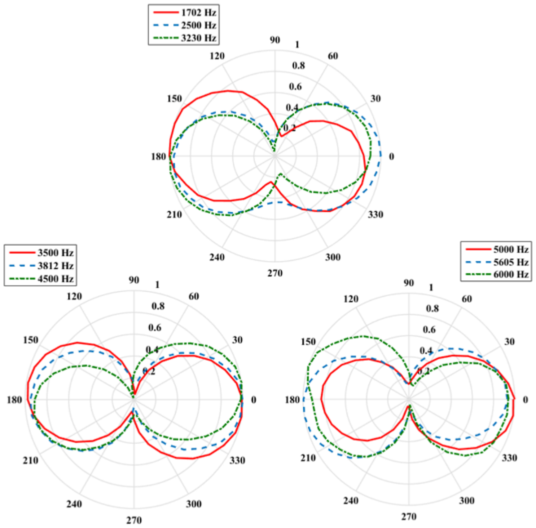

Fig. 7. Measured directional patterns of the fabricated prototype excited at resonance frequencies and other frequencies off main resonance.

V. Discussion and Conclusion

This new multi-band MEMS microphone inspired by the mechanical properties of the *Ormia* fly's hearing organ provides two different sensing methods: piezoelectric bending cantilevers and capacitive comb fingers, which convert the mechanical response of the rotating plates to electrical signals with maximum values of 12 mV/Pa and 0.42 V/Pa. The capacitive sensing increases the electric response at the first resonance, compensating for the shortcomings of the electric response produced by the piezoelectric sensing around the same frequency. The measured directional patterns clearly indicate that this new MEMS microphone is bi-directional across the frequency band below 10 kHz.

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