Bandwidth and Sensitivity Optimization in CMUTs for Airborne Applications

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Abstract – We previously proposed venting the cavities of CMUTs for using them in environments with extreme pressure variation. Such CMUTs have zero differential pressure across the plate at any ambient pressure, thus ensuring a stable operating point and preventing mechanical failure. The air in the cavity between the moving CMUT plate and the substrate forms a squeeze film which gives some stiffening and damping effect to the CMUT. The additional damping from the squeeze film helps to enhance the CMUT's bandwidth significantly. By properly selecting the size, number, and location of the venting holes, the squeeze film effect can be controlled and the sensitivity and bandwidth of the CMUT can be optimized.

We developed a finite element model for simulating such CMUTs with vented cavities. Using this model, we designed a variety of CMUTs with varying sensitivity and bandwidth. These CMUTs were fabricated and characterized. The measurements closely match our finite element model results.

Keywords: vented CMUT, varying pressure, squeeze film damping

I. INTRODUCTION

Capacitive Micromachined Ultrasound Transducers (CMUTs) offer many advantages over traditional piezoelectric transducers. The flexural plate of a CMUT has much lower mechanical impedance than bulk piezoelectric transducers. This makes CMUTs ideal for use in airborne applications due to their better impedance matching characteristic [1]. When used in immersion applications like medical ultrasound imaging, the lower mechanical impedance of the CMUT flexural plate enables it to have a wider bandwidth. However in airborne applications conventional CMUTs with a vacuum cavity still have a narrow bandwidth.

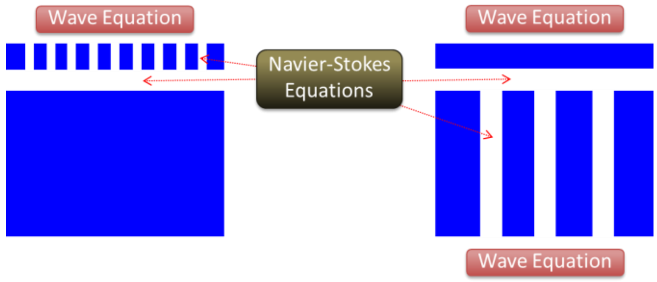
Many airborne ultrasound applications could benefit from a wider bandwidth CMUT design. In flow metering or ranging applications where transit time for an ultrasound pulse is to be measured, a wider bandwidth would increase the accuracy of the measurement using cross-correlation techniques [2]. In ultrasonic gesture sensing or airborne ultrasonic imaging application, a wider bandwidth transducer would enable reducing the pulse width and improving the axial resolution. The smaller ring-down times due to a wider bandwidth would enable faster measurement rates. Clearly there is a need to develop a wide bandwidth CMUT design for airborne applications.

Previously we had demonstrated a CMUT design with vented cavities for using them in ultrasonic flowmeters in environments with extreme pressure variation [3, 4]. In such a design the air in the cavity between the moving CMUT plate and the substrate forms a squeeze film which gives some stiffening and damping effect to the CMUT. The additional damping from the squeeze film helps to enhance the CMUT's bandwidth significantly. The vents allow us to control the squeeze film effect. The vents also cause additional damping due to viscous and thermal losses. By varying the size, location and number of vents, the bandwidth and sensitivity of the CMUT can be optimized.

The CMUT cavity can be vented either through the plate or through the substrate. Each of these configurations has unique advantages. Having the vents in the substrate allows us to separate the air inside the cavity from the ambient air. This makes it possible to use such a CMUT in harsh environments. Also this provides an option to pressurize the cavity independent of the ambient pressure. We previously reported CMUTs with this configuration. Such a CMUT exhibits additional resonant modes due to Helmholtz resonance. Also, such a CMUT transmits and receives ultrasound through its vents on the back. The housing used for such a CMUT affects its acoustic boundary conditions and hence the housing needs to be carefully designed to optimize the CMUT's performance. For application in a clean environment CMUTs vented through the plate can be used. Such a CMUT is not affected by the housing design and is easier to fabricate and package. Also because of the smaller length of the vents such a CMUT does not have a significant Helmholtz resonance.

II. MODELING

CMUTs with vented cavities present a challenging multi-physics problem to model. Apart from the structural mechanics, electrostatics and acoustics, fluid mechanics in the cavity and the vents needs to be modeled accurately. Typically in MEMS devices, Reynolds equation from classical lubrication theory is used to model squeeze films [5]. However the Reynolds equation neglects fluid inertia. This gives inaccurate results, especially at higher pressure. Also Reynolds equation cannot model the Helmholtz resonance commonly seen in CMUTs vented through the substrate. We used Navier-Stokes equations to model the fluid inertia in the squeeze film. Navier-Stokes equations were also used to accurately model the viscous and thermal losses for the fluid in the vents. The fluid domain into which the CMUT radiates sound was modeled using the acoustic wave equation. A



(a) (b)

Fig. 1. Modeling fluid domains in a CMUT with vented cavities: (a) cavities vented through the plate, (b) cavities vented through the substrate

commercial finite element analysis tool, COMSOL was used to solve these coupled equations.

III. FABRICATION

We previously reported the fabrication process for CMUTs vented through the substrate [3]. CMUTs vented through the plate have a similar fabrication process. The process starts with a low resistivity silicon wafer [Fig. 2(a)]. The wafer is patterned and cavities are etched in the silicon using Tetra methyl Ammonium Hydroxide (TMAH) [Fig. 2(b)]. The wet TMAH etch has good uniformity across the wafer and the etch depth can be controlled quite accurately after the etch rate is characterized for the setup. The oxide used as the masking layer is then stripped and 1.5-µm thick thermal oxide is grown again as an insulation layer as well as for oxide posts for bonding [Fig. 2(c)]. The plate SOI wafer is then bonded on top using direct fusion bonding [Fig. 2(d)] and annealed in nitrogen at 1050 °C for 4 hours. The handle layer and the buried oxide layer of the plate SOI wafer are then etched away to release the CMUT plates [Fig. 2(e)]. A 500-nm thick layer of aluminum is evaporated on the front and back of the wafer to provide better electrical contact. Finally, vias are etched though the aluminum and silicon plate to vent the cavities [Fig. 2(f)]. Excess aluminum and silicon surrounding the CMUT element is also etched away in order to reduce parasitic capacitance. We fabricated a variety of CMUTs with this process. The size of the vent holes was varied to vary the effect of the squeeze film.

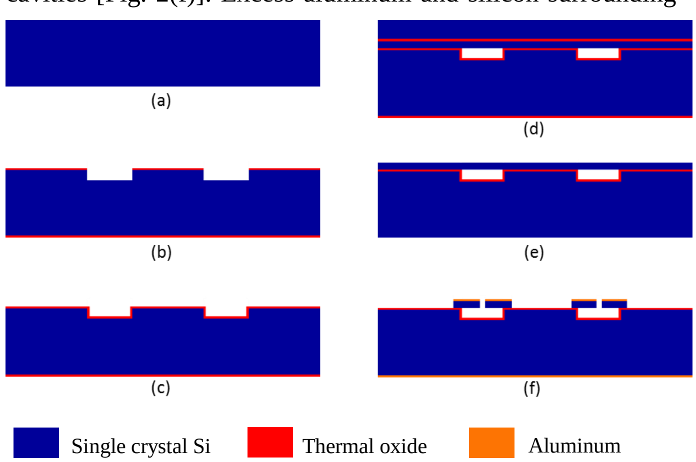


Fig. 2. Fabrication process flow for CMUTs with cavities vented through the plate

IV. CHARACTERIZATION

(i) Input impedance measurement:

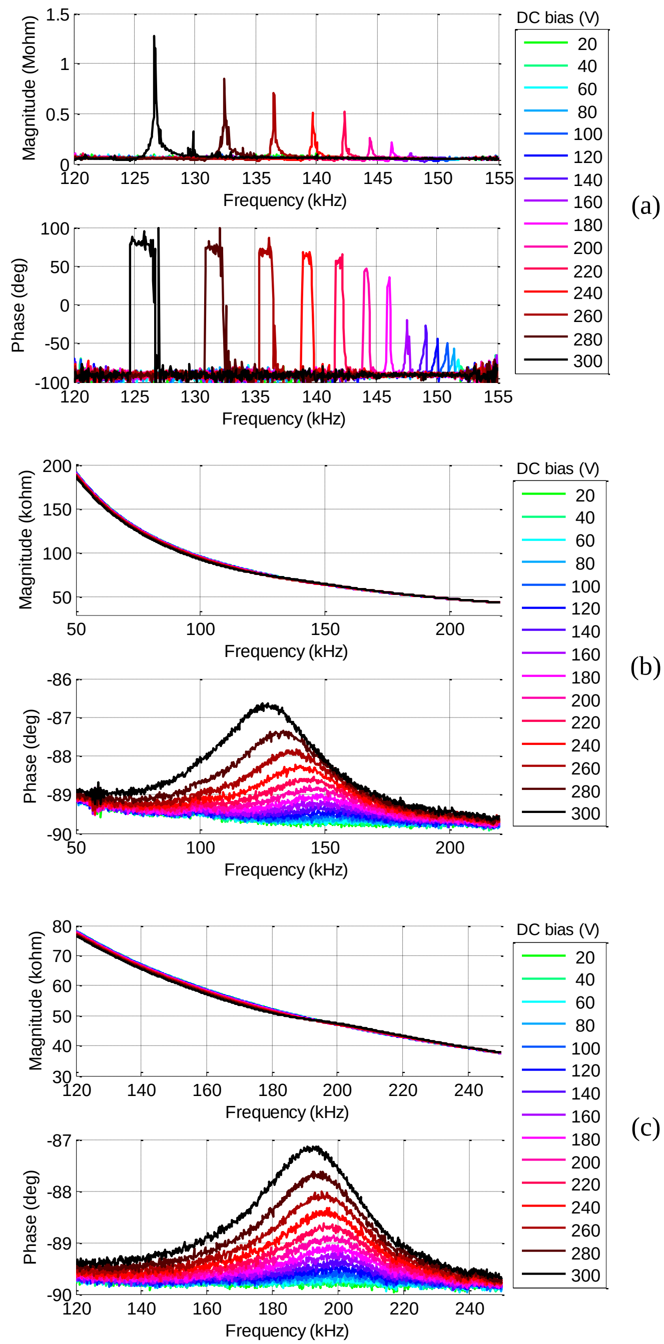


Fig. 3. Input impedance measurement: (a) measured in vacuum, (b) 1% vent area CMUT, measured in 1 atm, (c) 0.05% vent area CMUT, measured in 1 atm (Plate radius= 500 µm, plate thickness = 10 µm, gap height = 5.3 µm)

After fabricating the devices, their input impedance was measured. In vacuum, the devices have no squeeze film and no loading from the medium and exhibit a sharp resonance peak [Fig. 3(a)]. However when measured in air, the resonance peak is heavily damped. The damping and stiffening from the squeeze film depends largely on the area ratio of the vent holes. For devices with a 1% area ratio of the vent holes, no significant squeeze film stiffening is observed and the resonant frequency is almost the same as observed in vacuum [Fig. 3(b)]. However for devices with only 0.05% area ratio of the vent holes, air flow through the vents is constricted which causes compression and rarefaction of the air in the cavity as the plate vibrates. This leads to a significant squeeze film stiffening effect on the CMUT plate and raises its center frequency [Fig. 3(c)]. Also, the squeeze film stiffening effect dominates the electrostatic spring softening effect and the center frequency does not drop significantly with increasing DC bias voltage.

(ii) Displacement sensitivity measurement:

The devices were also measured using a laser Doppler vibrometer (LDV; OFV-511, Polytec GmbH, Waldbronn, Germany). Since the device with 1% vent area doesn't have significant squeeze film stiffening, most of its squeeze film force contributes towards damping giving it a wide fractional bandwidth of 36% (Fig. 4) (Table 1). The squeeze film force in the device with 0.05% vent area contributes to both stiffening as well as damping. As a result it has a relatively smaller fractional bandwidth of 19% (Table 1). As compared to the 1% vent area device, the center frequency of the 0.05% vent area device is raised from 129 kHz to 196 Hz. These measurements closely match our simulation results from the finite element model.

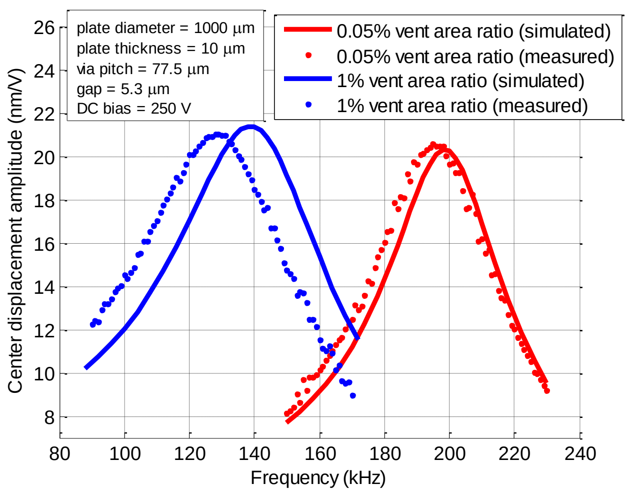


Fig. 4. Variation in squeeze film effect by varying size of vent holes

TABLE I
VARIATION OF FRACTIONAL BANDWIDTH WITH VARIATION IN VENT SIZE

	Simulation	Measurement
0.05% vent area	18%	19%
1% vent area	34%	36%

(iii) Pitch-catch measurement at elevated pressure:

A pair of devices with 0.05% vent area was arranged in a pitch-catch setup inside a pressure chamber at a distance of 15 cm from each other. Both CMUTs were biased at 175 V (~85% of collapse voltage). The transmitting CMUT was excited with a 20-cycle AC burst and the signal from the receiving CMUT was recorded. The frequency of the transmit burst signal was varied to get the frequency spectrum of the pitch-catch measurement.

The mechanical resonant frequency for a 10 μm thick silicon plate of 1300 μm diameter is ~90 kHz. However for this design the squeeze film stiffening raises the resonant frequency to 170 kHz even at 1 bar pressure. As the pressure in the chamber is raised up to 20 bar, the squeeze film stiffening effect raises the resonant frequency of the CMUT to 825 kHz (Fig. 5). These results agree well with the frequencies predicted by our finite element model (Fig. 6). The model slightly under-predicts the squeeze film stiffening effect as it currently does not consider the static deflection of the CMUT plate due to DC bias.

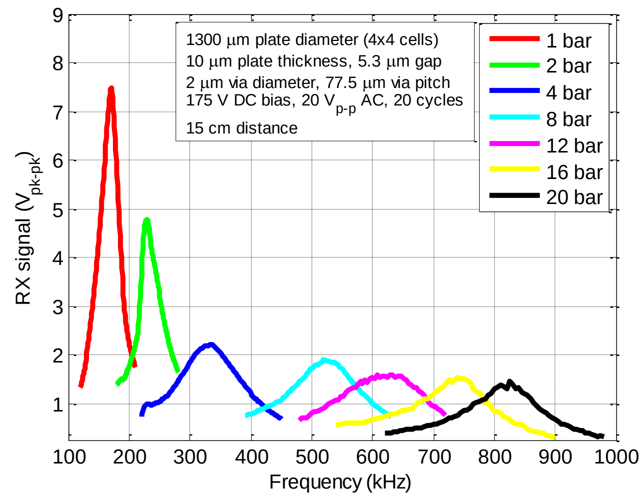


Fig. 5. Pitch catch measurement under varying ambient pressure

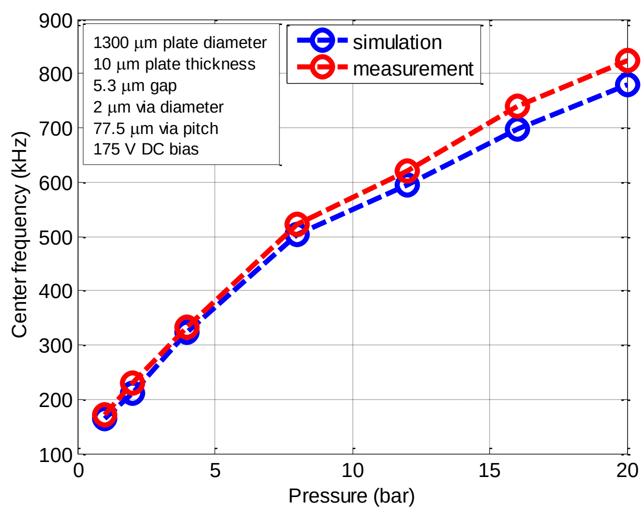


Fig. 6. Variation in resonant frequency with varying ambient pressure

IV. CONCLUSIONS

We developed a finite element model for CMUTs with vented cavities using Navier-Stokes equations to model the fluid dynamics of the squeeze film and the fluid in the vent holes. Using this model we designed and fabricated CMUTs vented through holes etched in the plate. The fluid squeeze film formed in the cavity of such CMUTs plays an important role in their performance. By carefully selecting the size, location, and number of vent holes, the frequency, bandwidth, and sensitivity of the CMUT can be controlled. We demonstrated CMUTs with up to 36% fractional bandwidth in air. Some of these devices were tested under elevated pressure of up to 20 bar. Our model correctly predicted the behavior of these CMUTs even at elevated pressure.

ACKNOWLEDGMENT

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