CHARACTERIZATION OF CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS IN AIR USING OPTICAL MEASUREMENTS

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Abstract - Capacitive micromachined ultrasonic transducers (CMUTs) are efficient transmitters and receivers for air-coupled nondestructive evaluation applications [1]. In this paper, we present optical measurements on CMUTs with circular and rectangular membranes. Use of a laser interferometer permits accurate measurement of individual membrane displacements as well as characterization of mode shapes on the membrane. When optical displacement measurements are combined with electrical impedance measurements, all elements of the equivalent circuit model can be evaluated. In particular, an estimate of the loss in the transducer is possible.

Loss mechanisms include structural losses and squeeze-film effects of air behind the membrane, the latter of which has both frequency-shifting and dissipative effects. Recently fabricated circular and rectangular membrane designs typically exhibit a real loss on the order of 500 rayls ± 200 rayls. The degree of resonant frequency shift for unsealed membranes in air depends strongly on the particular geometry, but can be as much as 30% of the transducer's resonant frequency in vacuum. Measurements of CMUT loss due to air are compared to squeeze-film theory and are included in an equivalent circuit model. This model is compared against the measurement results.

I. INTRODUCTION

The membrane structure of a CMUT is shown in Figure 1. The membrane consists of roughly 1 μm thick, metalized silicon nitride over a 1 μm air or vacuum gap, depending on whether the CMUT is sealed or unsealed. Several thousand such circular or rectangular membranes electrically connected in parallel form a CMUT, a section of which is shown in Figure 2. When the membranes are biased with a DC voltage, AC voltage excitations generate pressure waves in the air. Reception of ultrasound by the same device is analogous, as the impinging sound pressure moves the membrane, modulating the voltage (or charge) on the membrane.

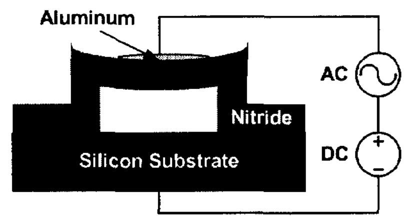

Figure 1: Schematic cross-section of a single CMUT membrane

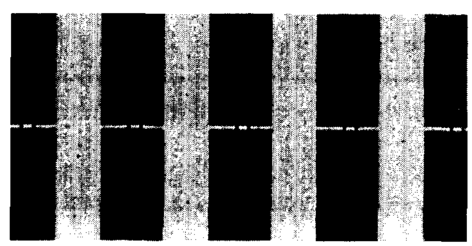

Figure 2: Magnified top-view of a string of 4 rectangular CMUT membranes of 100 μm width

II. EQUIVALENT CIRCUIT MODELS

The derivation of a small-signal circuit model facilitates analysis of the transducer since circuit theory can be leveraged for understanding and insight. An equivalent circuit of a CMUT operating in air is presented in Figure 3 and is based on the Mason model [1,2].

The mechanical membrane impedance Z_{mem} can be replaced by a series inductor-capacitor circuit which models its fundamental resonance. The

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complex loss Z_{loss} represents squeeze-film damping effects behind the membrane and coupling to the substrate. As will be discussed later, this impedance can be treated as a resistance, representing components of energy loss, and a capacitance, representing the energy storage of compressed air behind the membrane. Finally, if the lateral extent of the CMUT is far greater than the wavelength of ultrasound emitted, the radiation impedance of the air becomes purely real, indicating nearly plane wave excitation from the transducer. All of these mechanical impedances can be transformed to the electrical side of the circuit to yield the equivalent circuit shown in Figure 4. As is evident from the models, understanding the loss and damping impedance terms is critical to estimate the bandwidth, resonant frequency, and amount of power that is actually radiated to the air.

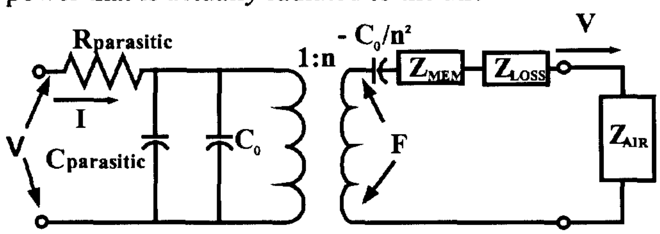

Figure 3: Model of a transmitting CMUT in air

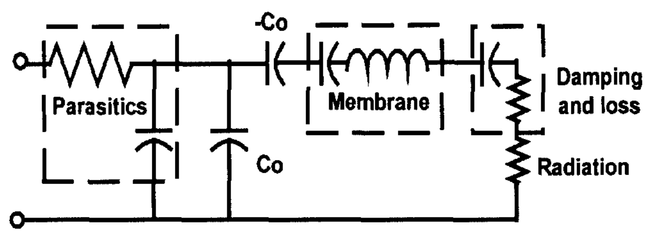

Figure 4: Equivalent electrical model of a transmitting CMUT in air

III. SQUEEZE-FILM THEORY AND CMUT LOSSES

Sources of loss in CMUTs

The primary sources of loss in CMUTs are the coupling of movement from the membrane into the substrate and the damping of air behind the membranes. Measurements of the impedances of CMUTs in vacuum, an environment without any squeeze-film damping, confirms that the loss due to coupling is only about 10% of the total real loss. We also presume the frequency shift due to substrate coupling to be negligible compared to squeeze-film effects.

Squeeze-film theory

To the authors' knowledge, the body of work on squeeze-film damping has not been applied to CMUTs as yet, though the mathematics has been developed for some simple cases [3]. Solutions to the squeeze-film equations assume piston motion and a free boundary with the atmosphere at the edges of the plates as shown in Figure 5. Given these assumptions, the force on the vibrating plate consists of two components. One component is in phase with velocity and therefore dissipates energy like a resistance. The other component is in phase with the plate displacement, and therefore stores energy through compression of the gas like spring, or electrically, a capacitor. This capacitive element in the equivalent circuit of Figure 4 is responsible for the frequency shift that occurs when a CMUT is operated in air.

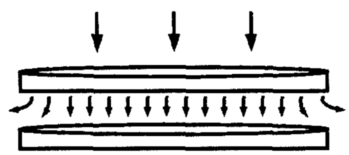

Figure 5: A representation of squeeze-film damping between two parallel plates in air

The equations for the equivalent frequency-dependent resistor and capacitor values can be obtained through simple modification of the formulas for squeeze-film forces [3]. In the case of a single circular plate of radius a, air gap l_a, radian frequency ω, atmospheric pressure P_{atm}, and air viscosity μ, the equivalent mechanical resistance in [kg/s] is given by Equation (1). Likewise, the equivalent mechanical capacitance [kg/s^2] is given by Equation (2) where $\sigma = \dfrac{12\mu a^2\omega}{P_{atm}\ell_a^{\,2}}$.

$$R_{loss} = \left(\frac{P_{atm}\pi a^2}{\omega \ell_a}\right)\left(\sqrt{\frac{2}{\sigma}}\,\frac{ber\sqrt{\sigma}\left(ber_1\sqrt{\sigma}+bei_1\sqrt{\sigma}\right)+bei\sqrt{\sigma}\left(bei_1\sqrt{\sigma}-ber_1\sqrt{\sigma}\right)}{\left(ber\sqrt{\sigma}\right)^2+\left(bei\sqrt{\sigma}\right)^2}\right) \quad (1)$$

$$C_{squeeze} = \left(\frac{\ell_a}{P_{atm}\pi a^2}\right)\left(1-\sqrt{\frac{2}{\sigma}}\,\frac{ber\sqrt{\sigma}\left(bei_1\sqrt{\sigma}-ber_1\sqrt{\sigma}\right)-bei\sqrt{\sigma}\left(ber_1\sqrt{\sigma}+bei_1\sqrt{\sigma}\right)}{\left(ber\sqrt{\sigma}\right)^2+\left(bei\sqrt{\sigma}\right)^2}\right)^{-1} \quad (2)$$

The expressions for resistance and capacitance in the case of rectangular membranes of width W and length L are given by Equations (3) and (4):

$$R_{loss} = \frac{64\sigma P_{atm} LW}{\omega \ell_a \pi^6} \sum_{m,n,odd}^{\infty} \left(\frac{m^2 + \left(\frac{nL}{W}\right)^2}{(mn)^2 \left(\left(m^2 + \left(\frac{nL}{W}\right)^2 \right)^2 + \frac{\sigma^2}{\pi^4} \right)} \right) \quad (3)$$

$$C_{squeeze} = \frac{\ell_a \pi^8}{64 P_{atm} L W \sigma^2} \left(\sum_{m,n,odd}^{\infty} \left(\frac{1}{(mn)^2 \left(\left(m^2 + \left(\frac{nL}{W}\right)^2 \right)^2 + \frac{\sigma^2}{\pi^4} \right)} \right) \right)^{-1} \quad (4)$$

where $\sigma = \frac{12\mu L^2 \omega}{P_{atm} \ell_a^{\,2}}$.

These expressions can be used to calculate the damping and loss elements in the equivalent circuit of Figure 4 when scaled by the number of membranes and the electro-mechanical transformer ratio.

IV. OPTICAL MEASUREMENTS AND DISCUSSION

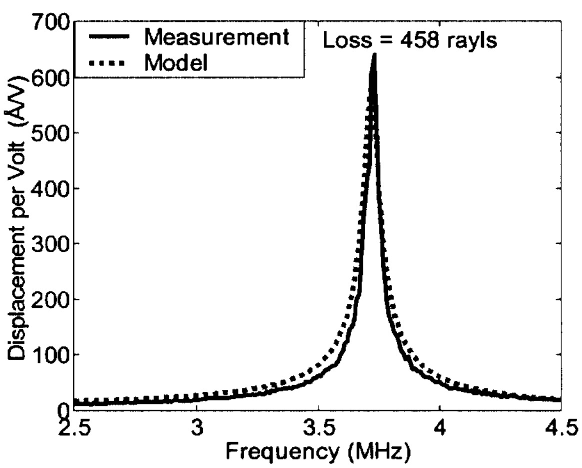

Figure 6: Measured displacement per volt across the transducer by frequency, compared to the prediction by the equivalent circuit model

Real loss measurements

Displacement measurements using an optical interferometer, when combined with electrical input impedance data, can be used to determine the value of real loss in a CMUT. In the data that follows, an optical heterodyne interferometer as described by Hsieh is used to measure the displacement on the membrane surface [4]. Figure 6 compares the actual and predicted displacement of a CMUT comprised of 50 μm radius circular membranes, neglecting the frequency shift of the squeeze-film capacitor. Measurements indicate a real loss term of 458 rayls (normalized for transducer area) for this transducer. Squeeze-film theory estimates a real loss of 557 rayls for this transducer geometry. In general, we find that squeeze-film theory is able to predict the real loss of the transducer within a third of the measured value.

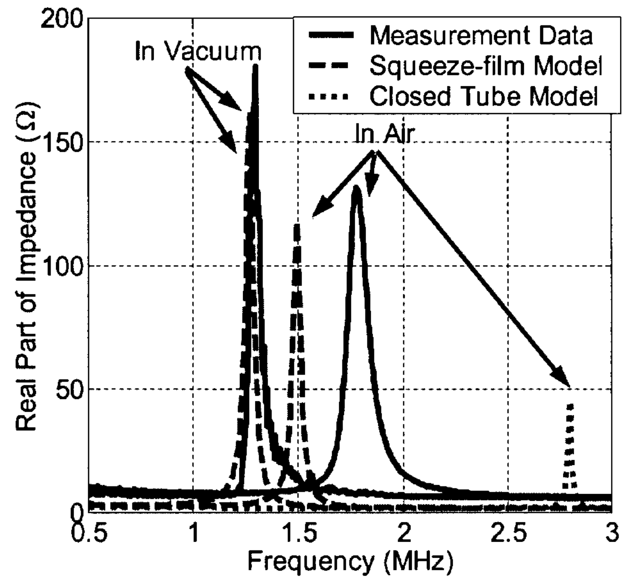

Figure 7: Real part of impedance in vacuum and air comparing predicted frequency-shift of the squeeze-film model and closed-tube model with the measurement

Frequency shift measurements

Measurement of the frequency shift due to squeeze-film effects in unsealed CMUTs is most easily accomplished by comparing impedance measurements in vacuum, where squeeze-film effects will not be present, to measurements in air. The solid line in Figure 7 shows vacuum and air impedance measurements of a 100 x 800 rectangular CMUT. The resonance in vacuum is 1.29 MHz, and the resonance in air is 1.77 MHz. The equivalent circuit model including squeeze-film effects, shown by the dashed line, underestimates the frequency shift in air, predicting a resonance of 1.49 MHz. The dotted line, representing the closed-tube model predicts a resonance of 2.8 MHz using the formula for the equivalent capacitance of a closed acoustic cavity [5]. This prediction thus represents a CMUT which has completely trapped the air in a cavity behind the membrane.

As shown by Figure 7, squeeze-film theory does not accurately predict the frequency shift experience by a CMUT operating in air. However, the expressions derived under this theory assume a free boundary with the atmosphere at the edges of the membrane. In reality, CMUT membranes have regularly spaced via holes around the edge of the membrane, so some trapping of the air is expected. The vast overestimation of resonance using a closed-tube approximation, however, suggests that there is some movement of air through the via holes.

Rectangular membrane modes

Optical displacement measurements taken as a function of distance along the membranes can be used to determine the mode shape of the membranes. For a 100 x 500 μm membrane with a fundamental resonance at 1.83 MHz, the mode shape is somewhat bell-shaped. As Figure 8 shows for this membrane, a higher-order mode can be excited at a slightly higher frequency of 2.1 MHz. In general, many higher-order modes are observed for rectangular membranes at various other frequencies. One probable cause of the irregularities might be the inherent asymmetry of the rectangular shape or metalization shape. Non-uniformities in processing might also have a greater effect for rectangular geometries. We have not measured similar unexpected mode shapes in circular membranes.

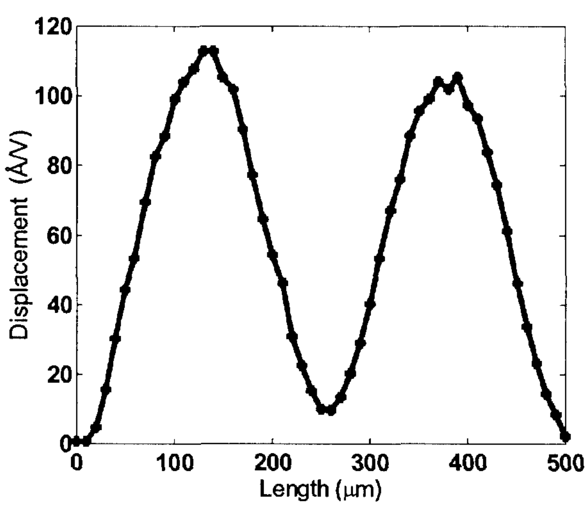

Figure 8: Unexpected second-order mode shape across length of a rectangular transducer

V. Conclusion

Measurement of membrane displacement using an optical interferometer provides a means to measure a transducer's loss, as well as calculate all other modeling parameters when combined with electrical impedance data. Optical measurements also permit analysis of mode shapes in membrane movement, as seen with rectangular membranes. Higher-order modes complicate analysis with equivalent circuit models, which generally assume only one resonance and piston-like membrane behavior and radiation.

Squeeze-film theory generally provides a reasonable estimate of the real losses associated with movement of the air behind the membrane cavity. However, the theory appears to underestimate the frequency shift of a CMUT in air by almost half. Some modification to the theory that accounts for discrete via holes for air to escape along the edge of the membrane might improve predictions. Refinements of this model could provide insight into variations in device performance due to changes in geometry and environmental conditions, such as ambient pressure.

VI. Acknowledgements

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VII. References

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