Finite Element Analysis of CMUTs: Conventional vs. Collapse Operation Modes

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Abstract — **Collapse mode has been proposed to improve Capacitive Micromachined Ultrasonic Transducer (CMUT) performance in terms of output pressure and receive sensitivity. The focus of this study is to compare the performance of optimized designs for conventional and collapse mode operations using finite element analysis (FEA). For this purpose, we have developed a 2D finite element model for output pressure calculation of CMUTs using commercially available FEA software (ANSYS 10.0). The model is composed of a membrane, a fluid waveguide and an electrical port. The membrane and the fluid part are constructed using axisymmetric plane elements. The electrical port is added to the model by using transducer elements that are already available in ANSYS. Through transient analysis non-linear calculations are performed and average output pressure over the membrane surface is calculated for a given electrical excitation that is applied to the electrical port. First, the effect of various transducer parameters such as radius, thickness, bias voltage, are investigated for conventional mode. Then, the performance of membranes operating in different modes are compared. The parameters of the membranes are selected such that their center frequencies and the collapse voltages match for a fair comparison of transducer performance. Our calculations show that the membrane operating in conventional mode required 100 Vpp AC amplitude for 2 MPa peak-to-peak output pressure whereas 38 Vpp AC excitation generated the same output pressure for collapse mode membrane. In addition, we have compared the second harmonic levels generated by the both designs. For 2MPa peak–to-peak output, the second harmonic amplitude is found to be 13.5 dB below the fundamental for conventional mode design. However, the second harmonic amplitude is -12.0 dB for the collapse mode design.**

I. Introduction

Capacitive micromachined ultrasonic transducers (CMUTs) have been introduced more than a decade ago as an alternative to piezoelectric transducers [1]. However challenges in getting high output pressure as well as relatively high second harmonic generation are holding CMUTs back from becoming the choice of industry for applications such as medical imaging. Especially, contradicting requirements over the gap height to get both high receive sensitivity and high output pressure is one of the most important difficulties of CMUT technology. To overcome these difficulties various methods have been introduced. Dual electrode membranes were reported for improved sensitivity in both transmit and receive [2]. Collapse mode operation was also introduced to address the same problem [3,4].

CMUTs are usually operated by applying a DC voltage that is less than the collapse voltage. The AC voltage amplitude is adjusted such that the membrane does not make contact with the substrate. In the collapsed-mode, however, first the membrane is biased beyond collapse voltage, and then the bias voltage is reduced without losing the contact between the membrane and the substrate. In this case, the annular region between the membrane center and the rim is vibrated by the AC voltage.

Experimental [3] as well as FEM [4] characterization of collapse mode have been reported previously. However, the performances of transducers operating at conventional and collapsed mode with the same center frequency have not been compared. The main purpose of this paper is to perform such a comparison.

In this paper, first we will demonstrate the effect of various transducer parameters on the performance of a transducer operating in conventional mode. Then, the optimized design will be compared to another transducer operating in collapse mode in terms of output pressure and harmonic generation.

II. Finite Element Method Calculations

We used ANSYS 10.0 for the FEM calculations. A 2D ANSYS model similar to the ones presented in references [5] and [6] was developed. The model was axisymmetric around the line passing through the center of the membrane. This simulates infinitely large transducer where all the membranes are driven in phase. Contact elements were also added to the model to be able to simulate the contact between the membrane and the substrate as shown in Fig. 1. The contact elements were defined on the bottom surface of the membrane and the top surface of a thin silicon block as shown in the Figure. The frequency response of the transducer operating in conventional mode was calculated by adding an absorbing boundary at the end of the water mesh. In harmonic analysis, the contact elements were disabled. In transient analysis, the length of the water mesh was chosen long enough to eliminate reflections coming from the end of the mesh.

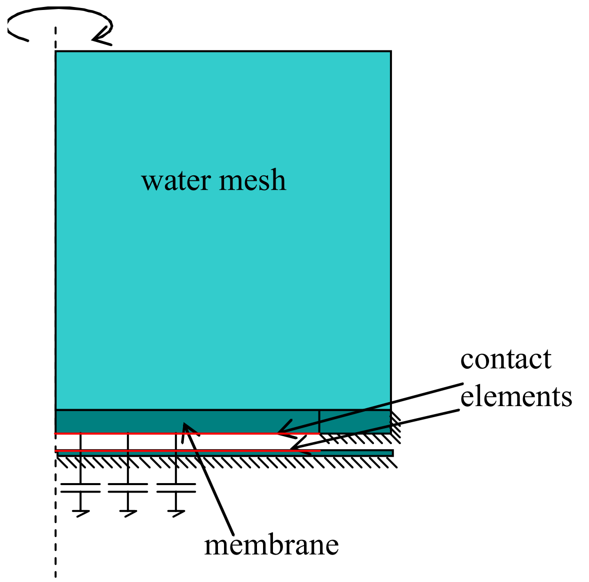

Figure 1. Finite element model used in the calculations. For harmonic analysis of conventional mode, an absorbing boundary is added at the end of water mesh.

A. Conventional mode

We have analyzed 4 different membrane geometries operating in conventional mode. The parameters of the transducers are listed in Table I.

Table I. Membrane geometry

	mem14	mem18	mem22	mem26
Radius (µm)	14	18	22	26
Thickness (µm)	0.87	1.42	2.00	2.80
$V_{collapse}$ (V)	43	54	61	71

The gap height of all the membranes, which are made of silicon, is equal to 0.1 µm. Also, each design has an insulator of 0.1 µm thick silicon oxide (relative permittivity 3.9) layer over the substrate. The membrane thickness was adjusted to get the same center frequency (10 MHz).

The frequency response of each design is depicted in Fig. 2. As the membrane radius increases, the stiffness and the mass increase. This resulting in a reduced bandwidth for the stiffer membrane designs.

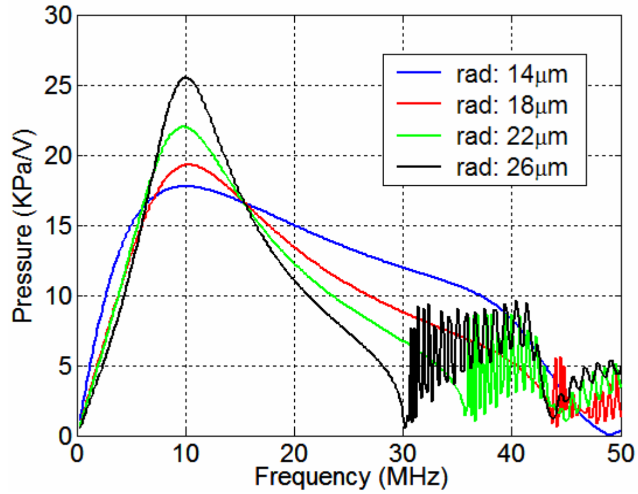

Figure 2. Frequency response of the membranes listed in Table I. The largest (26 µm radius) membrane resulted in the smallest bandwidth.

We performed non-linear transient analysis to find the maximum output pressure attainable from 0.1 µm gap. First, the membranes were biased at a certain fraction of their collapse voltages then 5 cycle sinusoidal wave at 10 MHz was applied. The corresponding peak to peak output pressure as well as the minimum and maximum center displacement over the last three cycles were measured. The aim of this study is to determine the optimum bias voltage and the required AC voltage that yield the maximum output pressure.

Fig. 3 shows a typical set of output pressure curves obtained from one of the designs (22 µm radius). In all of the designs, the maximum output pressure was obtained when the bias voltage was set to 60% of collapse voltage when there is no limit was set on the AC voltage amplitude.

Fig. 4 compares the output pressure levels for 60% bias. The softest (14 µm) membrane generated the least maximum pressure. As the bandwidth increases, the membrane swing decreases within the gap. For small bandwidth membranes, the center of the membrane can move above the rest position of the membrane. This increases the output pressure. As shown in Fig. 4, the 26 µm radius membrane which has the least bandwidth yielded the maximum output pressure from 0.1 µm gap. Also note that, for small AC amplitudes (much less than the bias voltage), the stiffer membranes always generate higher pressure levels compared to softer membrane designs due to the higher electric field in the gap [6]. However, as the AC voltage amplitude increases, the sensitivity of the softer membrane increases and for large enough AC voltages, it can be higher than the sensitivity of a stiffer design. Nevertheless, the stiffer designs outperform the softer designs regarding the maximum output pressure.

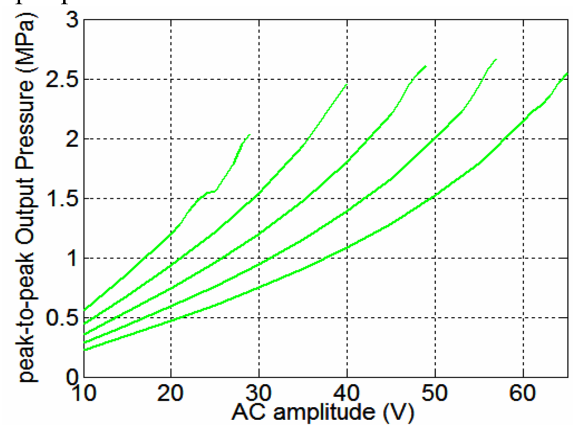

Figure 3. Output pressure at different bas levels. The most right curve represents the pressure level for 50% bias. To the left, bias increases 10%, the most left one being 90%.

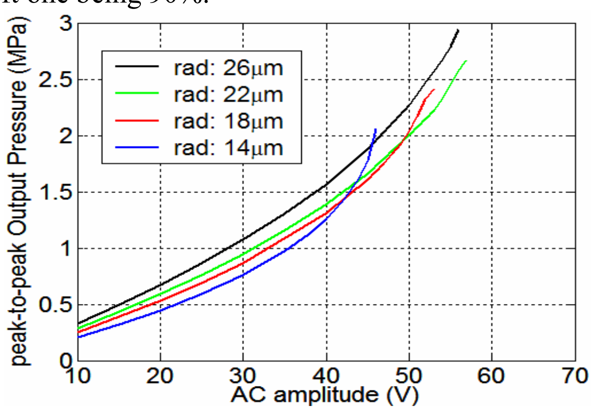

Figure 4. Output pressure for 60% bias.

If one considers both bandwidth and pressure, 22 μm radius membrane represents a good compromise. It generates relatively high output pressure levels and 100% bandwidth.

B. Collapsed-mode

The geometry of the membrane operating in collapse mode is selected to get 10MHz center frequency. Also, the gap height is adjusted so that the collapse voltage is 61V, which is the same as the collapse voltage of 22 μm radius membrane. Fig. 5 shows the center displacement as a function of bias voltage.

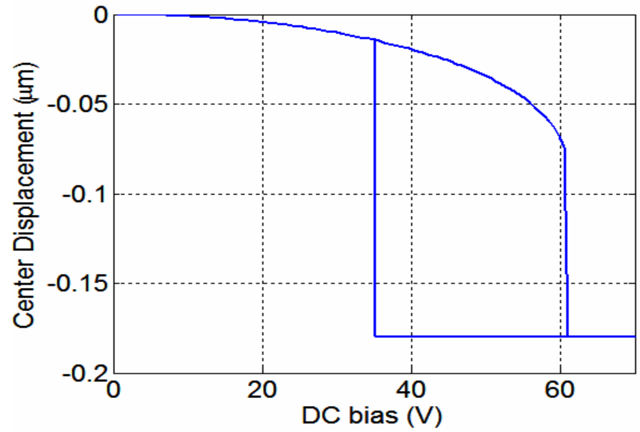

Figure 5. Center displacement as a function of bias voltage. The collapse voltage is 61V and the snap-back voltage is 33V.

For collapse mode operation, the membrane was first biased to 65V then the bias was reduced to 47V. Then a 5 V, 0.02 μsec square pulse was applied to obtain the frequency response which was determined by calculating the FFT of the resulting pressure pulse. The result was also corrected for the input pulse spectrum. Fig. 6 shows the bandwidth of the transducer in collapse mode.

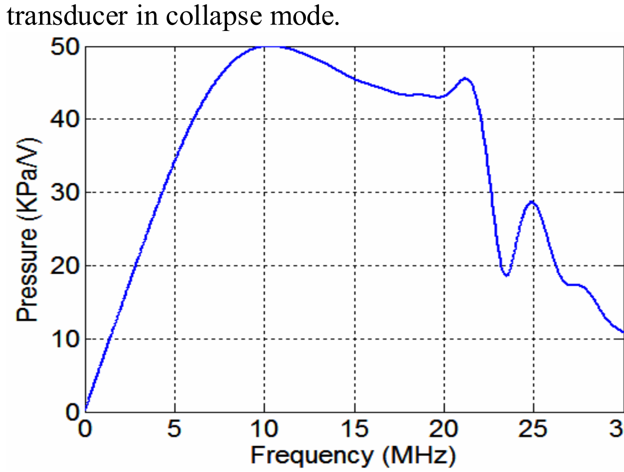

Figure 6. Frequency response in collapse mode.

In Fig.6 there is a small peak around 21.5 MHz. The reason for this peak is due to a higher order mode.

C. Comparison

Figure 7 compares the output pressures of 22 μm radius membrane (biased at 60%, 36.6V) and collapse mode membrane (biased at 47V). For collapse mode, the AC amplitude is limited by the snap back of the membrane. Higher AC amplitudes start to remove the contact between the membrane and the substrate. The sensitivity of the collapse mode operation is approximately 3 times higher than that of conventional mode.

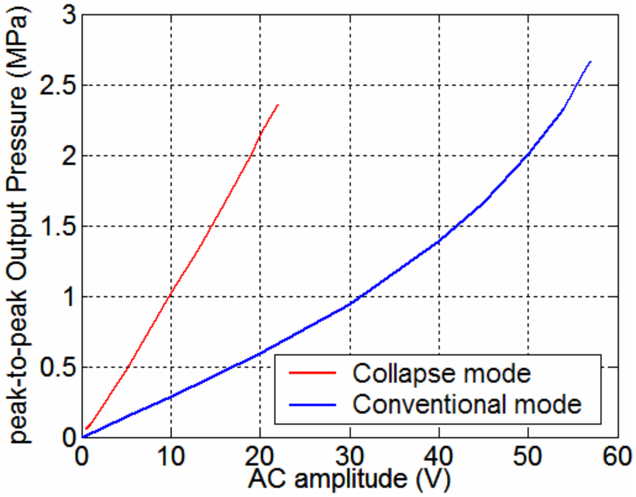

Figure 7. Pressure as a function of AC amplitude.

Second harmonic generation is another important feature of an ultrasonic transducer. Fig. 8 compares SHD level for the same membranes considered above.

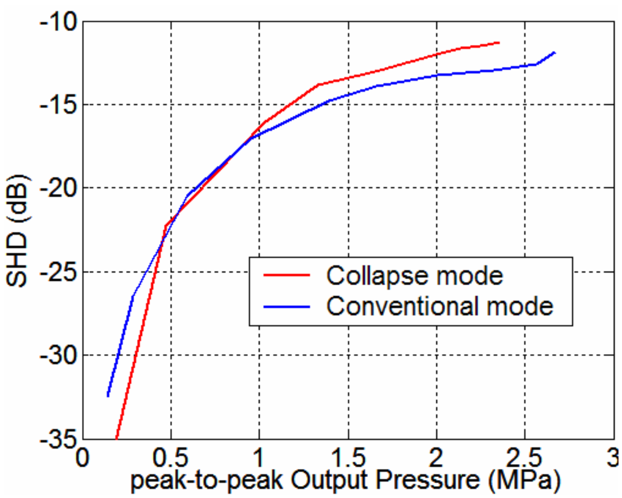

Figure 8. Second harmonic generation.

III. CONCLUSION

In this paper we presented the performance comparison of collapse mode and conventional mode CMUT transducers operating at the same center frequency. In terms of output pressure, collapse mode generates higher sensitivities and consecutively higher pressure levels at smaller AC drive amplitudes. For large pressure levels, both operation modes resulted in similar second harmonic generation.

Optimization of membrane geometry is important to get maximum performance from a transducer. Different applications might impose different design criteria such as limitations on AC or DC voltage amplitudes. The process and fabrication limitations (minimum feature sizes, parasitics) as well as material properties (breakdown) should be also considered. To get the optimum design one needs to run similar non-linear analysis to the ones demonstrated in this paper.

In this paper, we have only considered optimization of membrane parameters for conventional mode when there is no limitation over the AC and DC voltages. Optimization for collapse mode is more involved and will be the subject of future research.

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