Finite Element Simulation and Analysis of Capacitive Micromachined Ultrasonic Transducer

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Keywords: Capacitive micromachined ultrasonic transducer, Simulation, Resonant frequency.

Abstract. Capacitive micromachined ultrasonic transducers (CMUTs), which are suitable for operation in both air and water, have been simulated and fabricated with sacrificial release method. We have proposed four models for CMUT, that are block-shape membrane model, the BOX model, the BOX model with etch holes and the BOX model with etching channels that were more closely match the actual structure. And, the effects of those models on the resonant frequency are analyzed. It can be concluded that the value of percent difference between block-shape membrane model and the BOX model is about 8.7% when the ratio of L/W is above 4. In addition the thinner the CMUT membrane thickness, the smaller the percent difference. We analyzed the size of the etching channel. A dynamic range in less of (0.125% or 0.25%) is observed when the height ratio of cavity and (channel or hole) increased. When the width ratio of cavity and (channel or hole) is analyzed, the results obtained are also very small. Based on the analysis of the size of the etched hole, the influence of the etching channel on the structure frequency can be obtained as a result of the small percent difference.

Introduction

Ultrasound is widely used in many occasions of human society, including medical imaging, non-destructive testing and ultrasonic treatment, industrial cleaning and et al. The piezoelectric transducer has been developed greatly after the Curie brothers found the piezoelectric effect in 1880 [1]. Since the forty's of last century, the piezoelectric ultrasonic transducer has been occupying the leading position [2] [3].

However, the application of piezoelectric transducer in air and liquid has a very big problem because of the mismatch of impedance [4][5]. And it is relatively difficult to obtain the change of the resonant frequency by using the piezoelectric manufacturing process to change the structure parameters.

The capacitive micromachined ultrasonic technology has emerged as a promising alternative to piezoelectric transducers since 1994s [6]. Ultrasonic transducers are capable of converting electrical energy into ultrasonic energy and vice versa. Due to the adoption of micro processing technology, CMUT well overcomes many shortcomings of the pressure electric transducers, and the structures with small sizes including CMUTS’ cell and gap, even in submicron range, are easily achieved [7], the frequency of CMUT cell can be tuned by changing structure parameters of the membranes.

In order to better study the CMUTs, many researchers have developed simulation models capable of accurately depicting CMUT behavior. Much of the previous research has involved building models that can represent a single design. These models were then utilized to investigate different CMUT designs.

In previous research, most of the analytical models were derived from the governing mathematical theory that has been presented in [8], [9], and [10]. An early mathematical simulation model to describe the static deflection of a membrane due to the bias DC voltage is presented in [9]. This model utilized a first order analysis of a CMUT that was approximated as a spring-mass-capacitor system. These simplified simulation models showed good accuracy for certain CMUT designs, they could not account for complex geometric conditions. To overcome these limitations, more complex finite
element simulation models were created. These models have been presented and verified using theoretical and experimental results in [10], [11], and [12]. In both [10] and [11] a two dimensional (2D) axisymmetric model was subjected to a structural analysis and the collapse voltage was calculated for varying electrode geometric parameters. And in [13] three dimensional (3D) solid modeling was used to model the resonant frequency of a CMUT membrane with varying electrode size.

In this paper, we proposed four models to simulate the CMUTs’ structures employing sacrificial release method.

Modeling and Simulation

ANSYS finite-element software is used for the calculations and analysis. First, we develop a rectangular CMUT to investigate the relationship between membrane geometry and resonant frequency. The resonant frequency in air is used as an initial estimate of the working frequency. Commonly, the resonant frequency in air will principally be governed by the first modal frequency of the CMUT although higher order mode vibrations may also contribute the membrane.

Block-shape membrane model for CMUT

To model the membrane, 20-noded structural brick elements (SOLID45) were used. The air gap was modeled with a transducer element (TRANS126) that converts energy between the electrostatic and structural domains. We put a hard constraint around the rectangular CMUT. Figure 1 illustrates a diagram of a typical CMUT structure.

The changes of resonant frequencies versus rectangular CMUT’s thicknesses and the relationship between resonant frequency and ratio of L/W can refer to reference [14]. It can be concluded that the resonant frequencies rise when the membrane thicknesses increase.

BOX model for CMUT

We develop a CMUT’s model as similar to box. The membrane was modeled by 3D elements (SOLID45) for simulation of resonant frequencies and we put a hard constraint at the bottom of CMUT membrane, as shown in Figure 2.

The ratio of membrane's L/W was once again from 1 to 10 and the shift in resonant frequency was observed in Figure 3. All other parameters were held constant. The membrane's thickness was once again from 0.5um to 3um in Figure 4.

Figure 1. Block-shape membrane model.  
Figure 2. BOX model for CMUT.

Figure 3. Changes in Resonant Frequency vs. ratio of L/W.  
Figure 4. Change in resonant frequency vs. thickness.
Figure 3 illustrates that the BOX model results closely follow the rectangular CMUT modal results. The block-shape membrane model and BOX model all illustrate the similar trend in resonant frequency due to the increase in aspect ratio. The smallest difference of 7.26% is found for the modal responses behave more like square cells rather than the modes we described for rectangular cells. When the Ratio of L/W is increased the percent differences rise to 8.7% and basically no longer changes. But the small percent difference between the models insignificant.

As seen from Figure 4, the membrane's ratio of L/W was 3 and the shift in resonant frequency was observed. All other parameters were held constant. The thickness for rectangular membrane also affects the resonant frequency of CMUTs, and the smaller the CMUT membrane thickness, the smaller the percent difference.

BOX model with etching holes for CMUT

Figure 5 shows a diagram of the model of CMUT with etching hole.

![Figure 5. ANSYS simulation of CMUT with etching hole.](image)

Figure 5. ANSYS simulation of CMUT with etching hole.

The membrane's ratio of L/W was once again from 1 to 10 and the shift in resonant frequency was observed in Figure 3. In addition, the percent difference was shown in figure 7.

![Figure 6. CMUT resonant frequencies vs. L/w. ](image) ![Figure 7. Percent difference vs. Ratio of L/W.](image)

Figure 6 illustrates that structural changes lead to changes in modal frequency. As seen from Figure 7, it illustrates that the percent difference between BOX model with etching holes and BOX model become similar for aspect ratios larger than 1:4 and basically no longer changes. The smallest difference of 8.7% is found for the modal responses behave when compared the models between BOX model with etching hole and block-shape membrane model.

BOX model with Etching channels for CMUT

The model of CMUT with etching channels is shown in Figure8.

![Figure 8. BOX model with Etching channels.](image)
The relationship between resonant frequency and ratio of L/W is shown in figure 9. Four models have been developed to illustrate the operating frequency of CMUTs with constant width.

![Figure 9. Change in Res. frequency vs. Ratio of L/W.](image)

![Figure 10. Percent difference vs. Ratio of L/W.](image)

By comparing the results obtained above, the resonant frequencies of several models (BOX model, BOX model with etching holes and BOX model with etching channels) are closely when the aspect ratio is larger than 1:4, and the smallest difference close to 8.7% is found for the modal responses behave when the aspect ratio is larger than 1:4.

**Discussion**

The CMUTs’ properties are defined by its structures and the geometric configuration of membrane including thickness and the aspect ratio. It can be concluded that the resonant frequencies rise when the membrane thicknesses increase and the frequency will decline when the ratio of L/W rises until the value plateaus when L/W is above 3.

We have constructed four models for CMUT. And, the effects of those models on the resonant frequency are analyzed. It can be concluded that analysis result of the BOX model is closely to the result of the block-shape membrane model and the ratio of L/W is increased the percent differences rise from 7.26% to 8.7%. In addition, the percent difference between the two models (block-shape membrane model and Box model) is small with less thickness.

When compared the models between the block-shape membrane model and the BOX model with etching holes, it can be concluded that the frequency will decline to 8.7% when the ratio of L/W rises until the value changes smoothly when L/W is above 4, but the percent difference between the other models (BOX model and BOX model with etching holes) will decline to 0% in the same situation.

The analysis results of model with etching channels are basically the same as above.

From the results above, it is apparent that the block-shape membrane model is the simple model to investigate the resonant frequency of CMUTs. The BOX model, BOX model with etching holes and BOX model with etching channels have significant advantages over block-shape CMUT models.

**Conclusion**

Using rectangular CMUTs, four CMUTs’ models, that are rectangular-shape membrane, Box shaped CMUT, CMUT with Etching hole and CMUT with Etching channel, are proposed and simulated. The different for the models were analyzed based on the geometric parameters of the CMUT including thickness, and the aspect ratio and et al. The properties of CMUTs are not only effected by the geometric parameters of the CMUT, but influenced by the release structures of CMUTs during the process.

**Acknowledgement**

Qing GUO and Shang GAO contributed equally. This research was financially supported by the united project for cooperation of enterprise, university and institute from Office of science and technology of Henan(CX0001F01797), the key projects for university from Office of education of
Henan(CX0001F01770) and the comprehensive strength project of Midwestern University from
Ministry of education of China.

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