Sensors & Transducers, Vol. 196, Issue 1, January 2016, pp. 52-56

www.sensorsportal.com

Sensors & Transducers

http://www.sensorsportal.com

Collapse Mode Characteristics of Parallel Plate Ultrasonic Transducer Radiating in Air and Water

[1] Rashmi Sharma, Rekha Agarwal and [2] Anil Anil Arora
[1] Amity School of Engineering & Technology, New Delhi,110061, India
[2] Thapar University, Patiala, 147004, India
[1] Tel.: 9958810676
[1] E-mail: rashmiapj@gmail.com

Received: 6 December 2015 /Accepted: 8 January 2016 /Published: 31 January 2016

Abstract: A 2D finite element analysis of capacitive micromachined ultrasonic transducer (CMUT) is proposed taking into account radiation in air and water. Different CMUT element geometries circular, square and hexagonal have been considered for FEM simulations. FEM simulation software COMSOL is employed to determine the structural deflections caused by electrostatic forces. Since the structural deformation alters the electrostatic field, a coupled-field simulation is required wherein the electrostatic mesh is continuously updated to coincide with the deflection of the structure. In this paper the deflection profile, resonance frequency, material parameters and collapse mode characteristics are being compared with device in air and under water. The CMUT is an electromechanical system, therefore, the physics of electrical and structural mechanics is coupled to describe its dynamics. Maximum frequency of operation is obtained by deriving the time evolution of the device for several frequencies. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Ultrasonic transducer, Pull in voltage, Resonant frequency, Collapse mode.

1. Introduction

Capacitive micromachined ultrasonic transducers (CMUT) are a promising alternative to piezoelectric transducers and receive considerable attention due to their advantages such as wider bandwidth, higher sensitivity, ease of array fabrication and integration [1]. Capacitive micromachined ultrasonic transducers (CMUTs) were introduced as micromachined suspended plate structures with a moving top electrode and a rigid substrate electrode [2]. When immersed in a liquid medium, CMUTs are capable of generating wideband acoustical pulses with more than 100 % fractional bandwidth [3]. However, many applications require high transmitted pressures for increased penetration and signal quality. The power output capability of CMUTs can be increased by utilizing the collapsed state of the plates [4-6]. Accurate and fast simulation methods are necessary for understanding CMUT dynamics and for designing high-performance CMUTs. CMUT models are based either on finite element method (FEM) models [7-8] or on equivalent circuits [9-12]. Precise modeling of capacitive micromachined ultra-sonic transducers (CMUT) is important for an efficient design process.

A CMUT structure comprises a capacitor which consists of two plates in which one of them is fixed and the other can deflect. Electrostatic forces act when a voltage is applied causing deflection of moving plate. The deflection of the movable plate is an important parameter that influences several basic CMUT parameters such as pull-in voltage and capacitance.

In this paper, we simulate the mechanical behaviour of a transmitting CMUT under electrical excitation. The model is dependent on plate dimensions and mechanical properties and it can predict the plate movement in the collapsed state as well as in the uncollapsed state. The simulation results for deflections are compared with CMUT in air and under water for future design reference.

2. Principle of Operation

2.1. Physical Principle

A basic parallel plate capacitor cell made of a thin membrane is shown in Fig. 1.

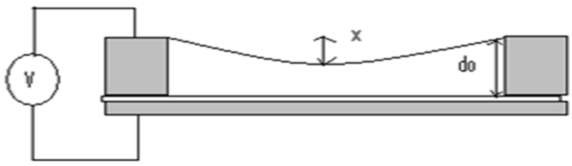

Fig. 1. Cross sectional view of CMUT.

The electrostatic force generated on the membrane of the capacitor cell is proportional to the square of the applied voltage, the area of the capacitor and the permittivity of the material between the plates, and inversely proportional to the square of the separation between the plates [1]:

$$F_{elect} = \frac{\varepsilon_0 AV^2}{2(d_0 - x)^2}, \quad (1)$$

where ε_0 is the permittivity of free space, A is the area of the plates, V stands for the applied bias voltage between the plates, d_0 is the initial gap height and x is the membrane displacement. Because the electrostatic force is proportional to the square of the bias voltage, linear cMUT operation requires DC bias voltage together with the AC excitation. Then the electrostatic force can be written as

$$F_{elect} = \frac{\varepsilon_0 A}{2(d_0 - x)^2}\left(V_{DC}^2 + 2V_{DC}V_{AC} + V_{AC}^2\right) \quad (2)$$

The first term in the parenthesis represents the static force, the second term represents the excitation force proportional to the applied AC voltage, and the last term represents the harmonic contribution of the AC voltage. When the DC bias voltage is much larger than the AC excitation, the harmonic contribution can be ignored. The membrane can be thought of as a mass clamped with a spring that opposes the electrostatic attraction force. The static force on the membrane is balanced by the mechanical restoring force.

$$F_{mech} = -kx, \quad (3)$$

where k is the spring constant. The minus sign indicates different direction from the electrostatic force, the spring trying to pull upwards. When the sum of the electrical force and the spring force equals zero, the following expression is obtained:

$$V = \sqrt{\frac{2kx}{A\varepsilon_0}}(d_0 - x) \quad (4)$$

Expression (4) gives a relation between membrane displacement x and applied bias voltage V. Pull-in or collapse occurs when dV/dx = 0. Making the calculation and substituting into (3) the pull-in voltage results as:

$$V_{Pullin} = \sqrt{\frac{8kd_0^3}{27\varepsilon_0 A}} \quad (5)$$

An important design parameter of a CMUT membrane is the collapse voltage, above which the attractive force can no longer be balanced by the restoring force of the membrane. This collapse voltage determines the operating point of the device. Therefore, it is crucial to calculate the collapse voltage accurately. The membrane of thickness t_m is coated with a thin layer of conducting material on the top side, and the bottom electrode is separated from the membrane by a distance t_a. The electrical capacitance can be written as:

$$C(t) = \frac{\varepsilon_0 \epsilon A}{\varepsilon_0 t_m + \epsilon t_a}, \quad (6)$$

where ε is the dielectric constant of the membrane material, and is A the area of the membrane. The list of parameters used for simulation are listed in Table 1.

Table 1. Parameters used for Simulation.

Parameter	Value
Plate Thickness	1 μm
Al Thickness	0.2 μm
Gap Height	1 μm
Insulation Layer	0.2 μm
DC Voltage	80 V
AC Voltage	10 V

2.2. Resonance Frequency

In a CMUT, a membrane is actuated by a time varying input voltage and the vibration of the membrane generates ultrasound waves. The resonance frequency increases with increasing intrinsic stress. At low stress levels the membrane behaves as a plate with the material parameters giving the plates own stiffness and frequency [13]. As intrinsic stress level increases, this stress will dominate over the flexural rigidity. The membrane will operate more as a membrane with no bending stiffness [14]. The wave equation is used for solving the plate resonance frequency as a fourth order partial differential equation:

$$\nabla^4 x + \frac{12\rho(1-\upsilon^2)}{Et^2}\frac{\partial^2 x}{\partial t^2} = 0, \quad (7)$$

where x is the deflections, E is the Young's modulus of the membrane, ν is the Poisson ratio, ρ is the density of the membrane and t is the thickness of the membrane. Solving with boundary conditions no deflection and rigid fastening at the border x(r) = 0 and dx/dr|r = R = 0 gives the resonance frequency of the first mode as:

$$f_r = 0.47\frac{t}{r^2}\sqrt{\frac{E}{\rho(1-\nu^2)}} \quad (8)$$

In the plate model, intrinsic model is not considered. It is only material dimensions and properties which determine the resonance frequency [10].

2.3. Results and Discussion

Resonant frequency calculated for different geometries are being shown in Table 2 with areas. Fig. 2 shows the simulation carried out in COMSOL.

Table 2. Resonant Frequencies for Different Geometries.

Geometry	Area	Resonant Frequency	Deflection
Circular	3.14 r^2	1.31418e6 Hz	0.08 μm
Square	2 r^2	1.47245e6 Hz	0.083 μm
Hexagonal	2.6 r^2	1.363994e6 Hz	0.1 μm

Fig. 2 shows that if the area and thickness of the membranes are kept constant and silicon is selected as a membrane material then deflection is 0.1 μm for hexagonal membrane at Eigen frequency of 1.36 MHz, and deflection is 0.08 μm for circular membrane at Eigen frequency of 1.31 MHz.

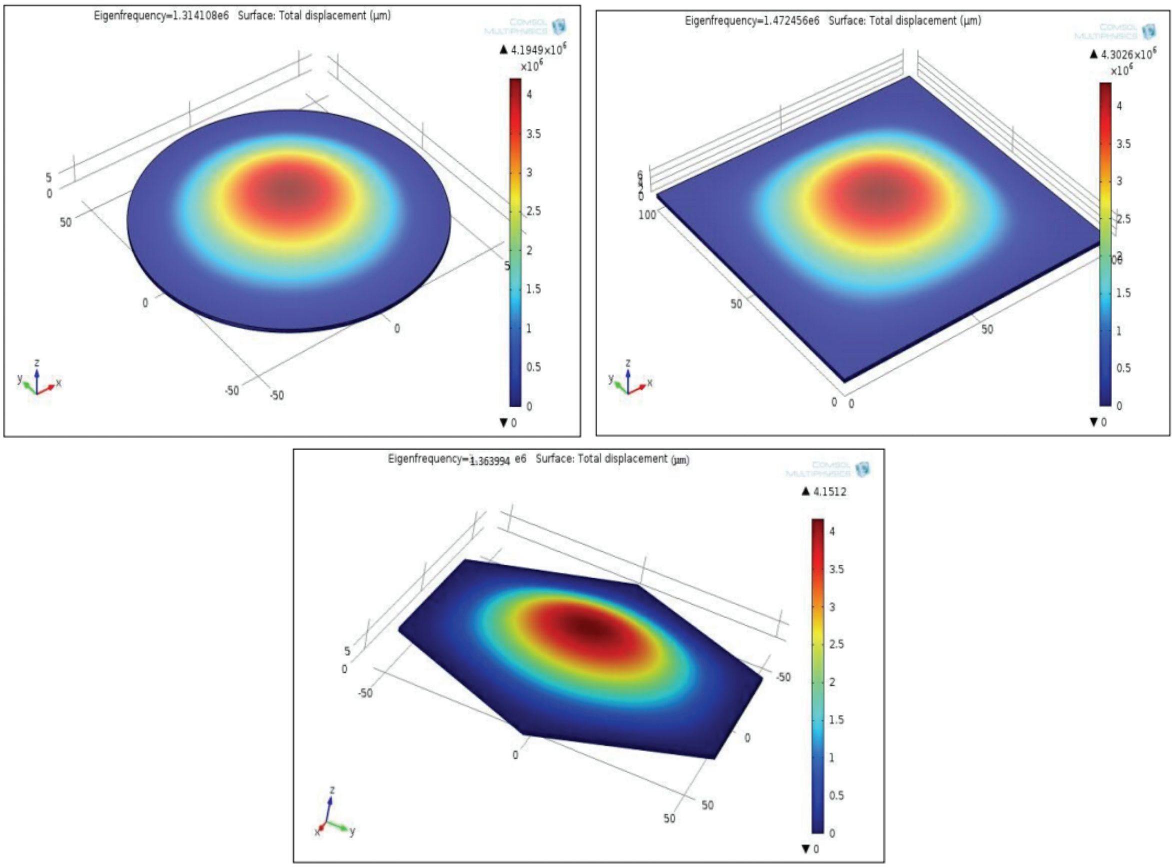

Fig. 2. Eigen Frequency for Circular, Square and Hexagonal.

In case of square membrane, the deflection is 0.083 μm at the Eigen frequency of 1.41 MHz. In other words, for the same area and same material, deflection is lesser for square membrane and in order to obtain this deflection, it requires a higher frequency as compared to other membranes. Though circular membrane produces nearly the same deflection at a lower frequency. Also, we can conclude that hexagonal membrane shows maximum deflection at a frequency of 1.36 MHz which is lower than square membrane but in close approximation with the circular membrane having frequency 1.31 MHz.

Fig. 3 illustrates the results of displacement versus DC voltage when transducer is placed in air. In this case, pressure of 1 atm acts on the membrane. At 0 V, the deflection of membrane is observed as 0.34 μm in case of circular geometry, 0.31 μm for hexagonal geometry and 0.25 μm for square geometry. Here, CMUT operates in collapse mode as expected and is able to generate and detect ultrasound more effectively than a CMUT operating in conventional mode.

Fig. 4 illustrates the results of displacement versus DC voltage when the transducer is placed in water at a depth of 5 m.

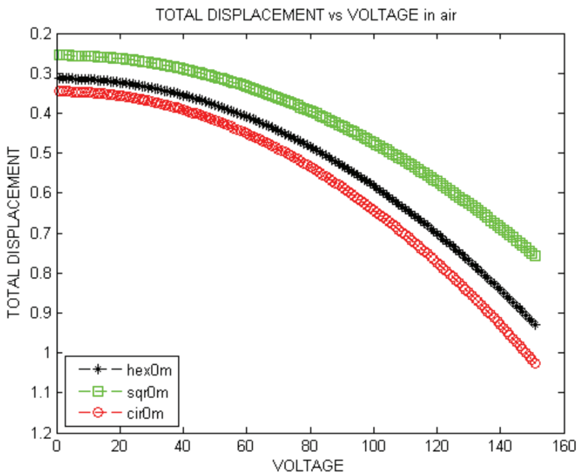

Fig. 3. Displacement with applied Voltage in Air.

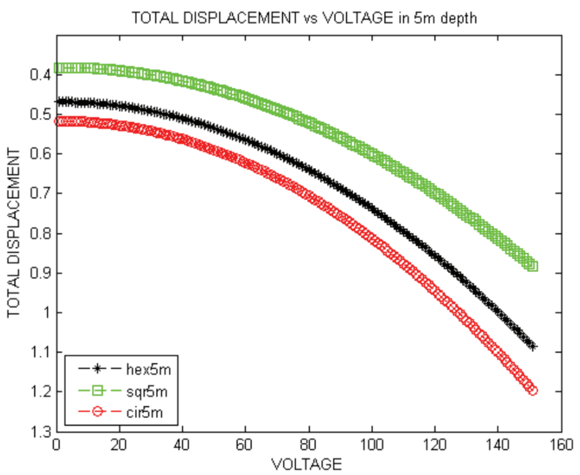

Fig. 4. Displacement with Voltage under Water.

At zero volt, the observed deflection is 0.51 μm in case of circular geometry, 0.46 μm in hexagonal geometry and 0.38 μm in square geometry. Thus, we observed that the deflection for the discussed cases is highest for circular geometry. Although, hexagonal geometry is also in close approximation to this.

3. Conclusions

CMUT have been compared with geometries namely circular, square and hexagonal. Resonance frequency is minimum for Circular and maximum for Square membranes. Maximum displacement is shown by Circular and minimum by Square when device is subjected in air as well as underwater with DC bias. CMUT offers best performance with circular geometry in terms of Eigen frequency, pull in voltage and in maximum deflection as a function of DC bias. But for array formation the results are not satisfactory because of voids, so area is not effectively utilized. So we can use hexagonal geometry for effective utilization of area. The deflection of membrane is more when immersed in water as compared to deflection in air. These results can be considered for further designing of CMUT for various applications.

References

[1]. I. Ladabaum, X. Jin, H. T. Soh, A. Atalar, B. T. Khuri Yakub, Surface micromachined capacitive ultrasonic transducers, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 45, Issue 3, 1998, pp. 678-690.

[2]. O. Oralkan, A. Ergun, J. Johnson, M. Karaman, U. Demirci, K. Kaviani, T. Lee, B. Khuri-Yakub, Capacitive micromachined ultrasonic transducers: next-generation arrays for acoustic imaging?, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 49, Issue 11, Nov. 2002, pp. 1596-1610.

[3]. R. O. Guldiken, J. Zahorian, F. Y. Yamaner, F. L. Degertekin, Dual-electrode CMUT with non-uniform membranes for high electromechanical coupling coefficient and high bandwidth operation, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 56, Issue 6, 2009, pp. 1270-1276.

[4]. Ö. Oralkan, B. Bayram, G. G. Yaralioglu, A. S. Ergun, M. Kupnik, D. T. Yeh, I. O. Wygant, B. T. Khuri-Yakub, Experimental characterization of collapse-mode CMUT operation, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 53, Issue 8, 2006, pp. 1513-1523.

[5]. Y. Huang, E. Hæggstrom, B. Bayram, X. Zhuang, A. S. Ergun, C.-H. Cheng, B. T. Khuri-Yakub, Comparison of conventional and collapsed region operation of capacitive micromachined ultrasonic transducers, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 53, Issue 10, 2006, pp. 1918-1933.

[6]. S. Olcum, F. Y. Yamaner, A. Bozkurt, H. Köymen, A. Atalar, Deep collapse operation of capacitive micromachined ultrasonic transducers, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 58, Issue 11, Nov 2011, pp. 2475-2483.

[7]. A. Bozkurt, F. L. Degertekin, A. Atalar, B. T. Khuri-Yakub, Analytic modelling of loss and cross-coupling in capacitive micromachined ultrasonic transducers, in *Proceedings of the IEEE Ultrasonics Symposium*, Vol. 2, 1998, pp. 1025-1028.

[8]. G. G. Yaralioglu, A. S. Ergun, B. T. Khuri-Yakub, Finite-element analysis of capacitive micromachined ultrasonic transducers, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 52, Issue 12, 2005, pp. 2185-2198.

[9]. A. Lohfink, P. C. Eccardt, Linear and nonlinear equivalent circuit modeling of CMUTs, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 52, Issue 12, 2005, pp. 2163-2172.
[10]. A. Caronti, G. Caliano, A. Iula, M. Pappalardo, An accurate model for capacitive micromachined ultrasonic transducers, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 49, Issue 2, 2002, pp.159-168.
[11]. S. Olcum, M. N. Senlik, A. Atalar, Optimization of the gainbandwidth product of capacitive micromachined ultrasonic transducers, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 52, Issue 12, 2005, pp. 2211-2219.
[12]. H. Köymen, M. N. Senlik, A. Atalar, S. Olcum, Parametric linear modeling of circular CMUT membranes in vacuum, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 54, Issue 6, 2007, pp. 1229-1239.
[13]. Bayram B., Yaralioglu G. G., Kupnik M., *et al.*, Dynamic analysis of capacitive micromachined ultrasonic transducers, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* Vol. 52, Issue 12, Dec. 2005, pp. 2270-2275.
[14]. Rashmi Sharma, Rekha Agarwal, Anil Arora, Performance Analysis of MEMS-based UltrasonicTransducer with Different Membrane Materials, *Recent Trends in Sensor Research & Technology*, Vol. 1, No. 3, 2014.
[15]. A. Caronti, R. Carotenuto, M. Pappalar, Electromechical coupling factor of capacitive micromachined ultrasonic transducers, *J. Acoust. Soc. Am.*, Vol. 113, No. 1, 2003, pp. 279-288.
[16]. I. O. Wygant, M. Kupnik, B. T. Khuri-Yakub, Analytically calculating membrane displacement and the equivalent circuit model of a circular CMUT cell, in *Proceedings of the IEEE Ultrasonics Symposium*, 2008, pp. 2111-2114.
[17]. H. K. Oguz, S. Olcum, M. N. Senlik, V. Tas, A. Atalar, H. Köymen, Nonlinear modeling of an immersed transmitting capacitive micromachined ultrasonic transducer for harmonic balance analysis, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 57, Issue 2, 2010, pp. 438-447.
[18]. B. Bayram, Ö. Oralkan, A. S. Ergun, E. Hæggström, G. G. Yaralioglu, B. T. Khuri-Yakub, Capacitive micromachined ultrasonic transducer design for high power transmission, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 52, Issue 2, 2005, pp. 326-339.