Characterization and Optimization Design of Polymer-based Capacitive Micro-arrayed Ultrasonic Transducer

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ABSTRACT

This study constructs a two-dimensional, axisymmetric finite element (FE) electro-mechanical model of a polymer-based capacitive micro-arrayed ultrasonic transducer (P-CMUT) using the ANSYS parametric design language (APDL). Simulations are performed to investigate the collapse voltage and resonant frequency characteristics of the P-CMUT. The numerical results are found to be in good agreement with experimental observations. The genetic algorithm (GA) is then applied to optimize the principal geometric parameters of the P-CMUT. The results show that the geometric parameter values obtained using the GA satisfy the conflicting objectives of the P-CMUT design procedures, namely to minimize the collapse voltage while simultaneously maintaining a high resonant frequency. Overall, the present results confirm that the combined GA optimization/FE modeling approach presented in this study provides an efficient and versatile means of optimizing the design of a P-CMUT.

Keywords: polymer-based, capacitive ultrasonic transducer, finite element method, optimization

1 BACKGROUND

The capacitive micromachined ultrasonic transducers (CMUTs), designed to excite and detect acoustic waves, were first introduced by Haller and Khuri-Yakub in 1994 [1]. Compared to traditional piezoelectric transducers, CMUT devices have an improved efficiency and a superior performance. CMUTs have a broad range of engineering applications and have been the subject of many experimental and numerical studies [2,3].

In 2006, Chang *et al*. [4] presented a novel polymer-based CMUT (P-CMUT) for surgical imaging applications. The device was fabricated primarily using epoxy-type photoresist since this particular polymer is chemically and thermally stable, is both durable and cheap, and has excellent flexibility [5]. The greater flexibility in the constituent material of P-CMUT renders P-CMUT an ideal solution for a range of scanning and detection applications, including non-destructive evaluation of solids, medical *in-vivo* imaging, RFID sensor-tag, and so forth.

In an attempt to optimize the geometrical parameters of CMUTs, early researchers proposed simple mathematical models to simulate the CMUTs operation [6]. However, these models can not accurately represent the complex geometrical constraints and electro-mechanical coupled field nature of CMUTs. Accordingly, researchers have more recently applied finite element modeling (FEM) techniques to obtain detailed insights into the fundamental characteristics of CMUTs [7].

The current study continues with the use of FEM to investigate the collapse voltage and resonant frequency characteristics of the P-CMUT. The validity of the FE model is confirmed by comparing the numerical results with experimental observations. Finally, the genetic algorithm (GA) is coupled with the FE model to optimize the P-CMUT parameters which minimize the collapse voltage while simultaneously achieving a high resonant frequency of 1 MHz.

2 FINITE ELEMENT MODELING

The modeling components include a membrane, a passivasion layer, an upper electrode, a lower grounded electrode, an insulation layer, an edge post, and a silicon substrate. The membrane, passivasion layer and edge post are all made of polymer; an epoxy-type photoresist. The passivasion layer is designed to protect the aluminum (Al) upper electrode from wear and corrosion during operation. Meanwhile, the thin layer of silicon oxide (SiO_2) deposited on the platinum (Pt) grounded electrode prevents short-circuiting when the membrane collapses. Thin titanium (Ti) film is evaporated over the silicon (Si) substrate to enhance the bonding between the Pt lower electrode and the substrate.

Ideally, the FE model of the P-CMUT should be generated using a 3-D mesh. However, an axisymmetric mesh that represents 3-D circular cell structure generally provides a sufficiently high level of accuracy and is far more computationally efficient. Accordingly, the present study constructs a 2-D FE model of the P-CMUT using the commercial ANSYS package (ANSYS 9.0, [8]). The model is constructed using the ANSYS parametric design language (APDL), which enables common tasks to be automated or even a complete analysis model to be constructed given the requisite parameters. The FE model of the P-CMUT and the APDL parameters are illustrated schematically in Fig. 1, while the geometric parameters and parameter settings are summarized in Table 1.

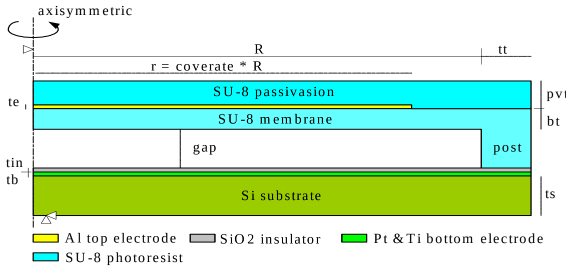

Figure 1: APDL Parameterized P-CMUT base line model.

Component	APDL parameter		
Membrane radius	R	50	μm
Top electrode coverage	cov	0.6	
Top electrode outer radius	r (=R*cov)	30	μm
Passivation layer thickness	pvt	2.8	μm
Top electrode thickness	te	0.2	μm
Membrane thickness	bt	2	μm
Cavity gap	gap	2	μm
Insulator thickness	tin	0.03	μm
Bottom electrode	tb	0.17	μm
Silicon substrate	ts	2	μm
Post thickness	tt	5	μm

Table 1: Geometric parameters and parameter settings of the P-CMUT APDL model.

The current coupled electrostatic-structural analysis was performed using the iterative ESSOLV macro in ANSYS Multiphysics^{TM} based on two physics environment files to represent the electrostatic and structural fields, respectively. This coupled-field, iterative process was controlled via the designed convergence criterion and terminate when the convergence condition is satisfied. In the simulations, the structural and electrostatic physics environment files were based on the standard ANSYS PLANE82 element and the PLANE121 element, respectively. Meanwhile, the contact surface was modeled using the contact-target pair elements CONTA172 and TARGE 169. The offset of the contact surface from the insulation layer was as assigned a value of 0.01 μm, and was deliberately included in the model in order to robustly re-morph the meshes in the air gap when the membrane collapsed. In the structural environment, a vertical symmetry plane with no displacements in the x-direction was applied, and a fully fixed boundary condition was imposed on the bottom of the substrate. Meanwhile, in the electrostatic environment, a non-zero was applied to the boundaries of the upper electrode and a zero voltage was applied to the lower electrode.

The mechanical and electrical properties of the major components in the FE model are summarized in Table 2. The property of the current polymer photoresist was measured using a commercial nanoindention system (Hysitron Inc., TriboIndenter®). The elastic modulus was determined to be 4.82 GPa.

Component	Membrane/ Passivation /post	Insulator	Top electrode	Bottom electrode	Substrate	Air gap	Unit
Material	Polymer	SiO_2	Al	Pt	Si	Air	
Young's modulus	4.82 E9	7.5 E10	6.76 E10	1.7 E11	1.69 E11		Pa (N/m^2)
Density	1200	2200	2700	2140	2332		Kg/m^3
Poisson's ratio	0.22	0.17	0.3555	0.38	0.27		
Permittivity	3	3.9			11.8	1	

Table 2: Electrical and mechanical properties of constituent materials in P-CMUT.

3 CHARACTERIZATION OF P-CMUT

The performance of the current P-CMUT was evaluated numerically with regard to two fundamental operational characteristics, namely the collapse voltage and the resonant frequency. Generally, the working efficiency is dependent on the operating DC bias, which should ideally be close to the collapse voltage, i.e. the voltage at which the membrane snaps down to the substrate. Additionally; for reasons of operational safety, mechanical integrity and minimum energy consumption, the collapse voltage should be as low as possible. Figure 2 illustrates the variation of the maximum membrane deflection with the magnitude of the DC bias. The magnitude of the applied bias at which this snap-down event takes place, is referred to as the collapse voltage of the P-CMUT. As shown in Fig. 2, the displacement of the membrane increases asymptotically as the bias voltage is increased. From inspection, the calculated collapse voltage is found to be 551 V. To verify the numerical results, a ZYGO surface profiler (Model NewView 200, ZYGO Corp., Middlefield CT) was used to measure the membrane deflection over the DC bias range of 0 ~ 280 V. As shown in Fig. 3, a reasonable agreement was observed between the two sets of results.

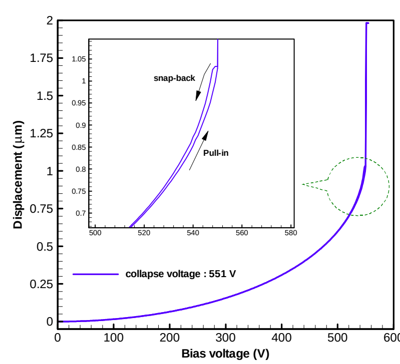

Figure 2: Variation of maximum membrane displacement as function of applied bias voltage.

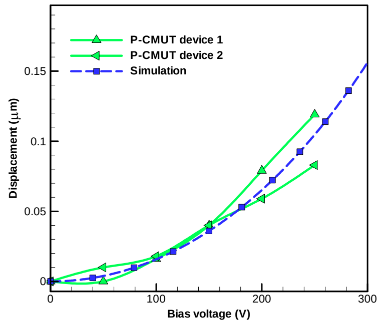

Figure 3: Comparison of experimental and numerical results for membrane deflection as function of applied bias voltage.

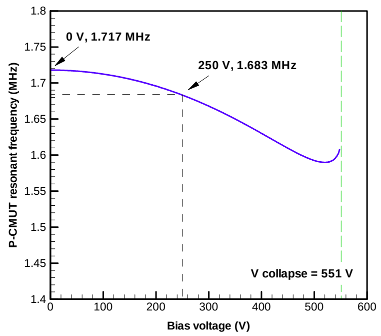

Figure 4: Variation of resonant frequency as function of applied bias voltage.

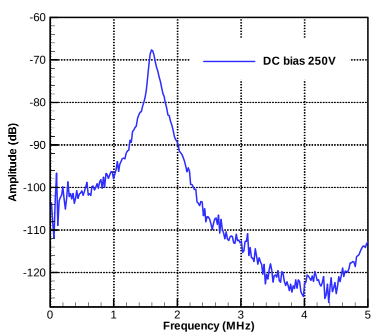

Figure 5: Amplitude of membrane vibration induced by single pulse excitation.

When operating an emitting transducer in air, the mechanical impedance of the membrane should be properly matched with the acoustic impedance of the air. Typically, this is achieved by operating transducers at their resonant frequency. Similarly, receiving transducers are also generally operated at their resonant frequency in order to increase their bandwidth. The resonant frequency of the current P-CMUT was determined by performing a pre-stressed modal analysis using the FEM approach. First, the static deflection due to an applied bias was calculated. The PSTRES,ON command was then applied by introducing prior electrostatic results. Finally, the resonant frequency of the P-CMUT was calculated using Block Lanczos method. Figure 4 illustrates the variation of the resonant frequency of the membrane as a function of the applied DC bias. In general, the results show that the resonant frequency decreases as the bias voltage increases. The presence of spring softening phenomenon is demonstrated. From inspection, the resonant frequency at a DC bias of 250 V is found to be approximately 1.683 MHz. The accuracy of the numerical results was confirmed by measuring the resonant frequency using a heterodyne Doppler laser interferometer. In the experiments, the P-CMUT was excited electrically using a single pulse with a peak-to-peak voltage of 16 V and a bandwidth of 40 MHz. Figure 5 illustrates the variation of the vibrational amplitude of the membrane as a function of the applied bias. As shown, the first resonance peak occurs at 1.594 MHz, which is in good agreement with the numerical result of 1.683 MHz.

4 GA OPTIMIZATION OF P-CMUT DESIGN PARAMETERS

Ideally, the design of a P-CMUT should be such that the designer can customize the resonant frequency while simultaneously minimizing the collapse voltage. However, these two parameters are mutually contradictory. Therefore, in practice, it is necessary to obtain an acceptable compromise between the two design objectives. In the current study, this is achieved by coupling the GA with the FE model of the P-CMUT in order to determine the optimal values of the geometrical design parameters.

Much of the original work on GA was conducted by Holland in 1975 [9]. GA are designed to find optimal solutions to multi-objective optimization problems by performing an iterative random search of a defined search area using probabilistic rule-based operators similar to those found in the field of biological evolution. In previous studies, researchers have demonstrated the power of combining GA with FE models as a means of obtaining optimal solutions to complex engineering problems [10].

The GA optimization procedure initiates by constructing a random population of candidate solutions. Each solution is referred to as a chromosome and is encoded as a string of binary digits. Each bit in the string represents one of the decision variables in the problem of interest and is analogous to the genes of a biological chromosome. During the optimization procedure, three operators, namely selection, crossover and mutation, are applied iteratively to the population of individuals, and a fitness function is used to select the best individuals from the current generation to survive into the next generation. The iterative search process is continued until either the specified convergence criteria have been obtained.

By taking advantages of parametric modeling technique such as APDL, the optimization search routines can be easily combined with the ANSYS to obtain the best design variables. In the current P-CMUT device, the parameters of interest are the membrane radius, the passivasion layer thickness, the upper electrode thickness and the upper electrode coverage ratio. The prescribed search limits for each of these parameters are indicated in Table 3 together with the general GA parameter settings, i.e. a population size of 30 and a maximum number of 100 iterative generations. The aim of the GA optimization procedure is to establish the design variable values which minimize the collapse voltage, thereby ensuring user safety and reduced power consumption, while simultaneously obtaining a resonant frequency of 1 MHz. In solving the problem, the two design objectives are assigned an equal weighting.

Following 100 iteration loops, the optimal design parameter values were found to be as follows: a membrane radius of 65.01 μm, a passivasion layer thickness of 2.82 μm, an upper electrode thickness of 0.21 μm and an upper electrode coverage ratio of 0.87. The results showed that this optimal design achieved the required resonant frequency of 1 MHz and a decreased collapse voltage of 291 V. Figure 7 shows the evolution history of the fitness of the best design solutions generated over the course of the optimization procedure. The fitness value rapidly converges to 0.00552762 at the 48^{th} generation. The results confirm that the combined GA/FE approach adopted in this study provides an efficient and versatile means of optimizing the P-CMUT subject to two conflicting design objectives.

Designated parameter	Lower Limit	Upper Limit	Optimized result	
Membrane radius	25	75	65.01276	μm
Passivasion layer thickness	2.8	5	2.815943	μm
Top electrode thickness	0.1	0.5	0.213794	μm
Top electrode coverage ratio	0.1	1.0	0.867297	
Fitness	0.00552762			
Number of generation	100			
Number of population	30			
Objective functions:				
• Minimize the collapse voltage ($V_{collapse}$: down to 291 V)				
• Resonant frequency = 1 MHz (Freq: 1.00000253 MHz)				

Table 3: Genetic algorithm parameters and optimal P-CMUT design settings for P-CMUT with resonant frequency of 1 MHz.

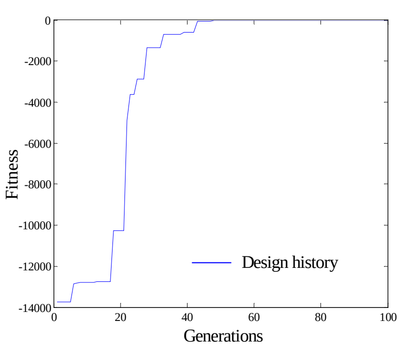

Figure 7: Evolution of design solution fitness over 100 iteration loops.

5 CONCLUSIONS

This study has constructed a 2-D axisymmetric FE model of the P-CMUT with APDL programming technique. Numerical simulations have been performed to investigate the collapse voltage and resonant frequency with the varied bias voltage. The numerical results have indicated that the collapse voltage is approximately 551 V. Furthermore, a pre-stressed modal analysis has shown that the resonant frequency of the current P-CMUT device is 1.683 MHz, corresponding to a bias voltage of 250 V. Both results are consistent with those obtained by experiments. Having confirmed the accuracy of the FE model, the GA was applied to optimize the design parameters of the P-CMUT such that an acceptable compromise was obtained between two conflicting design objectives, namely minimizing the collapse voltage while simultaneously maintaining a high resonant frequency of 1 MHz. The results indicated that the optimal membrane radius was 65.01 μm, representing a 30% increase in the value specified in the non-optimized design, while the upper electrode coverage ratio was 0.87, representing an increase of 45% compared to the original value. Besides, the optimal thicknesses of the passivasion layer and the upper electrode were found to be 2.82 μm and 0.21 μm, respectively. Both of the designated objective functions, i.e. a decreased collapse voltage of 291V and a resonant frequency of 1 MHz were achieved. Overall, the results presented in this study indicate that the coupled GA /FEM approach provides a powerful and computationally efficient means of optimizing the design of the P-CMUT.

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