Time-dependent, Coupled field ANSYS Simulation of a Water-Loaded Capacitive Micromachined Ultrasonic Transducer Cell in Transmission

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Abstract
Capacitive micromachined ultrasonic transducers (CMUTs) offer several advantages such as wide bandwidth, high sensitivity and ease of fabrication over piezoelectric transducers. Recently, the CMUTs have emerged as an alternative technology in biomedical imaging applications. Consequently, the design and performance evaluation of CMUTs using finite element method (FEM) have become an important research field.

This paper presents a method to compare, by means of a time-dependent simulation, transmission in the conventional, collapse-snapback and collapsed operation regime by a capacitive micromachined ultrasonic transducer (CMUT) using ANSYS 7.1. CMUTs were biased with a DC voltage and excited by an AC voltage. Depending on the amplitudes of these voltages relative to the device collapse and snapback voltages, they operated in the conventional, in the collapsed or in the collapse-snapback regimes. When the applied AC voltage was not negligible relative to the DC bias, it was not possible to fully characterize the dynamic behavior of a CMUT by performing harmonic analysis at the DC operating point. Instead, time-dependent analysis of the CMUT had to be performed by applying a time-varying voltage.

We performed electrostatic and structural analyses sequentially to simulate the coupling between these domains. At each time step, the force on the membrane at the current membrane deformation due to the applied voltage was recalculated and this updated force was applied in the succeeding time step. A single membrane cell was immersed in a sphere of fluid to simulate the loading effect of water. The spherical boundary of the fluid was defined as an absorbing boundary to simulate an infinite medium.

If the simulation time was prolonged, e.g. in order to model a steady-state response, the FLUID129 element, which used a second-order equation to approximate the absorbing boundary, became unstable. Furthermore, the approximate absorbing boundary required the radius of the surrounding sphere to be larger than 20 % of the largest wavelength of interest, which significantly increased computation time due to the large number of nodes in the model. We have implemented exact absorbing boundary conditions in our 2D axisymmetric model. This enabled us to have a highly efficient stable absorbing boundary and to reduce the radius of the fluid medium arbitrarily without loss of accuracy. Additional computation time due to the implementation of exact absorbing boundary is less than 10 % of the total computation time.

Introduction
Capacitive micromachined ultrasonic transducers (CMUTs) can be used to transmit and receive an acoustic pressure fluctuation in a fluid [1]. CMUTs rely on the principle of two electrodes on the membrane and the substrate attracting each other by an electrostatic force [2]. If such a biased CMUT is excited with a voltage pulse, the membrane responds with structural motion, which is coupled into the fluid medium through the fluid-membrane interface. The impinging of acoustic pressure on a biased CMUT results in the generation of voltage output reciprocally [3].
In general, CMUTs are characterized by their small-signal parameters based on equivalent circuit models and harmonic analysis of finite element (FE) models. In reality, however, we apply to the transducers, pulses or continuous AC signals with finite amplitudes. Hence the dynamic input voltage range of the CMUT at a specific bias voltage needs to be specified. With increased excitation amplitude, the membrane displacement can no longer be characterized at a constant DC operating point. Current CMUT theory is derived for devices operating in the conventional regime. This theory cannot deal with a large signal excitation in the classical regime operation, let alone with operation in the collapsed and collapse-snapback operation regimes.

As reported earlier, it is possible to increase the output power of the CMUT by operating it in the collapsed regime [4]. This is done by initially collapsing the membrane by applying a DC voltage higher than its collapse voltage. An AC excitation causes a torus-shaped displacement profile across the membrane since the center of the membrane is in constant contact with the substrate and the membrane periphery is supported by the circular post [4].

Since the membrane of a CMUT in collapsed regime operation is no longer only supported from the periphery, the structure has a different center frequency compared to that when operated in the conventional regime. The center frequency modification depends on the contact radius, which is a function of the bias voltage. Voltages close to the snapback voltage result in a minimal contact radius, whereas higher DC voltages increase the contact radius up to the metallization radius of the membrane.

Hence, the DC voltage alters the center frequency as well as the transmit pressure and receive sensitivity of the CMUT by modifying the geometry of the physical structure. In addition to this, the spring softening effect caused by increasing the DC bias in conventional operation is also present in collapsed operation. Both of these parameters, contact radius and spring softening, determine the coupling efficiency, bandwidth, center frequency, and maximum output pressure of the CMUT.

In collapsed and collapse-snapback regime operations where contact and electrostatic forces between the membrane and the substrate are present, both of which are coupled to the transducer structure, a FE analysis of the dynamics of the membrane is advantageous compared to an analytical treatment. Earlier work based on static analysis of the membrane motion reported on the coupling efficiency of a device operated in the collapsed regime [4].

A next step is to perform a transient analysis to predict the large signal characteristics of a transmitting CMUT operated in conventional and collapsed regimes. After identifying these two regimes, one might want to apply AC voltages that swing beyond the collapse and snapback voltages in order to operate the device within both regions during a pulse or continuous excitation. The impact of collapsing the membrane onto the substrate should then be taken into consideration, which necessitates the use of a time-dependent simulation. It should also be noted that for a membrane moving in a temporally varying electric field, the electrical forces across the membrane at a certain moment depend not only on the applied voltage but also on the profile of the displaced membrane at that moment. This profile is not known until the profile of the displaced membrane is calculated for all the preceding time steps. Due to the coupled nature of this problem, FE calculations are necessary to analyze this situation without relying on linearization. In this paper, we present a method to simulate the dynamic behavior of an active transmitting unit of a CMUT - the single capacitive cell - operated in three different operation regimes.

**Finite Element Calculations**

Finite element modeling (FEM) was used to analyze the CMUT using ANSYS 7.1 [5]. A 2D axisymmetric model was employed for a single circular CMUT cell which consisted of a silicon membrane separated by a vacuum gap from the silicon oxide insulation layer as depicted in Figure 1. The membrane was supported on silicon oxide posts surrounding the gap. A spherical fluid medium surrounded the CMUT for acoustic wave propagation.
The membrane and the insulation layer were meshed with PLANE42 structural elements using the axisymmetric key option. The gap was also meshed with PLANE42 elements but a new element number was used since it was set to null element in the structural analysis of the vacuum gap. The fluid medium was meshed with the FLUID29 acoustic element using the axisymmetric key option. Contact and target pairs were generated on the bottom surface of the membrane and slightly above the insulation layer (CONTA172 and TARGE169). This offset, 5% of the gap, was required to allow remeshing or remorphing of the gap as the membrane deformed. In the electrostatic analysis, the PLANE42 element type was changed to the PLANE121 electrostatic element since both element types were compatible with each other. The FLUID29, CONTA172 and TARGE169 element types were set to null elements since they were not required in the electrostatic analysis.

In the electrostatic analysis, the bottom of the insulation layer became the ground electrode and the voltage bias was applied to the bottom face of the membrane since high conductivity silicon was used in the membrane and in the substrate of the fabricated CMUTs. Maxwell surface flags were set on the surfaces of the gap to enable the electrostatic force calculations to be used in the subsequent structural analysis. Initially, the electrostatic force was calculated for the original geometry with electrostatic analysis. The subsequent electrostatic analyses were carried out on the last deformed geometry. The displacement results available at the end of the structural analysis were used to deform the original geometry to the current membrane shape by the DAMORPH command.

In the structural analysis, the bottom of the substrate was clamped in all directions. Symmetric boundary conditions were applied for the PLANE42 elements on the y-axis. Since the gap was formed in vacuum, an atmospheric pressure was applied to the bottom of the membrane. The resulting forces on the membrane from the last electrostatic analysis were applied as loads in the structural analysis by using LDREAD command.

Fluid-structure interface flags were set for the nodes sharing a boundary between FLUID29 and PLANE42 elements. This enabled the coupling of the structural displacement (UX, UY) to the fluid pressure (PRES). FLUID29 elements were defined to have only pressure degree of freedom (PRES) except for the ones that were on the fluid-structure interface. These elements were set to also have displacement degrees of freedom (UX, UY, PRES). The displacements were only calculated at those nodes of these elements on the interface. The displacements of the other nodes were set to zero to avoid “small pivot warnings” in the solution. The acoustic wave propagation took place in the FLUID29 elements and it was assumed to be infinite in size to avoid reflections contaminating the results. However, this is computationally expensive and it is common practice to define an absorbing boundary condition on a smaller size model in order to cancel spurious reflections.

The FLUID129 infinite acoustic element is available to surround the fluid elements. This element relies on a second order absorbing boundary approximation and is not accurate enough for our analysis. Therefore an exact absorbing boundary condition was implemented in the transient analysis [6]. This condition is local
both in time and space and can be implemented by specifying the pressure degree of freedom at the nodes of the FLUID29 elements on the spherical boundary enclosing all elements. The most important property of this absorbing boundary is that it is exact: no simplifying approximations have been made in its derivation and the fluid medium can be scaled down in size without loss of accuracy. Therefore, the required computation time for each time step was significantly improved by the reduction of the number of nodes in the model. The CMUTs that have been investigated had a center frequency between 1 MHz and 20 MHz. The frequencies of interest were 0.1 MHz up to 50 MHz. It has been known that 15 nodes per smallest wavelength provide reasonable accuracy for lower order element types such as FLUID29. The frequency of 50 MHz corresponded to the wavelength around 30 µm, which required an element size of 2 µm in the fluid. The lowest frequency of 0.1 MHz corresponded to the highest wavelength around 15000 µm. The FLUID129 infinite acoustic element requires the radius of the fluid medium to be larger than 20% of the largest wavelength, radius of 3000 µm in this analysis. An estimated number of total nodes required for this analysis was over 3 million nodes. For the exact absorbing boundary condition, there was no requirement on the radius of the fluid. So a radius of 84 µm was used in our analysis. This required around 5000 nodes in the model with an element size of 2 µm in the fluid. So the total number of nodes was scaled down by 600 and this drastically reduced the computation time for each time step. Implementation of this absorbing boundary in ANSYS was convenient since it supported restarts from the last load step of the transient analysis. Hence electrostatic and structural PHYSICS files were modified between load steps.

Voltages were applied between the ground and the membrane electrodes. This generated electrostatic forces which were a function of the voltage and the displacement of the membrane. We used uniform time steps in the transient analysis. The time step was selected to be small enough for the absorbing boundary and the contact to function properly. Time step of 0.5 ns provided satisfactory resolution in time and smaller values of time did not change the results. It should be emphasized that the time step used in this analysis was significantly smaller than any transient analysis performed with ANSYS with auto time stepping turned on (AUTOTS,ON). But the time step was still an order of magnitude larger than that used in any explicit solver. Considering the model size and ANSYS implicit solver, we believe, our transient analysis is faster than the explicit solvers. Implicit solvers deal with coupled equations over the whole model, whereas explicit solvers deal with uncoupled equations local in space. However, the uncoupling of the equations require the time step to be smaller than a specific time constant which depends on the smallest element size in the model. If the time step exceeds this limit, the analysis has a probability of becoming unstable in time. Implicit solvers are unconditionally stable but require more computation time for larger models due to the coupled equations. By using exact absorbing boundary conditions, the model size was kept moderate and time step was selected small enough for the absorbing boundary to function accurately.

The electrostatic analysis was a static analysis whereas the structural analysis was transient. Biasing the CMUT by setting TIMINT,OFF in the structural transient analysis, made this analysis static too, by turning off the time integration effects. So this method obtained the final membrane shape prior to the transient analysis. It was found that 30 iterations were sufficient to obtain the final membrane shape with the bias voltages used in our model. Due to the hysteretic behavior of a collapsed CMUT cell, two bias voltages were applied consecutively for biasing in collapsed operation. The first bias voltage was an arbitrary voltage, higher than the collapse voltage and at the end of the iterations, collapsed membrane shape was achieved. The next voltage was the actual bias voltage that was to be used in the collapsed operation. After several iterations the final collapsed membrane shape corresponding to this bias voltage was obtained. Using this implementation, all operating points along the hysteresis curve, depicted in Figure 2, could be explored. For each load step, two substeps (NSUBST,2) with step loading (KBC,1) were used so that the initial membrane velocity would be zero when the transient analysis started with time integration effects turned on (TIMINT,ON).
In our transient analysis, the voltage changed as a function of time. The resulting electrostatic force depended not only on the voltage but also on the membrane deformation at the present time (ntSTEP). The pressure at the next time ((n+1)STEP) on the absorbing boundary was related to the pressure results at the nodes on the absorbing boundary (mR_MESH) and their neighboring nodes ((m-1)R_MESH) both at the present (ntSTEP) and the past time ((n-1)STEP). This required performing the transient analysis at every time step (tSTEP) to update the electrostatic forces on the membrane and the pressures on the absorbing boundary. Therefore, after completing the transient analysis at the present time, the pressure values for the next time step were calculated using the pressure results in the postprocessor, and the structural physics file was modified accordingly. Then the electrostatic physics file was modified with the next voltage and the electrostatic analysis was performed on the present deformed membrane to calculate the electrostatic forces for the next time step. Finally, the transient analysis was restarted to continue from the last load step and the electrostatic forces were transferred from the last electrostatic analysis.

The material properties used in the model are shown in Table 1.

Table 1. Material properties

<table>
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<th>Material Property</th>
<th>Si</th>
<th>SiO</th>
<th>Vacuum</th>
<th>Water</th>
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<td>Poisson’s Ratio</td>
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<tr>
<td>Speed of sound (m/s)</td>
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<td>1500</td>
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Two types of analysis were performed on a CMUT biased in the intended operation regime: 1) the determination of the transient response of a CMUT cell at a specific bias point with square shaped voltage pulses, 2) determination of the response of the CMUT cell excited by a monochromatic continuous signal. These analyses were adequate to characterize the dynamic behavior of the single CMUT cell in transmission.

Results

The CMUT cell dimensions for this particular analysis are given in Figure 1. The silicon membrane was 1.65 µm thick and had a radius of 24 µm. These dimensions set the center frequency of the membrane to 5 MHz in water. The atmospheric pressure load on the membrane caused a 4% maximum deflection relative
to the gap on the center of the membrane. The vacuum gap (0.2 µm) and the silicon oxide insulation layer (0.1 µm) set collapse and snapback voltages as 80 V and 50 V, respectively.

The transient response of the CMUT cell biased in collapsed operation ($V_{bias}=55-80$ V) for a 5 V square pulse excitation ($t_{pulse}=20$ ns) was depicted in Figure 3. Bias voltage dependence of the transient response was revealed. The largest average membrane displacement (14 Å/V) was achieved for 70 V bias whereas lowest center frequency of 8.3 MHz was observed for 65 V bias.

![Figure 3](image1.png)

**Figure 3.** Average membrane displacement as a function of time. The bias voltage was $V_{DC}$ in collapsed operation. A pulse of +5 V for a duration of 20 ns is applied at $t=0.1$ µs.

![Figure 4](image2.png)

**Figure 4.** Average membrane displacement as a function of time. The bias voltage was 65 V. Dash line: conventional operation, $V_{AC}(p-p)=20$ V. Dot line: collapsed operation, $V_{AC}(p-p)=20$ V. Solid line: collapse-snapback operation, $V_{AC}(p-p)=40$ V.

A CMUT cell biased at 65 V was excited with an AC voltage ($f_{exc}=1$ MHz, $V_{AC}(p-p)=20-40$ V ) in conventional, collapsed and collapse-snapback operation regimes as shown in Figure 4. Here it is seen that the collapse-snapback operation offers a larger average membrane displacement (30 Å/V) than the conventional (10 Å/V) and collapsed operation (7 Å/V) do.
Maximum and average membrane displacements of a CMUT biased at 65V operating in the collapse-snapback regime are shown in Figure 5 \( (V_{AC}(p-p)=60 \text{ V}) \). The corresponding average membrane pressure is given in Figure 6, where high frequency components of the average pressure are clearly seen. The spectral content of the average pressure is given in Figure 7. Collapse-snapback operation resulted in approximately 10 dB higher nonlinearity in comparison to what was seen when the CMUT was operated in the other regimes.

![Image](image1.png)

**Figure 5.** Displacement as a function of time in collapse-snapback operation. \( V_{DC}=65 \text{ V}, \ V_{AC}(p-p)=60 \text{ V}, \ f_{EXC}=5 \text{ MHz} \). Solid line: maximum displacement on the center of the circular membrane. Dash line: average membrane displacement.

![Image](image2.png)

**Figure 6.** Average pressure on the membrane as a function of time in collapse-snapback operation regime. \( V_{DC}=65 \text{ V}, \ V_{AC}(p-p)=60 \text{ V}, \ f_{EXC}=5 \text{ MHz} \).
Figure 7. Spectral content of average pressure from a CMUT cell biased at 65 V and excited with a 5 MHz, $V_{AC}(p-p)=60$ V signal

Conclusion

Time-domain, coupled field ANSYS simulation model of a single CMUT cell is presented. This FEM proved to be a vital resource in the characterization of the CMUTs in large signal excitations, particularly for the collapsed and collapse-snapback operation regimes where contact between the membrane and the substrate must be taken into consideration. An exact absorbing boundary condition was implemented to truncate the infinite fluid medium to a finite size without introducing any reflections. Future work will focus on the 3-D modeling of CMUT arrays.

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References


