Modeling and Design of Capacitive Micromachined Ultrasonic Transducers Based-on Database Optimization

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Abstract. A Capacitive Micromachined Ultrasonic Transducers simulation database, based on electromechanical coupling theory, has been fully developed for versatile capacitive microtransducer design and analysis. Both arithmetic and graphic configurations are used to find optimal parameters based on serial coupling simulations. The key modeling parameters identified can improve microtransducer’s character and reliability effectively. This method could be used to reduce design time and fabrication cost, eliminating trial-and-error procedures. Various microtransducers, with optimized characteristics, can be developed economically using the developed database. A simulation to design an ultrasonic microtransducer is completed as an executed example. The dependent relationship between membrane geometry, vibration displacement and output response is demonstrated. The electromechanical coupling effects, mechanical impedance and frequency response are also taken into consideration for optimal microstructures. The microdevice parameters with the best output signal response are predicted, and microfabrication processing constraints and realities are also taken into consideration.

Keywords: varied capacitive microtransducers, electromechanical coupling parameters, optimal simulation.

1. Introduction  
Capacitive microtransducers have been extensively applied in precision measurements and biomedical imaging [1]. An important device is the capacitive micromachined ultrasonic transducer (cMUT). Devices with a wide bandwidth and a high sensitivity are used in precision measurement, structure analysis, and defect detection. Impedance mismatch and low sensitivity are common problems associated with piezoelectric materials [2-3]. W. P. Mason studied parallel-plate capacitive transducers and equivalent models. The membrane vibration and mechanical impedance models were solved in 1943 [4]. Recently, B. T. Khuri-Yakub’s group developed cMUT’s equivalent models and microdevices for different applications based on Mason’s circuit model [5-9]. But it is expensive to fabricate cMUTs, and processing results can be unpredictable. The electromechanical coupling effects
are complicated. Often, a trial-and-error technique wastes both time and money when it is used to design devices. Therefore, developing a database as a tool to design microdevices accurately is desired. The evaluation procedures to obtain optimal parameters are shown in Fig. 1. Following this procedure, the CAD database is assessed to predict microdevice’s characteristics and responses, in order to obtain optimal parameters. Design parameters include membrane radius, electrode thickness, cavity thickness, applied DC bias voltage, and desired AC signal ratio. The simulation is used to calculate membrane displacement, equivalent mechanical impedance, the electromechanical coupling effect, and 3D frequency response. After simulation, the best parameters are identified.

Fig. 1 Microdevice simulation flow chart.

2. THEORY AND DESIGN

The cMUT is a parallel-plate capacitor with an air dielectric layer, as shown as Fig. 2. It is operated with a DC bias, and its ultrasonic signal is driven by an AC voltage source. The vibration of the circular membrane is driven by the supplied voltage, and the vibrating displacement can be solved with Bessel functions, as shown in Eq.(1). \( I_0(k_1r) \) and \( J_0(k_2r) \) are modified zero order Bessel functions of the first kind. \( P \) is a constant pressure, the frequency is \( w \), \( \rho \) is density, \( t \) is membrane thickness, and \( k_1 \) and \( k_2 \) are characteristic parameters related to the structure’s material and geometry. If the displacement is much smaller than the air gap thickness, the equivalent mechanical impedance \( Z_m \), defined as the ratio of membrane strength and averaged speed, emerges from the electromechanical coupling effects, as shown in Eq.(2). In Eq. 2, \( T \) is tension, \( Y_0 \) is the Young's modulus, the membrane radius is \( a \), and \( \sigma \) is Poisson's ratio. The impedance can be expressed as a capacitance and inductance. The first term on the right hand side is an equivalent capacitance and the second term is an equivalent inductance. The total equivalent capacitor is formed in series by connecting several capacitors and accounting for parasitic effects.

\[
x(r) = -\frac{\rho}{w^2} \rho t \left[ \begin{array}{c} k_1 I_0(k_2r) J_1(k_2r) + k_2 J_0(k_2r) I_1(k_2r) \\ k_1 I_0(k_1r) J_1(k_1r) + k_2 J_0(k_1r) I_1(k_1r) \end{array} \right] \left( k_1^2 - k_2^2 \right) \left( k_1 - k_2 \right) \left( k_2 - k_1 \right)
\]

(1)

\[
Z_m = -\frac{j2l}{2l} \left( \frac{8l(T + Y_0) + 12a^2 T(1 - \sigma^2)}{3a^4(1 - \sigma^2)w} \right) + jw2\rho l
\]

(2)

The DC bias voltage applies tension on the membrane, and then AC voltage induces membrane vibration. A variation in capacitance is induced, and the rate of capacitance variation is related to the
vibration frequency. The signal transmission behavior is considered using an equivalent transmitting model. The voltage $V(t)$ and current $I(t)$ are signal driving sources, as shown in Eq. (3), where the parameter $n$ is related to the driving voltage and the device’s physical dimension. The averaged membrane vibration speed is $\bar{v}$. The AC voltage makes the membrane vibrate ultrasonically. Therefore, the equivalent circuits can be optimized by adjusting simulated parameters. The modified transformation of the biased emitting mode and the receiving mode in an air atmosphere is shown in Eqs. (4) and (5) [10]. $R$ is the sound wave impedance, $A$ is a proportional constant of mechanical impedance to sound wave impedance, $L_m$ is an equivalent inductance of the mechanical impedance, $L_D$ is an equivalent biased inductance of the mechanical impedance. $C_m$ is an equivalent capacitance of mechanical impedance, and $C_w$ is the equivalent capacitance of the cMUTs.

$$I(t) = C(t) \frac{dV(t)}{dt} - n \cdot \bar{v} \quad (3)$$

$$H(s) = n \times \frac{s^2 \times R \times A_d}{s^2 + s \times R \times A + A} \quad (4)$$

$$H(s) = \frac{n \times \frac{1}{C_w \times L_m} + \frac{n^2}{A \times C_w \times L_m}}{s^2 + \frac{R}{L_w} + \frac{1}{C_m \times L_m} + \frac{n^2}{A \times C_m \times L_m}} \quad (5)$$

These equations make expansion of the simulation database feasible and automatic. The friendly user interface includes input and output information. Multi-parameters can be simulated simultaneously and the results are displayed graphically or numerically. Square, hexagonal and octagonal membrane geometries can all be simulated approximately by a circular model. MATLAB is used to calculate membrane characteristics including maximum displacement, equivalent mechanical impedance, and frequency response. The electromechanical coupling efficiency varies with maximum displacement. The more the mechanical impedance matches, the better the electromechanical coupling efficiency. The output frequency response and bandwidth are depended on input conditions. After a serial simulation analysis, it is possible to extract the optimal parameters. The user interface is designed using BCB++, Builder (BCB). The design work is based on a graphical user interface (GUI) that links the calculation data with MATLAB. The simulation is easy to enter from the BCB homepage interfaces. There, one can choose operation items and desired parameters for any specified simulation. The required input parameters include thickness and radius of the membrane, Young's modulus, Poisson's ratio, material density, dielectric constant, environmental pressure, tension force, electrode thickness, air gap thickness, DC bias source, AC signal, and the amplitude ratio of the AC to DC voltages. Online parameter analysis to design micro devices can be done efficiently in real-time. Off-line functional analysis is also possible using stored data to find variation rates, extreme values, errors, and relative stability points. Consequently, the analyzed data can be used in follow-up characteristic studies for predicting device performance. Due to the database interface and results, it is convenient to observe a parameter’s variations at a different of location by rotating simulated figures that show all output parametric values and graphical results. The results of a simulated example, Fig.3 shows the relationship between membrane parameters and resulting displacement membrane. The example inputs are $25 \mu m$ membrane radius, $0.6 \mu m$ membrane thickness, $1 Pa$ pressure, $3270 kg/m^3$ density, a Young's modulus of $3.2 \times 10^{11} Pa$, a Poisson's ratio of 0.263, and a tension of 280MPa. The simulation results show the relation between membrane thickness and its frequency response. It also shows the maximum displacement versus frequency response in transmission mode. The control voltage limit is simulated to obtain the distribution of capacitor collapse voltages, as shown in Fig. 4.
3. ANALYSIS AND DISCUSSION

The more stable a simulation system, the more feasible the transducer operation. It is necessary to extract optimal parameters before manufacturing. Hence, transfer functions are constructed to analyze stability and robustness. By varying the transfer function frequency response, the optimal parameters of cMUTs can be deduced in biased transmission and receiving modes. Transducer operation is feasible due to the roots of the design parameters are located on the stable left side of the s-plane. By choosing suitable materials and operating frequency range, the simulated data can be applied to analyze output response of a specified cMUT. Eventually, it is possible to obtain geometry specifications of the membrane, the vibration modes and electromechanical coupling efficiency. Silicon nitride is chosen as the membrane material due to its great electromechanical transfer efficiency, as shown in Fig. 5.

Defining the operation frequency is the first issue for designing a cMUT. The simulation and analysis process is executed to get optimal design and fabrication parameters. A known baseline simulation example for optimal cMUT was demonstrated. The operating parameters are set as following: uniform pressure of 1Pa, membrane tension of 280MPa and operation frequency at 6.7MHz. The results show that an optimal radius and thickness of 19μm and 0.18μm, respectively, can produce the maximum displacement of 6.015×10^{-4}m, as shown in Fig. 6.
The GUI displays simulation results include optimal geometrical size, the best transmission efficiency, and the highest AC/DC voltage ratio, as shown in Fig. 7. The largest capacitor collapse (or breakdown) voltage is 59.6V that corresponds to the widest bandwidth in air and in water atmospheres of 3.92MHz and 120.10kHz, respectively. The AC-to-DC voltage amplitude ratio is 0.6. Furthermore, the DC biased voltage is 37.2V and AC voltage is 22.3V, and the transmission efficiency that can be achieved is up to 7.15×10⁻⁹Nt/V in air and 2.86×10⁻⁶Nt/V in water. The transmission efficiency in air is much lower than the efficiency in water, as shown in Fig. 8.

![Fig. 7 optimal analysis of bandwidth and collapsed voltage](image1)

![Fig. 8 analysis of optimal transmission efficiency](image2)

The uncertainty in manufacturing process precision degrades a microdevice’s performance, so that a reasonable tolerance must be considered when designing microdevices. All simulation must be completed before microfabrication. And the influence of stability factors on the transfer function must be analyzed. The first resonant frequency mode is the condition yielding the largest vibration displacement. For the simulation example, when the membrane radius is 48µm and the thickness is 1.3µm, a maximum displacement of 9.058×10⁻⁴µm is obtained at a resonance frequency of 3.7MHz. This design solution will produce the highest output signal response. At this design configuration, the capacitor breakdown voltage is 115.4V, with a bandwidth of 3.43MHz in air and 40.17kHz in water. Also, the optimal receiving efficiency is about 6.20×10⁴V/Nt in air and 6.81×10²V/Nt in water, as shown in Fig. 9. The membrane vertical vibrating displacement is computed and analyzed using MATLAB.

![Fig. 9 Analysis of optimal receiving efficiency](image3)

4. CONCLUSION

An engineering simulation database for designing versatile capacitive microdevices is developed. The microstructure-related electromechanical coupling parameters can be analyzed by the interactive simulation. The relative materials and geometries of the desired microstructures with electromechanical coupling effects can be analyzed by the developed database. The microfabrication feasibility can be estimated and the performance can be predicted after simulation and optimization. By abandoning trial-and-error procedures in the project, the system can be used easily to predict
optimal characteristic. Some simulation examples are executed for assessing and improving cMUTs. Optimal impedance matching, resulting in a wider bandwidth with high sensor resolution have been proven. The developed system has a friendly user interface that can be applied flexibly to obtain optimal parameters. After finding optimal parameters, a better microfabrication processes can be arranged to improve performance and yield, while reducing cost.

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