A 3-D FEM model for Capacitive Micromachined Ultrasonic Transducers for Ultrasound Imaging made by Reverse Fabrication Process

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Introduction

Ultrasound (US) imaging is the preferred technique for the investigation of human body tissues, such as organs, muscles, tendons and vessels. In fact, US imaging offers several advantages over other available imaging techniques: it is completely harmless and non-invasive, provides real-time images and is cost-effective. Images of anatomic structures are obtained by transmitting and receiving ultrasonic acoustic waves propagating through the human body, by means of an electroacoustic transducer device. The fabrication technology of transducer arrays for ultrasound imaging based on piezoelectric materials is nowadays very mature and therefore hardly improvable. During the last two decades, very promising results were obtained by new devices, fabricated by silicon micromachining technology and based on the electrostatic cell working principle. **Capacitive Micromachined Ultrasonic Transducers (CMUTs)** are MEMS devices consisting of miniaturized metallized membranes [1]; the membranes are forced into flexural vibration by an electric signal during transmission, and vice versa generate a voltage signal when actuated by an incident acoustic signal. The performance of CMUT arrays for US imaging applications are excellent [2,3]. Moreover, the CMOS-compatible fabrication technology enables the integration of the transducers with a dedicated front-end electronic circuit, allowing the design of miniaturized, low-weight, low-cost and energy efficient portable imaging systems. For this reason, many research groups are focusing their activities on the design of optimized CMUT arrays. In particular, University of Roma Tre proposed a new fabrication technique, named **Reverse Fabrication Process** [4], which allows the removal of the silicon substrate in favor of a properly designed acoustic backing, which improves acoustic coupling between the inactive area of the device with the body tissue [5]. The propagation of the acoustic wave produced by a source made of multiple vibrating membranes radiating into a fluid-like medium cannot be fully described by analytical models or equivalent electric circuits, thus CMUT devices are better simulated by Finite Elements Models (FEM) [6]. Our goal is to optimize RFP-CMUT arrays for medical imaging by means of an accurate 3-D FEM model.

Fig. 1. (a) The cell layout of a CMUT device; (b) a fully-packed CMUT probe head; (c) a fully assembled CMUT probe for ultrasound imaging.

FEM model

We developed a 3-D FEM model of a RFP-CMUT array that includes two quarters of circular membranes, centered at the opposite corners of a rectangular section of the array, as shown is Fig. 2. Symmetry boundary conditions applied at the outer edges of the modeled structure allow the simulation of an infinite repetition in the lateral dimension of identical cells, thus modeling an unbounded transducer composed of circular membranes arranged by hexagonal tiling. The structural model includes the membrane, made of Silicon Nitride by Low-Pressure Chemical Vapor Deposition, the Aluminum electrodes, the cavity and the structural SiN deposited by Plasma-Enhanced Chemical Vapor Deposition. The unbounded transducer model assumes that all the membranes are operating in phase, as can be seen by the modal analysis results shown in Fig. 3. The RFP-CMUT devices can be provided with custom backing layers, therefore we also added a backing to the model. Surface elements applied on the lower edge of the backing layer absorb plane waves, preventing the reflection of acoustic signals from the boundary. In order to take into account the electromechanical coupling, we applied transducer elements across the gap. The coupled model can be used, for example, to compute the device **collapse voltage** (i.e. the voltage that causes the membrane to collapse on the substrate, due to the increase of the attractive electrostatic force between the electrodes), or to evaluate the effect of the bias voltage on the resonance frequency **(spring softening effect)**. Finally, an acoustic fluid with water material properties was coupled to the device to simulate the acoustic wave propagation in human tissues. Due to the unbounded transducer simplification, the fluid load acoustic impedance is real, and the waves propagating in the medium are plane waves. This simplification is applied in order to reduce the computational burden and will be removed in future refinements of the model by considering transducers of finite lateral dimensions. On this model, multiphysics analysis for the solution of coupled structural, electrostatic and acoustic fields can be performed, so that the CMUT behavior in water-coupled transmission and reception operation can be observed.

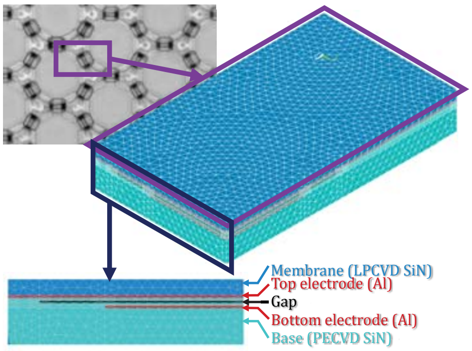

Fig. 2. The modeled structure (a) localized on the top-view of a CMUT array element, and (b) reproduced in the FEM 3-D model. (c) The layers composing the structure.

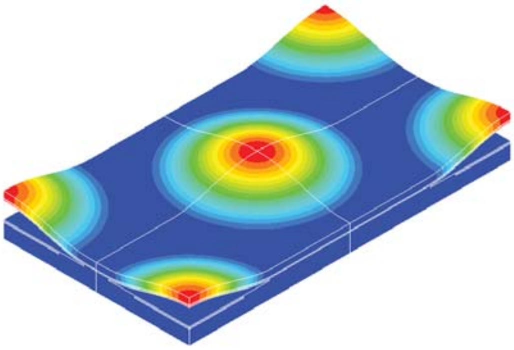

Fig. 3. The membrane displacement along the z-axis at the mechanical resonance frequency, obtained by expanding the results of a structural modal analysis. Due to the unbounded transducer simplification, the membranes all vibrate in phase.

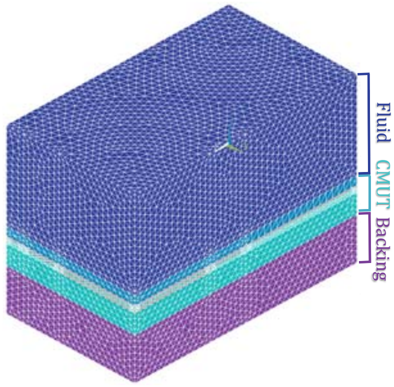

Fig. 4. The RFP-CMUT model, including the backing layer and the coupled acoustic fluid, used for multifield analysis.

Experimental validation

We performed harmonic analyses on the model with electromechanical coupling in order to validate the effectiveness of the mechanical coupling with the backing layer. The model accuracy was estimated by comparing simulations and measurements of the electrical impedance of two RFP-CMUT devices, each provided with a different acoustic backing. The backings were made of epoxy resin (Epotek 301) enriched by Al_2O_3 and W powders. Fig. 5 and Fig. 6 show the comparison between the simulated and measured real part and imaginary part of the electrical impedance of the considered devices. Simulations and measurements were carried out by varying the bias voltage. By increasing the bias voltage, the attractive electrostatic force between the electrodes increases; this increased attraction can be considered as a reduction of the membrane stiffness, which causes the reduction of the series resonance frequency. This phenomenon is also known as **spring-softening**. For both devices the model well represents the resonance frequency variation in response to the bias voltage variation (Fig. 5, 6).

The fluid-coupled model was used to compute the two devices transmission frequency response, i.e. the ratio between the pressure transmitted to the fluid and the voltage forced across the electrodes. This transmission transfer function represents the device sensitivity. We compared the harmonic analysis results to the measured response of the devices: the model correctly predicts the second mode resonance frequency in immersion operation for both devices (Fig. 7, 8).

Electrical Impedance

Device #1 – Backing Epotek 301 + W 11% + Al_2O_3 11%

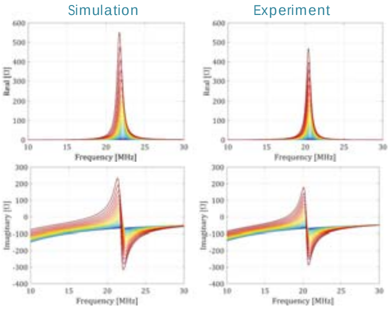

Fig. 5. The real part (up) and the imaginary part (down) of the electrical impedance of the first device, obtained by simulation (left) and measurement (right).

Electrical Impedance

Device #2 – Backing Epotek 301 + Al_2O_3 22%

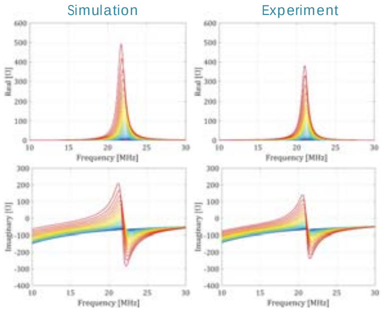

Fig. 6. The real part (up) and the imaginary part (down) of the electrical impedance of the second device, obtained by simulation (left) and measurement (right).

TX Frequency Response

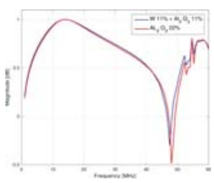

Fig. 7. The normalized simulated transmission frequency response. In the FEM analysis the devices were biased at 90% of the collapse voltage.

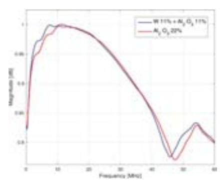

Fig. 8. The normalized transmission frequency response, measured at an on-axis distance of 7.5 mm by applying a -16 V, 8 ns pulse.

Immersion 2nd mode resonance frequency f_{r2}

	Simulation	Experiment
Device #1	47.49 MHz	45.87 MHz
Device #2	48.08 MHz	47.37 MHz

Conclusions

We built a 3-D FEM model for Capacitive Micromachined Ultrasonic transducer arrays for medical imaging applications realized by Reverse Fabrication Process. The FEM model is necessary to accurately predict the device behavior during water-coupled pulse-echo operation, and therefore to design the device for optimal performance. The model was validated by comparing electrical impedance and transmission sensitivity results with experimental measurements carried out on two different devices.

References

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