Coded signals in medical ultrasound allow both frequency and penetration depth to be increased while retaining image resolution and avoiding the need to augment the transmitted peak pressure amplitude. Such approach minimizes the potential for bioeffects even if the total amount of transmitted energy is enhanced. The goal of this work was to examine the bandwidth and noise immunity requirements of Golay coded waves used to determine frequency dependent attenuation of highly absorbing and scattering biological tissues. The measurements were performed in transmission and in pulse-echo mode using both conventional, narrowband PZT ceramic transducers and wideband PZT composites operating at frequencies of 0.5 MHz, 1 MHz and 2 MHz. The measurement system included custom-built Golay code transmitter, receiver electronics and PC based, off-line decoder. In vitro human heel bones with a cortical layer removed were tested and in vivo the measurements were carried out on volunteers’ heels. The results of the measurements obtained with 8 bit and 16 bit Golay codes were compared with the reference ones acquired using 2 cycles tone burst and indicated that coding faithfully retained all information related to frequency dependent attenuation. At the same time, advantageously, the coded transmission doubled the frequency range in which ultrasonic attenuation could be determined. The attenuation data obtained using narrowband and wideband composite transducers were compared and found almost identical. That indicates that the Golay coded signals are very robust, because despite their degradation due to limited bandwidth, they were successfully decompressed without losing their coding properties. Finally, the desirable noise immunity of the Golay system was verified by performing experiments with signal-to-noise ratio of 0 dB. The results indicated that under these conditions the sine-burst excitation mode failed completely while Golay coded signals allowed attenuation properties of the bone to be correctly determined.

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Session: 3E

CMUT MODELING
Chair: R. Lerch
University Erlangen

3E-1 10:30 a.m.

DERIVATION OF A 1D CMUT MODEL FROM FEM RESULTS FOR LINEAR AND NONLINEAR EQUIVALENT
CIRCUIT SIMULATION

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A new method is presented, which derives a 1D model of CMUT arrays from FEM simulations using piston radiator and plate capacitance theory. The model is suitable for fast linear and nonlinear parameter optimization.
A few static and harmonic FEM analyses of a single CMUT membrane cell are sufficient to derive the mechanical and electrical parameters of an equivalent piston as the moving part of the cell area. Parameters are area, mass, stiffness and damping of the piston as well as the electrically active piston area and parasitic capacity. These 1D model parameters are sufficient to describe the behavior of the CMUT in air and to simplify the investigation of wave propagation within the connecting fluid. For an array with all cells driven in parallel the complex mechanical impedance of the fluid will be derived depending on the membrane shape function. The real part as an additional damping term can be calculated from hydraulic transformation. The imaginary part will be described by an additional mass term and is responsible for the shift of the membrane modes towards lower frequencies. For operating modes with active and passive membranes a combined method was realized, where the transducers are single pistons within a rigid baffle and the propagating fluid medium is represented by FEM and transmission line matrix (TLM) models.

Results from linear and nonlinear 1D model simulations of single cells and CMUT arrays will be presented and compared with FEM and measurement results. All results fit very well for the first membrane mode. Higher order modes might be described by modal superposition with shape functions for each mode. The linearization of the 1D parameters also defines a two port network similar to the known models based on Mason’s theory. As a main advantage, the nonlinear behavior of the CMUT can be investigated easier and faster compared to FEM simulations. With a nonlinear model values like maximum applicable voltage as a function of operating frequency are calculated.

3E-2 10:45 a.m.

IMPROVED EQUIVALENT CIRCUIT AND FINITE ELEMENT METHOD MODELING OF CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS
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Equivalent circuit model has been widely used to predict the bandwidth of capacitive micromachined ultrasonic transducers. According to this model, the lower cutoff of the bandwidth is determined by the time constant of the parallel RC where R is dictated by the radiation and C is determined by the electrical capacitance of the transducer. The higher cutoff, on the other hand is determined by the membrane’s anti-resonance. In the mechanical part of the model, the radiation impedance is simply added to the membrane impedance assuming the membrane impedance does not change when it operates in the immersion medium. Therefore, the mass loading effect of the medium is neglected. Our finite element method calculations showed that the mass loading on the membrane impedance drastically lowers the membrane anti-resonance frequency degrading
the bandwidth. In this paper, we present results of equivalent circuit modeling combined with finite element analysis. We constructed a 3D finite element model for one element of a 1D array. The element has 7 hexagonal membranes in the width dimension and it is assumed that the membranes are replicated in the length dimension infinitely by using symmetry boundary conditions. By combining membrane impedance with equivalent circuit model, we found that the center frequency of operation is 11 MHz and the bandwidth is 12.5 MHz close to the collapse voltage. We also investigated the effect of the DC bias on the center frequency. Decreasing the bias voltage increased the center frequency without affecting the bandwidth assuming the source impedance is zero.

3E-3 11:00 a.m.

THEORY OF A DOUBLE-DIAPHRAGM MEMS ULTRASONIC TRANSDUCER
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Conventional capacitive MEMS transducer designs feature a single flexible diaphragm acting as a moving plate and an electrode patterned on the substrate acting as a stationary plate. Such devices generally function adequately as receivers. However, such devices sometimes show poor transmission efficiency because the gap dimension is limited by the manufacturing process and because the diaphragm would suffer "pull-in" collapse if deflected electrostatically beyond a critical fraction of the gap dimension. We describe a novel design, that can be easily fabricated within a multi-layer polysilicon process, to overcome many of these limitations. The design features two flexible diaphragms to be actuated by a coordinated series of pulses. The two flexible diaphragms and the stationary plate form three (upper, middle, and lower) parallel electrodes, and force can be exerted on the middle diaphragm by either the upper or the lower electrodes. A pulse on the upper electrode will reduce the gap to a value much less than the initial gap, and pulses on both upper and lower electrodes will then produce a large force on the upper electrode while simultaneously producing a net downward force on the middle electrode. In this way collapse is prevented while still realizing efficient conversion of electrical to ultrasonic energy. We present a theory of the improved performance of the double-diaphragm in reception and transmission, we calculate bounds on the energy that can be imparted to the flexible (moving) plates, and we compare the conventional and the novel designs for typical dimensions that would be employed with the MUMPS process.

This work has been funded by the Commonwealth of Pennsylvania through the Pennsylvania Infrastructure Technology Alliance program, administered at Carnegie Mellon by the Institute for Complex Engineering Systems, and by gifts from Krautkramer Inc.
PRE-COMPENSATED EXCITATION WAVEFORMS TO SUPPRESS SECOND HARMONIC IN MEMS CAPACITIVE TRANSDUCERS
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MEMS Electrostatic based transducers are finding growing application in the field of diagnostic ultrasound imaging. Simultaneously, diagnostic imaging is making extensive use of Tissue Harmonic Imaging (THI) wherein the non-linearly generated second harmonic echo signals are processed into B-Mode images. Unfortunately, electrostatic transducers inherently produce harmonics since the electrostatic force is a function of the square of the applied voltage. Thus, the filter used to isolate the non-linearly generated signal in imaging systems using THI cannot differentiate signals originating from non-linear propagation in the tissue from harmonic signals generated by the transducer source. Existing methods for linearizing the response by using a DC bias voltage have practical limitations. We explored the use of pre-distorted excitation waveforms as a means of controlling the transmitted second harmonic signal. PZFlex Finite Element Analysis and experimental results are presented. In the simplest analysis, the approach involves defining a desired function (including a DC offset) and then taking the square root of this function to determine the shape of the required input function. This calculated function is then divided into a DC component supplied by a DC source and an AC component supplied by a programmable function generator and an RF amplifier. This approach allows us to use AC voltages that are a large fraction of the DC bias level. In fact, we have used AC voltages as large as the DC bias. Using the pre-compensation technique, we have obtained a reduction in the transmitted harmonic of 7.5 dB in practical experiments. We believe that an even greater suppression of the harmonic may be possible if a more complete non-linear analysis of these devices is made. While the concept behind this technique was developed by several people (including one of the authors), independently, in recent years, we believe this is the first practical public demonstration of the technique.

Sensant Corp., The Whitaker Foundation

DYNAMIC ANALYSIS OF CMUTS IN DIFFERENT REGIMES OF OPERATION
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This paper reports on dynamic nonlinear analysis of immersed capacitive micro-
machined ultrasonic transducers (CMUTs) in transmit. A water loaded single 
circular membrane of a transducer is modeled. The radius and the thickness of 
the silicon membrane is 24 \( \mu \text{m} \) and 0.5 \( \mu \text{m} \), respectively. The vacuum gap is 0.2 
\( \mu \text{m} \) and there is 0.1 \( \mu \text{m} \) silicon oxide insulation layer on the bottom electrode. 
The calculated collapse and snapback voltages are 20 V and 18 V, respectively.

The membrane is excited with a combination of a constant DC voltage and 
a continuous sinusoidal AC voltage. The simulations are performed for various 
DC and AC voltages in order to analyze the membrane motion in three regimes 
of operation. These are: the conventional regime in which the membrane does 
not make a contact with the substrate, the collapse-snapback regime in which 
the membrane intermittently makes contact with the substrate and releases, 
and the collapsed regime in which the center of the membrane is in continuous 
contact with the substrate. In the collapsed regime a ring shaped section of the 
membrane around the contact region generates ultrasound.

The average output pressure as well as harmonic distortion is compared as 
the cmUT is operated in the conventional and collapse-snapback regimes. A 
continuous 4 V sinusoidal signal at 1 MHz is applied to the membrane. In con-
ventional regime operation, the membrane is biased at 15 V. To operate the 
membrane in the collapse-snapback regime, the bias voltage is set to 19 V. Our 
simulations showed that the average output pressure at the membrane could 
be as high as 41.6 kPa/V for collapse – snapback operation when conventional 
operation yielded only 6 kPa/V for the same CMUT. On the contrary, the cal-
culated second harmonic levels are 10 dB and 38 dB below the fundamental in 
collapse-snapback and conventional regime operation, respectively. A high out-
put pressure can be achieved by collapse-snapback operation with a trade-off in 
the form of significant second harmonic generation. However, collapsed regime 
operation provides a better compromise between maximum output pressure and 
harmonic distortion.

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3E-6  11:45 a.m.

SIMULATION OF CAPACITIVE MICROMACHINED 
ULTRASONIC TRANSDUCERS (CMUT) FOR LOW 
FREQUENCIES AND SILICON CONDENSER 
MICROPHONES USING AN ANALYTICAL MODEL

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Silicon micromachining is a promising approach to realize low frequency capac-
itive ultrasonic transducers and condenser microphones. The construction of 
micromachined low frequency capacitive ultrasonic transducers or microphones, 
respectively, differs considerably from that used for high frequency cMUTs [1]. 
In order to achieve high sensitivities at low bias voltages, perforated counterelec-
trodes are used to lower the stiffness of the air in the gap. For the simulation
of these devices it is state of the art to employ electromechanical equivalent circuits [2].

This paper describes an extended analytical model to calculate e.g. receiving and transmitting sensitivity, membrane deflection and input impedance of low frequency transducers. Electrical and mechanical elements of the transducers can be integrated into the same equivalent circuit. The membrane is modelled as a spring-mass system using a lumped element approach. In addition, dynamic effects as the mechanical reaction force of the airgap and flow losses in the airgap as well as the acoustic holes in the backplate are considered. An optimized backplate perforation is proposed to minimize these flow losses.

We will show the effects of different membrane materials, variations of airgap geometry and backplate perforation on frequency response and sensitivity for transducers in the audible and ultrasonic frequency range. Several optimization criteria are discussed considering the maximum usable membrane deflection due to the snap-in effect of the membrane.


Session: 4E
OPTICAL INTERACTIONS
Chair: D. Hecht
Palo Alto Research Center

4E-1 10:30 a.m.

GENERATION AND DETECTION OF ULTRASONIC WAVES IN MICROMETRIC AND SUB-MICROMETRIC FILMS USING PICOSECOND LASER PULSES, A COMPARATIVE STUDY WITH FEMTOSECOND LASER PULSES

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Femtosecond laser pulses have been used, since the end of the eighties, to perform generation and detection of longitudinal acoustic waves in sub-micrometric films, multilayers structures and other nanostructures[1]. Until now, the simultaneous use of picosecond laser pulses to generate and detect acoustic waves in micrometric and sub-micrometric films has not been explored.

In this paper, the effects of the laser pulse duration are investigated on experimental and theoretical acoustic signals. A model of generation and detection of ultrasonic waves with picosecond laser pulses is presented and compared with