A fluid-coupled transmitting CMUT operated in collapse mode

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A Fluid-Coupled Transmitting CMUT Operated in Collapse Mode: Semi-Analytic Modelling and Experiments

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Abstract

An electro-mechanical, semi-analytic, reduced-order (RO) model of a fluid-loaded transmitting capacitive-micromachined ultrasound transducer (CMUT) operated in collapse mode is developed. Simulation of static deflections, approximated by a linear combination of six mode shapes, are benchmarked towards state-of-the-art models and validated with digital holography microscope measurements of a fabricated CMUT device. The dynamic response of a detached single CMUT cell and an array of CMUT cells is predicted and analyzed for the effect of mutual radiation. The step-wise validation shows that our model predicts the static response including hysteresis behaviour of a collapse-mode CMUT with a high accuracy. The dynamic response and frequency-tunability are modelled with a satisfactory accuracy. The developed RO model is computationally efficient and in general faster than finite element methods. It is concluded that the presented RO model allows fast parameter analysis and is a powerful tool for CMUT pre-design.

Keywords: capacitive micromachined ultrasonic transducer, semi-analytic model, collapse-mode, simulations, experiments

1. Introduction

The development of capacitive-micromachined ultrasound transducers (CMUTs) has progressed significantly in the past years [1, 2, 3]. Especially the collapse mode operation of CMUTs has shown a potential for high performance medical
5 imaging [4]. Accurate and fast simulation methods are necessary to guide the

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CMUT pre-design for a given application prior to the CMUT fabrication and to understand the device behaviour afterwards. Simulation and subsequent model validation of a collapse-mode CMUT encompass a multi-scale, multi-physics, nonlinear problem [5, 6]. A few hundred nanometer displacement of thousands
 10 of CMUT cells results in a pressure propagation up to tens of centimeters [7]. Nonlinearity of the electrostatic actuation force introduces amplitude distortion of the time-domain response, and pull-in (collapse) and pull-out (snap-back) events, all of which should be accurately captured by the model [8].

The collapse-mode CMUT has been successfully modeled with a finite element method (FEM) [9, 10, 11]. However, the multi-scale problem definition
 15 requires fine meshing and the nonlinearity results in pull-in and pull-out hysteresis loops, which challenge the FEM model convergence. This results in time consuming FEM simulations that can take up to 4 hours to calculate collapse voltage of a CMUT [12]. They are therefore impractical for rapid collapse-mode
 20 CMUT prototyping.

State-of-the-art analytic models typically utilize a two-step approach for modelling of collapse-mode CMUT behaviour. First, a static deflection profile is predicted for a given DC (bias) voltage. The dynamic behaviour is then studied using an equivalent circuit model [13]. Analytic resolution of a circular
 25 plate equation has been done utilizing Timoshenko's uniform force solution to obtain the static deflection profile under the electro-static actuation [11]. The advantage of this approach is that no simplifying assumption on the shape of the plate for the collapsed state has to be made. The disadvantages are suitability only for the circular CMUT plates and a low accuracy due to the uniformity
 30 approximation of the highly non-uniform electro-static actuation force. This uniform electro-static force assumption has been later removed by discretizing the CMUT plate and introducing a spatially-dependent electro-static model force [14]. The resulting model was solved numerically under the assumption that the static displacement profile can be approximated by a 14-degree polynomial function. The dynamic behaviour of the top plate has been modeled using
 35 an equivalent circuit model. These lumped element models, however, introduce sporadic average displacements, negative capacitance or assumptions on loading effects of the fluid. Such simplifications hinder understanding of the underlying mechanics, e.g. the displacement of a single point on the CMUT top plate can
 40 not be modelled [15, 14].

Recently, an electro-mechanical fast time-domain model of a rectangular CMUT has been developed [16]. The model utilizes a numerical method to solve the dynamic plate equation. Although it has been developed for a CMUT operated in conventional mode, a simple penalty function has been introduced
 45 to accommodate for snap-back behaviour. The static and dynamic mechanical displacement of the top plate has been compared to experimental measurements with a digital holographic microscope (DHM). The model is also capable of simulating the fluid loading by introducing self and mutual acoustic coupling between the CMUT cells, which was validated by measurements of an impulse
 50 pressure response.

While the state-of-the-art collapse-mode CMUT models utilize intrinsically

slow FEM [10, 9, 17, 12], or equivalent circuit simulations of limited physical insight [14], our goal is to develop an insightful, electro-mechanical, semi-analytic model that allows fast parameter analysis to guide pre-design of the promising collapse-mode operation of CMUT [4]. We utilize a reduced-order (RO) model for electro-statically actuated clamped circular plates [18, 19], which we extend for the collapse-mode operation. The governing partial differential equation is discretized using the Galerkin method [20, p. 529 – 533]. The discretized model is analyzed to obtain both static displacement profiles and dynamic mechanical responses of an arbitrary point on the CMUT plate using time integration. Self and mutual radiations are then introduced to calculate the pressure field from distributed CMUT cells at an arbitrary location. We compare our model in terms of static simulations with state-of-the-art models and DHM measurements of a fabricated CMUT. The modelled dynamic behaviour of the fluid-loaded top plate is validated by acoustic field measurements in water. Using the developed model, frequency-tunability [21, 22] achieved by adjusting the bias voltage of a collapse-mode CMUT is demonstrated and compared to acoustic measurements of the fabricated frequency-tunable CMUT.

Outline

The following section provides a dimensionless formal description of the dynamic behaviour of an electro-statically actuated circular plate. The shape of the actuated CMUT plate is approximated by a linear combination of several undamped axisymmetric mode shapes and a Galerkin-discretized version of the equation of motion is introduced including contact pressure, fluid loading, and atmospheric pressure terms. Next, a classical relationship of pressure wave propagation theory is used to translate the CMUT plate acceleration to the pressure at an arbitrary point in the fluid. Section 3 describes the fabricated transducer and the experimental digital holographic and acoustic methods used to validate the developed CMUT model. The static and dynamic response of the modelled and measured CMUT are presented in Section 4 including an indication of the simulation time. The achieved results are discussed in Section 5. Finally, conclusions are drawn in Section 6.

2. Semi-analytic modelling

2.1. Formulation

A schematic overview of the geometrical parameters of a CMUT in collapsed state is shown in Fig. 1. The circular plate comprising a top electrode has a radius a and thickness t_m . It is separated from the bottom electrode by an insulation layer having a total thickness t_i , and a vacuum gap of height t_g . Applying a static (DC) bias voltage V_{bias} to the electrodes causes the movable top plate to deflect towards the bottom electrode, eventually collapsing the center area of the flexible top plate onto the bottom of the cavity. Then AC voltage $V_{AC}(t)$ is applied to excite the free part of the top plate, marginally

Figure 1: A schematic overview of the geometrical parameters of a CMUT in collapsed state.

relaxing the contact area from the bottom of the cavity (rolling contact). The CMUT transduces voltage and ultrasound as a result of these plate vibrations.

95 A CMUT operated in a conventional (non-contact) mode has been modelled previously by a nondimensional equation of motion governing the axisymmetric motion of a thin, isotropic, electro-statically actuated, clamped, circular plate [18, equations (6) and (7)]. We adapt and extend this state-of-the-art model for collapse mode operation,

$$\frac{\partial^2 \hat{w}(\hat{r}, \hat{t})}{\partial \hat{t}^2} + \nabla_{\hat{r}}^4 \hat{w}(\hat{r}, \hat{t}) = -\frac{\hat{V}(\hat{t})^2}{2(1 + \hat{w}(\hat{r}, \hat{t}))^2} + \hat{H}_{ab} \text{erfc}\left(\frac{\hat{t}_g + \hat{w}(\hat{r}, \hat{t})}{\hat{\sigma}}\right) + \frac{\hat{\tau}}{\hat{r}} \frac{\partial}{\partial \hat{r}} \left(\hat{r} \frac{\partial \hat{w}(\hat{r}, \hat{t})}{\partial \hat{r}} \right), 0 \leq \hat{r} \leq 1 \quad (1)$$

100 where the left-hand side contains the classical terms describing flexural deformations of a vibrating circular plate. The right-hand side terms model the electrostatic pressure, the contact pressure of the collapsed portion of the CMUT plate [23] (which is added to the original equation and explained in the following Section 2.2), and the biaxial residual stress [24], respectively. It is assumed
105 that the plate's transversal displacement is small as compared to its thickness (the ratio typically being smaller than 0.15) and that all stress components can be expressed in terms of a transverse deflection $\hat{w}$ of the plate. Further, it is assumed that no in-plane deformation occurs in the middle plane of the plate and that points lying initially on a normal-to-the-middle plane of the deformed
110 plate remain on its normal in the deformed state. Note that the assumption of axial symmetry is justified, since geometric imperfections are assumed to be negligible, initial conditions are zero, and the loads on the right-hand side of (1) are axial-symmetric. Moreover, the fundamental vibrational mode of the CMUT plate is axial-symmetric as well. $\hat{V}(\hat{t})$ is the total voltage applied to the
115 electrodes (e.g. $V_{bias} + V_{AC}(\hat{t})$), erfc is the complementary error function, $\hat{H}_{ab}$ is the effective indentation hardness, $\hat{\sigma}$ is the standard deviation of the combined surface roughness, and $\hat{\tau}$ is the residual stress parameter. For convenience, the model parameters from Fig. 1 are nondimensionalized in (1) according to (16) in Appendix A.

120 The nondimensional boundary conditions for the clamped circular plate in

Fig. 1 are given by

$$\hat{w}(1, \hat{t}) = \frac{\partial \hat{w}(1, \hat{t})}{\partial \hat{r}} = \frac{\partial \hat{w}(0, \hat{t})}{\partial \hat{r}} = \frac{\partial^3 \hat{w}(0, \hat{t})}{\partial \hat{r}^3} = 0. \quad (2)$$

These boundary conditions state that transversal displacements and rotations at radius a ($\hat{r} = 1$) are suppressed, and that rotation and shear force are zero in the middle of the plate ($\hat{r} = 0$).

2.2. Modelling of Contact Pressure

When the electrostatic actuation brings the two rough surfaces of the two insulated electrodes in contact, repulsive forces between the surfaces occur, which are a function of the distribution of distances between the two surfaces (see e.g. van Spengen et al [23] and Suy et al [25]).

A rough surface can be modeled as a rough plane with a mean height $\bar{z}$ and a standard deviation σ . In the case of two surfaces a and b , the Gaussian distribution of heights is schematically illustrated in Fig. 2 and mathematically described as

$$h_{ab}(z, \bar{z}_a + \bar{z}_b) = \frac{1}{\sqrt{2\pi(\sigma_a^2 + \sigma_b^2)}} \exp \left[-\frac{(z - (\bar{z}_a + \bar{z}_b))^2}{2(\sigma_a^2 + \sigma_b^2)} \right]. \quad (3)$$

Figure 2: Two surfaces with a Gaussian surface roughness distribution in contact.

To simplify (3) all properties of the two rough surfaces are combined to one rough surface by assuming the other surface to be flat and infinitely hard. The mean surface heights $\bar{z}_a$ and $\bar{z}_b$ are set to zero, which results in a standardized Gaussian distribution. Defining $\sigma = \sqrt{\sigma_a^2 + \sigma_b^2}$ as the standard deviation of the combined surface roughness, the distance distribution becomes

$$h_{ab}(z) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left[-\frac{z^2}{2\sigma^2} \right]. \quad (4)$$

The repulsive force between the two surfaces is now

$$F_c = H_{ab} A_{contact}, \quad (5)$$

with the contact area $A_{contact}$ calculated as

$$A_{contact} = A \int_{-\infty}^{\infty} h_{ab}(z) dz = \frac{A}{2} \operatorname{erfc} \left(\frac{z}{\sigma\sqrt{\pi}} \right). \quad (6)$$

The effective indentation hardness H_{ab} is calculated as

$$H_{ab} = \frac{H_a H_b}{H_a + H_b}, \quad (7)$$

where H_a and H_b are the indentation hardness of surfaces a and b , respectively. Combining (5), (6), and substituting $z = t_g + w(r, t)$ results in the contact pressure

$$P_c(r, t) = H_{ab} \frac{1}{2} \operatorname{erfc} \left(\frac{t_g + w(r, t)}{\sigma \sqrt{\pi}} \right), \quad (8)$$

145 Substituting the nondimensional parameters from Appendix A into (8) gives the second term on the right-hand side of (1).

2.3. Model Order Reduction

The partial differential equation (1) is approximated by a finite set of coupled ordinary differential equations using Galerkin discretization [20, p. 529 – 533],
150 an efficient and accurate technique commonly used in modelling of electromechanical systems [18, 26]. This technique eliminates the spatial dependence by discretizing the partial differential equation with respect to the spatial coordinates.

The transverse displacement $\hat{w}(\hat{r}, \hat{t})$ is approximated as a linear combination
155 of n linearly independent functions $\phi_i(\hat{r})$

$$\hat{w}(\hat{r}, \hat{t}) \approx \sum_{i=1}^n q_i(\hat{t}) \phi_i(\hat{r}), \quad (9)$$

where $q_i(\hat{t})$ is the generalized coordinate associated with the basis function $\phi_i(\hat{r})$.

The basis functions $\phi_i(\hat{r})$ are chosen to be the undamped axisymmetric eigenmodes of a circular plate without residual stress, electrostatic forcing, and
160 contact [18],

$$\phi_i(\hat{r}) = \frac{J_0(\hat{r}\sqrt{\Omega_i})}{J_0(\sqrt{\Omega_i})} - \frac{I_0(\hat{r}\sqrt{\Omega_i})}{I_0(\sqrt{\Omega_i})}, \quad (10)$$

where J_0 is the Bessel function of the first kind, I_0 the modified Bessel function of the first kind, and Ω_i is the i th nondimensional natural angular frequency. The nondimensional natural frequencies are calculated using the method described in [27, p. 7]. The number of mode shapes n represents a trade-off between
165 simulation accuracy and computational cost. A convergence study has shown that six mode shapes provide a transverse displacement accuracy of less than 2 nm, which is at the order of the expected surface roughness within the CMUT cavity [7].

2.4. Fluid Loading

When pressure is emitted to the surrounding medium from a point on the top-plate of one CMUT cell (which is in contact with the medium), it influences the top-plate motion of the cell itself. This effect is called self-radiation. Similarly, on a larger scale in the case of multiple CMUT cells, the acoustic pressure radiation of one cell is affected by other cells in the array [28]. This interaction between cells is commonly referred to as mutual radiation [16]. Both radiation effects are modelled in the time-domain by meshing the vibrating cell surface into N elements and using the fluid loading term of equation (3) in [29] to calculate the resulting radiation pressure P from all the interacting elements,

$$P(r, t) = \frac{\rho_{fl} A \frac{d^2 w(r, t)}{dt^2} \delta \left(t - \frac{d}{c_{fl}} \right)}{2\pi d}, \quad (11)$$

where ρ_{fl} is the mass density of the surrounding medium, A is the surface of the small mesh element, $\frac{d^2 w(r, t)}{dt^2}$ is the acceleration of the emitting mesh element, d is the Euclidean distance from one center of an element to another, δ is the Dirac function, and c_{fl} is the speed of sound in the surrounding medium.

Figure 3 shows a schematic image of the mesh of a single CMUT cell used for the fluid loading computation for the case of self-radiation. Quantities A_i and A_m represent the surfaces of the loaded and the radiating element, respectively. The total number of elements in the mesh of a single cell is $N = N_r N_\theta$, where $N_r = 101$ is the number of elements in radial direction and $N_\theta = 64$ is the number of elements in circumferential direction. A convergence study has shown that the chosen N of 6464 is sufficient for the dynamic response prediction by the model, in which every element can be considered to exhibit a piston like motion.

Figure 3: Schematic image of a single CMUT cell mesh used in the calculation of self-radiation loading. A_i and A_m are the surfaces of the loaded and the radiating element, respectively.

Under the assumption of axisymmetric loading and displacement of the membrane, the self-radiation pressure on a radial line is calculated. Figure 4 shows the equidistant mesh with N_r elements in radial direction, where $r_1 = 0$ and $r_{N_r+1} = a$.

Figure 4: Equidistant element mesh in the radial direction.

For the self-radiation, to approximate the total pressure at radius r , a discretized version of (11) is used

$$P_{self}(r, t) = - \sum_{i=1}^{N_r} \sum_{m=1, m \neq i}^N \frac{\rho_{fl} A_m \frac{d^2 w_m(r, t)}{dt^2} \delta\left(t - \frac{d_{m,i}}{c_{fl}}\right)}{2\pi d_{m,i}} \text{BF}_i(r), \quad (12)$$

where the block function BF_i is defined as

$$\text{BF}_i(r) = \begin{cases} 1 & r_i \leq r < r_{i+1} \\ 0 & \text{otherwise,} \end{cases} \quad (13)$$

where $d_{m,i}$ and $\frac{d^2 w_m(r, t)}{dt^2}$ are evaluated at $\frac{r_i + r_{i+1}}{2}$. Note that for each value of r only one block function BF_i (i.e. for only one value of i) is non-zero.

Similarly, the mutual radiation fluid loading accounts for the pressure loading contributions of the other CMUT cells as illustrated in Fig. 5 and is approximated for each loaded cell l at radius r as

$$P_{mut,l}(r, t) = - \sum_{k=1, k \neq l}^{N_c} \sum_{i=1}^{N_r} \sum_{m=1}^N \frac{\rho_{fl} A_m \frac{d^2 w_m(r, t)}{dt^2} \delta\left(t - \frac{d_{mk,il}}{c_{fl}}\right)}{2\pi d_{mk,il}} \text{BF}_i(r), \quad (14)$$

where N_c is the number of CMUT cells in the array. To prevent high CPU times, in approximation, it is assumed that all cells receive the same mutual radiation pressure. Therefore, equation (14) is calculated only once for a reference cell in the center of a virtual array that is large enough to practically represent an infinite array. The size of the virtual array is determined by the simulation time t and the speed of sound c_{fl} . A second approximation is that for the mutual radiation pressure of the reference cell axial symmetry is assumed. The mutual radiation pressure profile is calculated on the radial line coinciding with the line connecting the center of the reference cell and an adjacent cell. In reality, since the array is designed on a rectangular grid, mutual radiation pressure profiles are rotationally symmetric over 90 degrees only.

2.5. Reduced-Order Semi-Analytic Model

Adding the dimensionless self and mutual radiation fluid loading terms, $\hat{P}_{self}$ and $\hat{P}_{mut}$, respectively, and a dimensionless atmospheric pressure term, $\hat{P}_{atmos}$,

Figure 5: Schematic image of the meshing of the CMUT cells in an array used for the calculation of mutual radiation, which is indicated by the arrows. A_i is the surface of the loaded element.

to (1) and subsequently applying the Galerkin discretization method results in an extended set of discretized equations of motion,

$$\begin{aligned}
 \frac{d^2 q_j(\hat{t})}{d\hat{t}^2} + 2\zeta_j \Omega_j \frac{dq_j(\hat{t})}{d\hat{t}} + \Omega_j^2 q_j(\hat{t}) = & - \int_0^1 \frac{\hat{V}(\hat{t})^2}{\left(1 + \sum_{i=1}^n q_i(\hat{t}) \phi_i(\hat{r})\right)^2} \phi_j(\hat{r}) \hat{r} d\hat{r} + \\
 \int_0^1 \hat{H}_{ab} \text{erfc} \left(\frac{\hat{t}_g + \sum_{i=1}^n q_i(\hat{t}) \phi_i(\hat{r})}{\hat{\sigma}} \right) \phi_j(\hat{r}) \hat{r} d\hat{r} + \hat{\tau} \int_0^1 \frac{d}{d\hat{r}} \left(\frac{d \sum_{i=1}^n q_i(\hat{t}) \phi_i(\hat{r})}{d\hat{r}} \right) \phi_j(\hat{r}) d\hat{r} - \\
 \int_0^1 \hat{P}_{self}(\hat{r}, \hat{t}) \phi_j(\hat{r}) \hat{r} d\hat{r} - \int_0^1 \hat{P}_{mut}(\hat{r}, \hat{t}) \phi_j(\hat{r}) \hat{r} d\hat{r} - \int_0^1 \hat{P}_{atmos} \phi_j(\hat{r}) \hat{r} d\hat{r},
 \end{aligned}
 \tag{15}$$

220 for $j = 1, 2, \dots, n$. Note that on the left-hand side of (15) a viscous modal damping term has been added. For each mode, the dimensionless modal damping co-

efficient ζ_j may be tuned to account for (secondary) dissipation mechanisms such as material damping, anchor loss, thermoelastic damping, squeeze film damping etc. The self ($\hat{P}_{self}$) and mutual ($\hat{P}_{mut}$) radiation pressure terms are calculated from (12) and (14), respectively and are, together with the atmospheric pressure term ($\hat{P}_{atmos}$), nondimensionalized according to the expression (16) in Appendix A.

The generalized coordinates $q_i(\hat{t})$ are found with (15) and thus the transverse displacement $w(\hat{r}, \hat{t})$ via (9) and (10). Static deflection profiles and dynamic responses based on the developed reduced-order model (ROM) (15) are determined numerically due to the absence of an analytic solution. Therefore, the integrals over r appearing in (15) are for each time step evaluated numerically with the trapezoidal method using the generalized degrees of freedom q_i of the previous time step. The discretized equations of motion (15), which are in second order form, are transformed to first order form and then integrated over time using the implicit, variable order solver *ode15s* from MATLAB toolbox (version R2010b, MathWorks Inc., Natick, MA, USA).

Table 2 in Appendix B summarizes the model parameter values that were derived from the CMUT design specifications, except for the values of τ and σ , which have been obtained by tuning the model to the experimentally measured static displacement profiles.

2.6. Pressure propagation

The dynamic response of a single CMUT cell in a square array of CMUT cells is calculated and, for the sake of reducing computational cost, it is assumed to be the response of all individual CMUT cells in a fabricated octagonal array. In other words, it is assumed that all cells move in-phase. Pressure at an arbitrary point from the CMUT array surface is calculated from all the cell surface accelerations predicted by the RO model using a discretized version of (11) [29].

3. Prototype and Experimental Methods

3.1. Fabricated Transducer Prototype

The collapse-mode CMUT prototype device is fabricated in a professional cleanroom facility on a 6-inch thick silicon wafer utilizing the standard sacrificial release process, in which the cavity underneath the flexible top plate is created by deposition and subsequent selective etching of a sacrificial metal layer [30]. The complete layerstack of the prototype is provided in Fig. 11 in Appendix B.

The fabricated array consists of 932 30- μm -radius CMUT cells arranged on a rectangular grid in an octagonal shape as shown in Fig. 6. Each cell has a 3.6 μm spacing with the neighboring cells. All the top electrodes are short-circuited and the same holds for all the bottom electrodes. The whole array is driven as a single element transducer, which avoids extensive wire bonding and signal channel management at an early stage of development. More information

on the CMUT design and its patented fabrication process can be found in [21] and [31], respectively.

265 The CMUT device is mounted and wirebonded on a printed circuit board (PCB) for experimental characterization. The DC bias and the AC excitation voltage are applied to the CMUT electrodes via a bias-T which features a 5 nF coupling capacitor, a 1 M Ω resistor, and a high-impedance probe connector to measure the excitation pulse directly at the PCB.

Figure 6: Photograph of the fabricated CMUT prototype used for the experimental model validation.

270 3.2. Digital Holographic Microscopy

A digital holography microscope (DHM; R2100, Lyncée Tec SA, Lausanne, Switzerland), commonly used for CMUT characterization [7], is utilized to validate the static behaviour of a CMUT cell in air predicted by the RO model. The DHM uses two optical wavelengths of 666 nm and 794 nm to create an interference pattern and to record a digital hologram, which is then converted by the accompanying software into an image.

275 A single CMUT cell in the center of the array is positioned in a 10 $\times$ magnified field of view. Multiple 50-times averaged holograms are recorded at a range of bias voltages. A phase unwrapping algorithm calculates the static displacement profiles which are then compared to the RO model results. This configuration allows to measure a vertical displacement range of 2.1 μm with an accuracy of ± 3 nm and a lateral resolution of 1.15 μm .

280 3.3. Hydrophone Measurement Setup

A hydrophone measurement is utilized to validate the dynamic behaviour of the RO model. To protect the CMUT from the capacitive and conductive effect of water, it is immersed in a holder filled with olive oil ($c_{fl} = 1432 \text{ m s}^{-1}$),

290 facing an acoustic window. The whole assembly is placed in a water tank. The CMUT is biased and driven with a half period of a 60-MHz 45-V sine. A needle hydrophone ($\varnothing$ 0.2 mm, Precision Acoustics, Dorchester, Dorset, UK) is placed at a distance of 10.8 mm from the center of the CMUT prototype and used to measure the acoustic output at a range of bias voltages. The recorded voltage traces are converted to pressure waveforms using the hydrophone calibration data and compared to the RO model dynamic response results.

4. Static and Dynamic Response Results

295 4.1. Static Behaviour

In Fig. 7(a), the static transverse deflection of a single cell CMUT top plate predicted by our RO model is compared to the state-of-the-art collapse-mode CMUT models for bias voltages of 100 V, 120 V, and 140 V. The RO model predicts larger transverse deflections in comparison to the model developed by the Bilkent University group [11], which is expected due to the uniform electrostatic force assumption in [11]. In comparison to the parametric nonlinear lumped element model developed by the same group [14], in which the uniform force assumption was removed, the RO model shows a maximum deviation of 1 nm (0.4 % of the gap height).

305 The static behaviour predicted by the RO model is validated towards DHM displacement measurements of a fabricated CMUT cell. During the measurements dielectric charging effect has been observed [32], which resulted in a DC bias offset of about 20 V. It was found that the amount of charge saturates after minimally three pulses have been applied to the device. The offset of the zero voltage point was therefore carefully monitored by measuring the positive and negative pull-in voltages. The measured bias voltage was corrected for the induced offset for a fair comparison to the RO model.

315 As shown in Fig. 7(b), the RO model accurately predicts the static response for the bias voltage of 100 V and 120 V. The model slightly underestimates the deflection profile at the higher bias voltage of 140 V. The maximum deviation of the model prediction from the measurement is about 10 nm (4 % of the gap height).

320 The hysteresis behaviour of the CMUT predicted by the RO model is in a good agreement with the DHM static measurements as shown in Fig. 8. The model predicts the plate pull-in and pull-out voltages of 59 V and 55 V, respectively, which match well the experimental observation.

4.2. Dynamic Behaviour

325 The static deflection profiles are used as initial conditions for the dynamic simulations under electrostatic actuation. The RO model is utilized to simulate the dynamic plate deflections of both a detached single CMUT cell and a CMUT cell in a square array, both immersed in water. Half a period of a 100-MHz 60-V squared sine ($V_{AC}(t) = 60 \sin^2(10^8 T t)$, where $0 \leq T \leq \pi$) is used as the dynamic excitation signal for the simulation. Figure 9(a) shows the time

Figure 7: Static response of the reduced-order model (ROM) compared to state-of-the-art uniform [11] and non-uniform [14] electrostatic force model (ESFM) of a collapse-mode CMUT (a), and validated towards measurements with a digital holographic microscope (b).

330 responses and Fig. 9(b) the corresponding frequency spectra of the transversal displacement at a radial position of 15 μm on the top plate of the CMUT cell. A shorter response and therefore broader bandwidth is obtained for the CMUT cell within the square array of CMUT cells as compared to the detached single CMUT cell. This can be explained by the mutual radiation forces (that are

Figure 8: Static deflection of the middle point (at $r = 0$) on the CMUT plate in relation to the bias voltage.

obviously lacking in the case of the single cell) damping out the motion of the CMUT plate in the square array earlier. During the first few nanoseconds, only the self-radiation is acting on the CMUT cell and thus the two responses are similar. The first mutual radiation forces reach the chosen radial position of the analysed cell after 12.5 ns, which is the minimum time needed for sound to travel from a neighbouring CMUT cell. For the cell in the square array of CMUT cells, a minor overshoot is observed after about 50 ns followed by negligible steady-state vibrations giving a second peak at 30-MHz in the corresponding spectrum shown in Fig. 9(b). The peak resonance frequency of the CMUT top plate is 6.5 MHz and 7.5 MHz for the detached and the square array configuration, respectively.

Capacitive and conductive effects of water make direct immersion of a CMUT into water for a subsequent validation infeasible. Typically, a non-conductive oil is used instead of water, which is however not compatible with the immersion objective of our DHM. Therefore, and in line with further investigation, the dynamic part of the model was validated towards hydrophone measurements.

The dynamic pressure measurements utilized half a period of a 60-MHz 45-V sine as an excitation signal to the CMUT. The excitation signal was experimentally measured at the PCB and used as an input to the RO model for a fair comparison of the modelled dynamic behaviour to the measurements.

Figs. 10(a) and 10(c) compare the RO model-predicted pressure waveform towards the acoustic measurement for bias voltages of 100 V and 160 V, respectively. The overall shape of the simulated waveforms is in a satisfactory agreement with the measurement, even though the absolute amplitude is significantly overestimated by the RO model. The subtle waves in the time signals

Figure 9: Simulated impulse (a) and frequency (b) response of a point at $15 \mu\text{m}$ radius on a CMUT cell plate biased at 120 V, excited with half a period of a 100-MHz 60-V squared sine, and immersed in water. The arrow in (a) indicates a time stamp at which the first mutual radiation forces reach the chosen radial position.

between $7.0 \mu\text{s}$ and $7.3 \mu\text{s}$ in Figs. 10(a) and 10(c) are caused by a discontinuity in the hydrophone calibration data curve below 1 MHz and above 30 MHz.

Frequency spectra corresponding to the pressure waveforms are shown in Figs. 10(b) and 10(d). At a bias voltage of 100 V (Fig. 10(b)), center frequencies of 12.9 MHz and 11.1 MHz are observed for the RO model-predicted and experimentally measured frequency spectra, respectively. Increasing the bias voltage to 160 V (Fig. 10(d)), shifts the center frequency of the RO model-predicted and measured responses to 16.6 MHz and 16.1 MHz, respectively. This effect has been experimentally observed and described as the frequency-tunability [21, 22, 33].

4.3. Simulation Time

The simulation time needed to generate the RO model deflection profiles shown in Fig. 7(a), was about 10 s on a laptop equipped with 2.3 GHz Intel Core i5 processor and 8 GB RAM. This is comparable to about 45 s needed for the lumped element model implementation published in [34], when the same zero-deflection initial guess is used. The dynamic behaviour is predicted by the RO model within 30 min for the detached single CMUT cell and it takes about 65 min for the CMUT cell in the square array (Fig. 9), which is in general faster as compared to a finite-element method (FEM) simulation.

5. Discussion

The developed semi-analytic, electro-mechanical, fluid-coupled, RO model predicts both the static and dynamic behaviour of a collapse-mode CMUT. The static deflection profiles are predicted within an accuracy of 10 nm (4 %) for the worst case scenario, which is observed at a bias voltage of 140 V, as validated with the DHM measurements. The model captures the hysteresis behaviour

Figure 10: Acoustic impulse (a – c) and frequency (b – d) response of the simulated and fabricated CMUT array excited with half a period of a 60-MHz 45-V sine and biased at 100 V (a – b) and 160 V (c – d). The reference pressures corresponding to the 0 dB magnitudes equal to 13.6 kPa (b) and 13.1 kPa (d).

of the CMUT and predicts pull-in and pull-out voltages, which are in a good agreement with the experimental observation.

The RO model has been utilized to simulate an impulse response of a detached single CMUT cell and a cell in a square array (Fig. 9). It has been found that mutual radiation forces significantly affect the CMUT's dynamic response in immersion. A CMUT cell in the square array exhibits larger bandwidth due to the increased damping caused by the mutual radiation as compared to a single detached cell. The geometrical distribution of the CMUT cells in an array will therefore influence the bandwidth of CMUT response. As an alternative for the current rectangular grid CMUT array, another array grid design might be considered to increase the CMUT's bandwidth.

The dynamic behaviour of the CMUT is captured with a satisfactory accuracy as validated towards the acoustic measurements (Fig. 10). The model demonstrates the center frequency-tunability in a range from 12.9 MHz (–3 dB fractional bandwidth of 63 %) to 16.6 MHz (bandwidth of 47 %) by changing the bias voltage from 100 V to 160 V. For the same voltage range, the acoustic measurements show tunability from 11.1 MHz (bandwidth of 82 %) to 16.1 MHz (bandwidth of 60 %). Both the simulations and experiments at the different bias voltages indicate that the frequency tuning comes at a cost of additional ringing observed after 7.4 μs in Fig. 10(c). An increase in the bias voltage from 100 V

to 160 V leads to a larger contact radius, which in turn results in a higher natural resonance frequency. However, at the same time the CMUT plate vibrates longer. This effect is observed by an (undesired) increased number of cycles in the high frequency pressure waveform simulated or measured at the bias voltage of 160 V (Fig. 10(c)).

The difference in amplitude of the simulated and measured waveforms shown in Figs. 10(a) and 10(c), may be explained by the simplifying assumption of identical response of all the CMUT cells. In this assumption, a square array of cells is used, where the cells are placed on a rectangular grid. As stated earlier in Section 2.4, is assumed that every cell in the array experiences the same axial-symmetric mutual radiation pressure, which in fact means that an infinite array is assumed. This assumption may be rather coarse for cells near the edge of the square array. Taking into account the speed of sound in the fluid and the total simulation time (which is chosen considering the position of the hydrophone in the fluid relative to the array), the mutual radiation pressure is calculated by the means of a virtual array with a size large enough to practically represent an infinite array. The calculation of the mutual radiation pressure is then reduced to that of a single reference cell lying in the center of the virtual array. Furthermore, as mentioned before in the current approximation, the mutual radiation pressure acting on the reference cell is calculated on a single radial line coinciding with the line connecting the middle points of the reference cell and an adjacent cell. It is assumed that this mutual radiation pressure profile is axial-symmetric, whereas for a rectangular grid, it is actually only rotationally symmetric over 90 degrees. The above assumptions are needed to prevent high CPU-times. While investigating the effect of these assumptions is considered out of the scope of the present paper, it targets the focus of our future research interest.

For the case of self-radiation, it can be assumed that geometric imperfections will be so small that, starting from axial-symmetric initial conditions, non-axial symmetric modes will hardly be excited in the case of axial-symmetric loading of the circular CMUT plate with a rolling contact. Furthermore, for a single CMUT cell, it is a valid assumption that the electrostatic loading and fluid loading due to self-radiation are axial-symmetric.

The developed model features a damping term, of which the coefficients ζ_j were set to zero for the fluid-loaded simulation. This is a commonly accepted approach, because the "damping" is expected to be dominated by the fluid load (modelled by the self and mutual radiation) rather than by mechanical losses in the CMUT plate [16, 36]. The amplitude deviation between the simulation and measurement, especially of the second minima shown in Figs. 10(a) and 10(c), however, indicates that in the case of a collapse-mode CMUT secondary damping mechanisms may play an important role, e.g. contact damping, anchor loss, thermoelastic damping, squeeze film damping etc.

In the presented model, the shape of the deflected plate is modeled as a linear combination of six free vibrational mode shapes and, for the purpose of radiation modelling, meshed by a limited number of (piston) elements. The number of mode shapes and meshing elements is chosen based on a trade-off between model

450 accuracy and computational cost. Although the model was developed for a circular plate design, it can be used for any other simple geometry, e.g. a square or rectangular design, that can be approximated by analytic mode shapes.

In the current situation, the RO model features two tuning parameters, the uniform residual biaxial plane stress ($\hat{\tau}$) and the combined surface roughness ($\hat{\sigma}$).
 455 In future work, fabrication of multiple CMUTs of at least two different plate radii could be utilized to estimate the initial plane stress using the procedure described in [7]. To measure the surface roughness, a sample would have to be cut through and measured with a stylus profiler.

Finally, it is recommended to couple the developed model to an ultrasound
 460 image simulator. For instance, a Field II ultrasound simulation program [37] requires transducer's surface acceleration to excitation voltage response as an input for the transducer definition [38]. Such a response prediction is readily available in our model and can be therefore utilized directly in the Field II to predict the imaging performance of a given collapse-mode CMUT design.

465 6. Conclusions

We have developed and validated an electro-mechanical, semi-analytic, RO model of a CMUT operated in collapse mode. The step-wise validation shows that our model, based on six vibrational mode shapes, predicts the static response including hysteresis behaviour of a collapse-mode CMUT with a high
 470 accuracy, which is computed within 10 s. The dynamic response and frequency-tunability are modelled with a satisfactory accuracy and computed within 65 min. Compared to FEM-based simulation methods, our model allows fast parameter analysis for larger penetration depths and is an accurate tool for CMUT pre-design. In future work, it is recommended to interface the developed model
 475 with an ultrasound image simulator to obtain a powerful tool that would link the CMUT design parameters with imaging performance.

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Appendices

The appendices introduce dimensionless parameters used in the equation of motion, and provide a summary of the geometrical and physical model parameters.

485 Appendix A: Dimensionless model parameters

The model parameters and variables in Fig. 1, and mentioned in (1) and Tab. 2 are nondimensionalized according to the following expressions, partly given in [18, equation (6)],

$$\begin{aligned}
 \hat{r} &= \frac{1}{a}r & \hat{t} &= \frac{1}{a^2}\sqrt{\frac{D}{\rho_{tp}t_m}}t \\
 \hat{w}(\hat{r}, \hat{t}) &= \frac{1}{t_{eff}}w(r, t) & \hat{\tau} &= \frac{a^2t_m}{D}\tau \\
 \hat{H}_{ab} &= \frac{a^4}{2Dt_{eff}}H_{ab} = \frac{a^4H_aH_b}{2Dt_{eff}(H_a + H_b)} & \hat{\sigma} &= \frac{\sqrt{\pi}}{t_{eff}}\sigma \\
 \hat{t}_g &= \frac{1}{t_{eff}}t_g & \hat{V}^2 &= \frac{\epsilon_0a^4}{2Dt_{eff}^3}V^2 \\
 \hat{P}_{self}(\hat{r}, \hat{t}) &= \frac{a^4}{Dt_{eff}}P_{self}(r, t) & \hat{P}_{mut}(\hat{r}, \hat{t}) &= \frac{a^4}{Dt_{eff}}P_{mut}(r, t) \\
 \hat{P}_{atmos} &= \frac{a^4}{Dt_{eff}}P_{atmos} & & (16)
 \end{aligned}$$

Appendix B: Transducer and model parameters

490 Figure 11 shows the layerstack of the fabricated and modelled CMUT device, of which the geometrical and mechanical properties are summarized in Tab. 1.

Figure 11: Material layers of the fabricated CMUT stack reproduced from [21]. t_1 and t_2 represent the first and second effective layers, respectively.

Table 1: Thickness and mechanical Properties of the CMUT layers indicated in Fig. 11.

Layer material	Thick- ness [nm]	E [GPa]	ν [–]	Effective parameter		
				Layer	E [GPa]	ν [–]
Plug layer	900	200	0.27	t_1	200	0.28
Nitride layer	150	200	0.27			
Insulating layer	50	70	0.3	t_2	70	
Top electrode	240	70	0.3			
Top 1/2 dielectric	225	70	0.3			

In a good approximation, the top layer is assumed to consist of a double-layered plate having an effective flexural rigidity D calculated as [39]

$$D = \frac{E_1^2 t_1^4 + E_2^2 t_2^4 + 2E_1 E_2 t_1 t_2 (2t_1^2 + 2t_2^2 + 3t_1 t_2)}{12 (E_1 t_1 + E_2 t_2) (1 - \nu^2)}, \quad (17)$$

where t_1 and E_1 are the total thickness and average Young's modulus of the plug and nitride layers, respectively; t_2 and E_2 are the total thickness and thickness-weighted average Young's modulus of the insulating layer, top electrode, and top-half dielectric, respectively; ν is the Poisson's ratio of the complete top plate.

The insulating dielectric layer inside the CMUT cavity can be modelled as an increased distance (effective gap height) between the two electrodes placed in vacuum

$$t_{eff} = t_g + \frac{t_i}{\epsilon_r}, \quad (18)$$

where ϵ_r is the relative permittivity of the dielectric material, t_g is the gap height, and t_i is the total dielectric layer thickness.

The RO model parameter values are summarized in Tab. 2. The values of τ and σ are obtained by fitting the RO model to experimentally measured static displacement profiles.

Table 2: Parameters of the reduced-order model.

Parameter	Value	Unit	Description
a	$30 \cdot 10^{-6}$	m	Plate radius
ϵ_0	$8.85 \cdot 10^{-12}$	F m ⁻¹	Dielectric permittivity of vacuum
ϵ_r	4.3	—	Relative dielectric permittivity of insulator
t_g	$230 \cdot 10^{-9}$	m	Gap height
t_i	$450 \cdot 10^{-9}$	m	Insulator thickness
t_{eff}	$3.347 \cdot 10^{-7}$	m	Effective gap height
t_m	$1.565 \cdot 10^{-6}$	m	Plate thickness
D	$4.092 \cdot 10^{-8}$	N m	Flexural rigidity of plate
P_{atmos}	$101.325 \cdot 10^6$	Pa	Atmospheric pressure
τ	$-100 \cdot 10^6$	Pa	Uniform residual biaxial plane stress
σ	$4 \cdot 10^{-9}$	m	Combined surface roughness standard deviation
$H_n, n = a, b$	$2 \cdot 10^9$	Pa	Effective indentation hardness [40]
ρ_{tp}	3290	kg m ⁻³	Combined mass density of the top plate
c_{fl}	1483	m s ⁻¹	Speed of sound in water
ρ	100	kg m ⁻³	Mass density of water
$\zeta_j, j = 1, 2, \dots, 6$	0	—	Modal damping coefficients

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Highlights of the manuscript:

A Fluid-Coupled Transmitting CMUT Operated in Collapse Mode: Semi-Analytic Modelling and Experiments

by: Martin Pekař, Stephan H. M. van Nispen, Rob H. B. Fey, Sergei Shulepov, Nenad Mihajlović, and Henk Nijmeijer

- a semi-analytic model of fluid-loaded, transmitting, collapse-mode CMUT is developed
- the model is validated by experimental measurements of a fabricated CMUT prototype
- static response incl. hysteresis behaviour is predicted with high accuracy
- dynamic response behaviour incl. frequency-tunability is predicted with satisfactory accuracy
- the model allows fast parameter analysis and is a powerful tool for CMUT (pre-)design

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