
Fast Nonlinear CMUT Simulation Model for Pull-In and Dynamic Fluid Coupled Deflection Analysis

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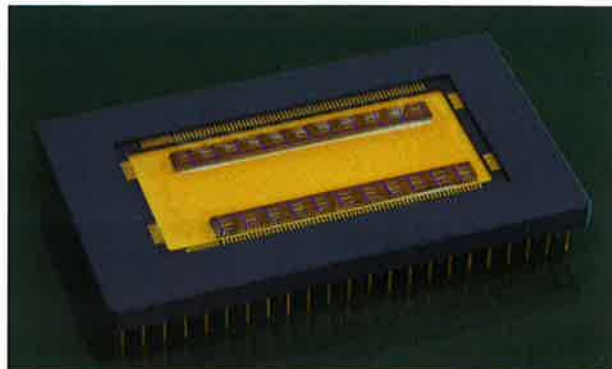
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Outline

- Introduction
- Static Analysis of Plate Deflection
- Dynamic Plate Simulation
- Structure Fluid interaction
- Simulation of Electronics



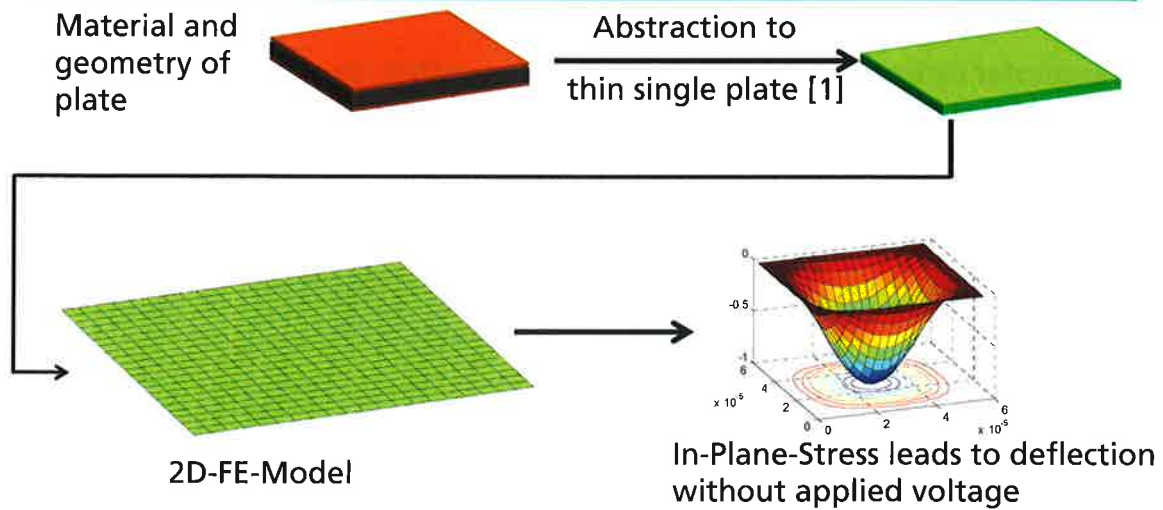
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Markus Klemm | MUT 2014 | slide 2

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CMUT Mechanic Simulation Model



[1] Senegond et al: Fast time-domain modeling of fluid-coupled cMUT cells: from the single cell to the 1-D linear array element. In: IEEE Trans. Ultrason., Ferroelect., Freq. Contr. 60 (7), S. 1505–1518.

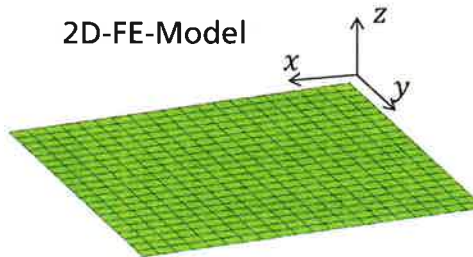
Static Analysis of Plate Deflection

$$\left(\mathcal{M} \frac{\partial^2}{\partial t^2} + \mathcal{D} \frac{\partial}{\partial t} + \mathcal{K} \right) \begin{pmatrix} w_z \\ \sigma_x \\ \sigma_y \end{pmatrix} = \begin{pmatrix} F_z \\ F_x \\ F_y \end{pmatrix}$$

Static simulation: $\frac{\partial}{\partial t} = 0$

$$\mathcal{K} \begin{pmatrix} w_z \\ \sigma_x \\ \sigma_y \end{pmatrix} = \begin{pmatrix} F_z \\ F_x \\ F_y \end{pmatrix}$$

2D-FE-Model



Design condition

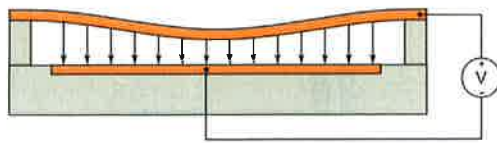
- Plate material
- Plate thickness
- Atmospheric pressure

Determined/ measured value

- In plane stress \rightarrow Initial deflection
- Centre deflection \rightarrow Residual Stress

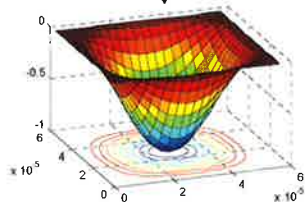
Information on

Static Analysis of Plate Deflection

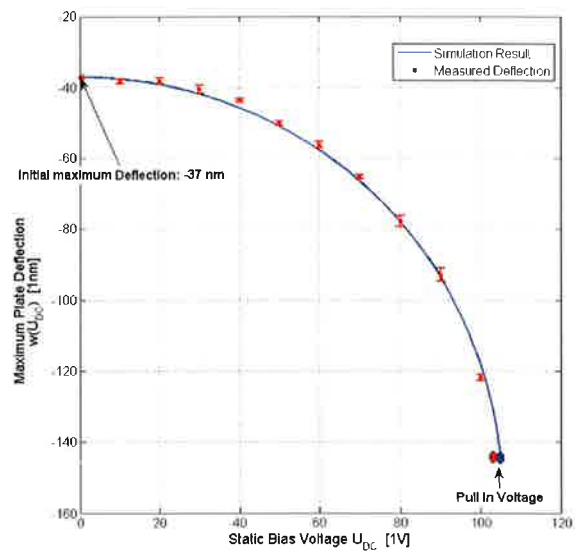


Elektrostatic Force

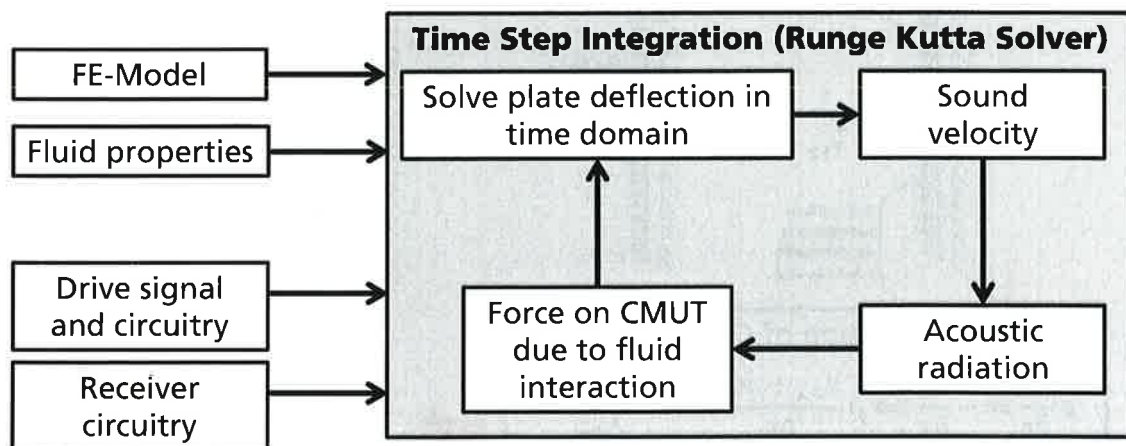
$$F(x, y) = \frac{1}{2} \epsilon_0 \frac{A}{h^2(x, y)} U_{DC}^2$$



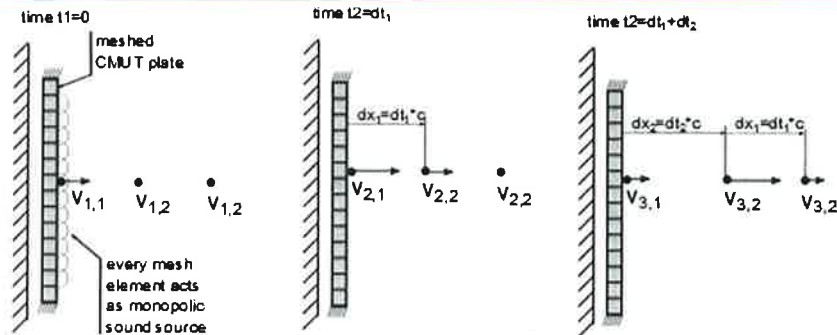
Static deflection $w(U_{DC})$



CMUT Simulation Model



Structure Fluid interaction



Near Field of spheric wave:

$$v_{2,2} = \frac{v_{1,1}}{(\Delta x_1)^2}$$

$$p_{2,2} = \frac{p_{1,1}}{\Delta x_1}$$

Conditions:

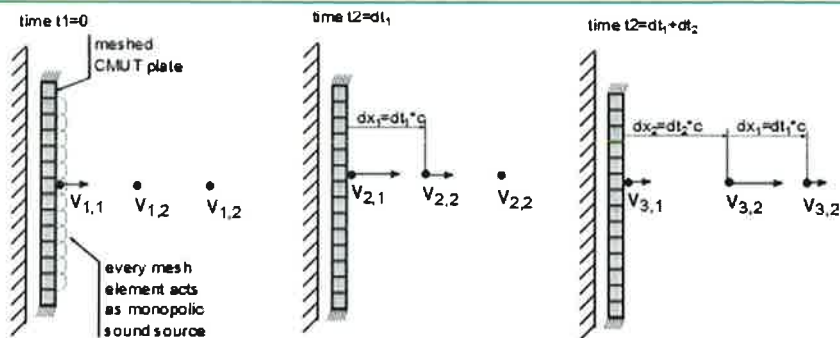
Constant phase of wave:

$$\Delta x \ll \lambda \Leftrightarrow \Delta t \ll \frac{1}{f}$$

Monopole source

$$\Delta y \ll \lambda$$

Structure Fluid interaction



Solve Equation of Continuity:

$$\rho \frac{\partial v}{\partial t} = -\frac{\partial p}{\partial x} \Rightarrow \rho \frac{v_{2,2} - v_{2,1}}{\Delta t_1} = \frac{p_{2,2} - p_{2,1}}{\Delta x_1}$$

$$p_{2,1} = \rho \frac{v_{2,2} - v_{2,1}}{\Delta t_1} \cdot \Delta x_1 + p_{2,2}$$



Sound pressure at surface of CMUT in time domain

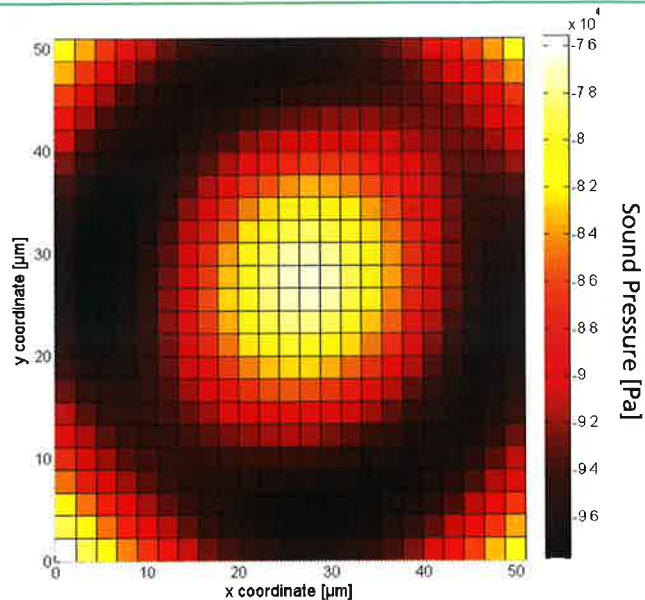
CMUT Simulation Model

Model covers:

- Simulation of sound pressure in front of CMUT

Further step done

- Implementation of a radiation matrix
-> acoustic "Cross coupling" between mesh elements



Influence of Electronics Current flow into CMUT

Values of interest:

1. Current flow into CMUT
2. Voltage drop over CMUT

$$i(t) = \frac{d}{dt}(U \cdot C) = C_{CMUT} \frac{dU(t)}{dt} + U_0 \frac{dC_{CMUT}(t)}{dt}$$

Current due to:

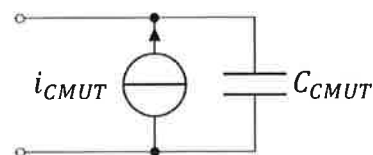
1. Charging of CMUT as Capacitor

$$C_{CMUT} \frac{dU(t)}{dt}$$

2. Capacity Change of CMUT

$$U_0 \frac{dC_{CMUT}(t)}{dt}$$

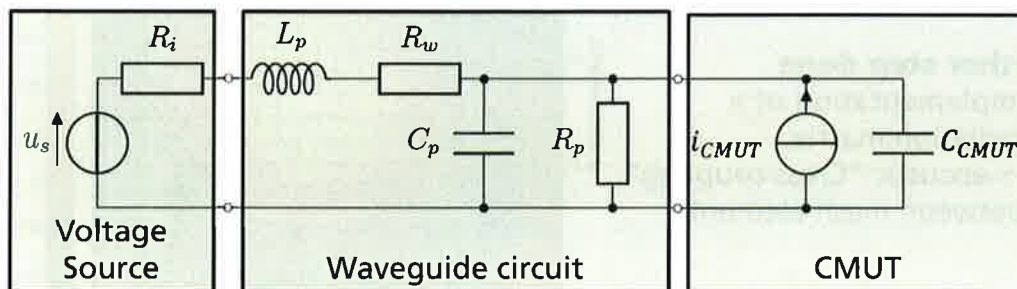
Equivalent circuit



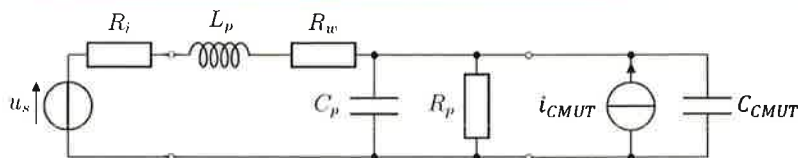
Influence of Electronics Voltage drop over CMUT

Values of interest:

1. Current flow into CMUT
2. Voltage drop over CMUT



Influence of Electronics State space representation



$$\frac{d\vec{z}}{dt} = A\vec{z} + B\vec{x}$$

$$\vec{x} = \begin{pmatrix} i_{CMUT} \\ u_s \end{pmatrix}$$

$$\vec{y} = (u_{CMUT})$$

$$\vec{z} = \begin{pmatrix} i_s \\ u_{CMUT} \end{pmatrix}$$

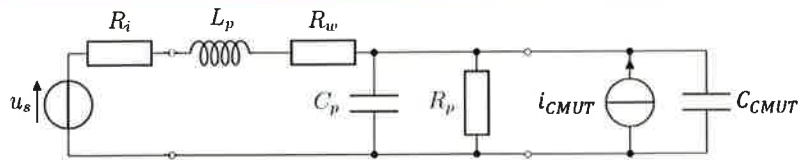
$$\vec{x} = C\vec{z} + D\vec{x}$$

- Input voltage u_s is given by user
- Calculation of current i_{CMUT} within time step integration

**Solving of i_{CMUT} , u_{CMUT} and plate deflection
for given ideal input signal.**

Influence of Electronics

State space representation



$$\frac{d\vec{z}}{dt} = A\vec{z} + B\vec{x}$$

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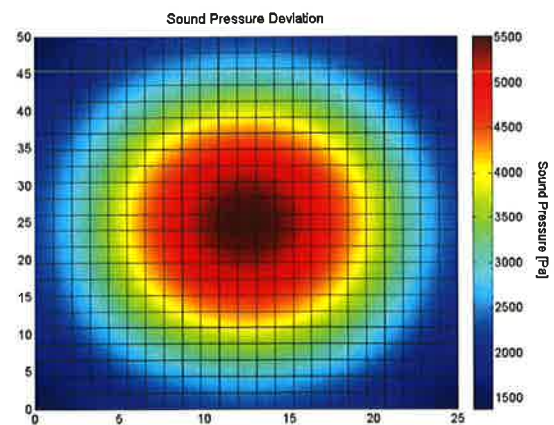
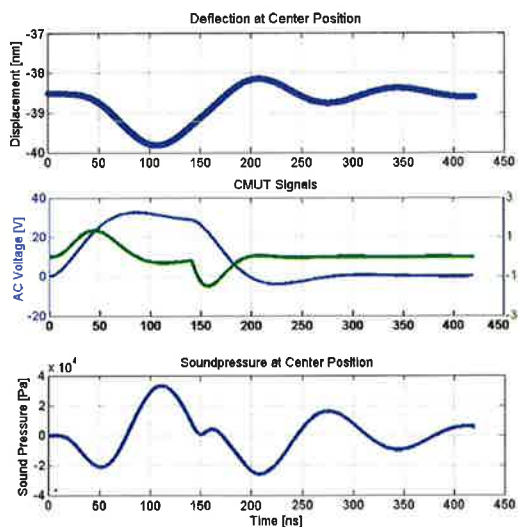
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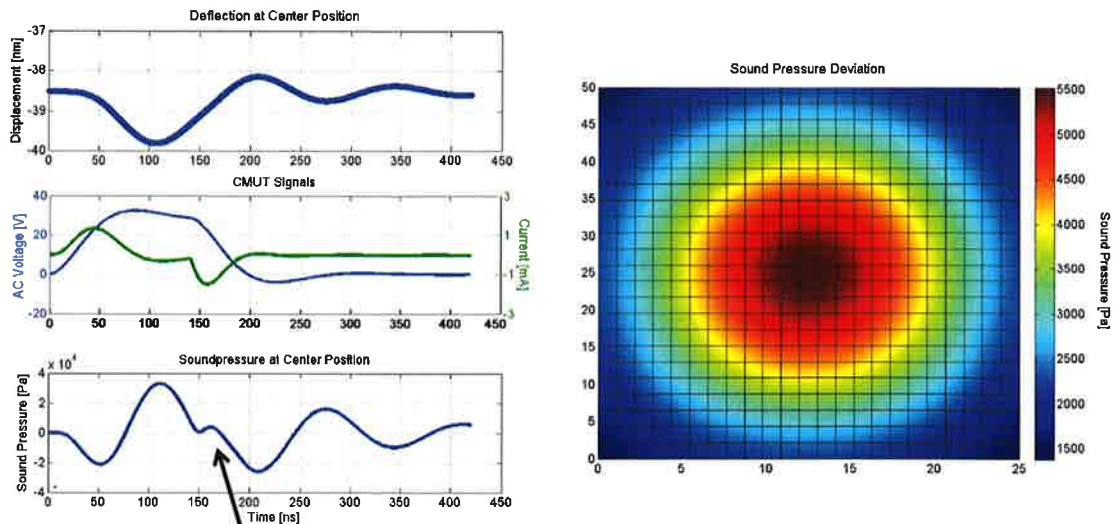
$$\vec{z} = \begin{pmatrix} i_s \\ u_{CMUT} \end{pmatrix}$$

- Input voltage u_s is given by user
- Calculation of current i_{CMUT} within time step integration

Results of Simulation



Results of Simulation



Potential for optimization of driving signal

Conclusion: Full Single Cell Simulation Tool

- Presented simulation:
 - Fast solved lumped model
 - Pays respect on electrical, mechanical and fluidic interaction
- Approximations in terms of:
 - In plane stress calculation
 - Boundary conditions
 - Electrical field in CMUT
- Results
 - Static deflection and pull-in analysis
 - Sound pressure on top of CMUT (self-radiation)
 - Plate deflection and radiated sound pressure in time domain

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Thank you!