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

Fraunhofer Institute for Photonic Microsystems IPMS, Dresden, Germany

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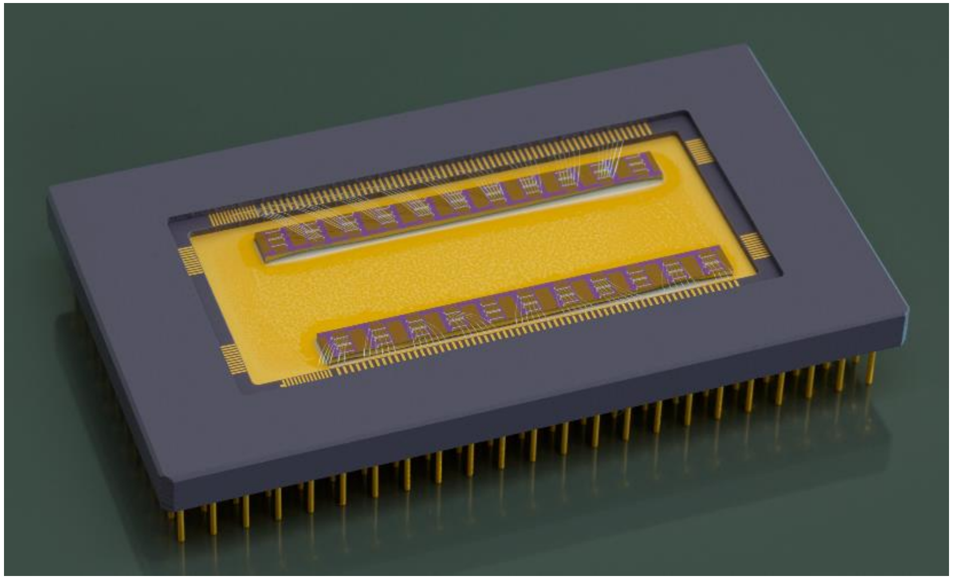
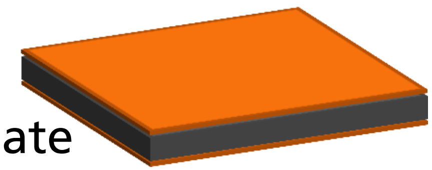
Outline

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

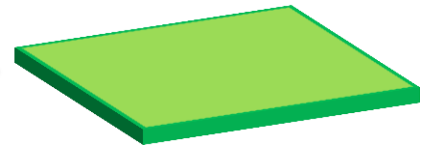


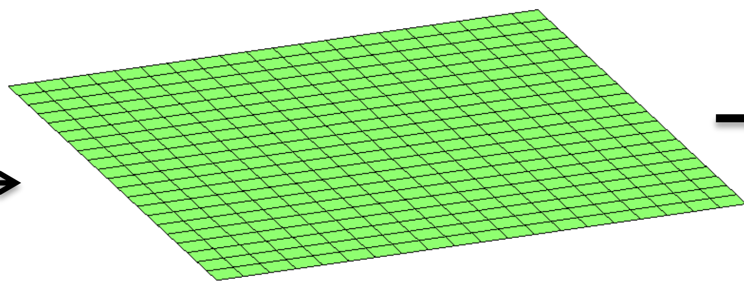
CMUT Mechanic Simulation Model

Material and geometry of plate

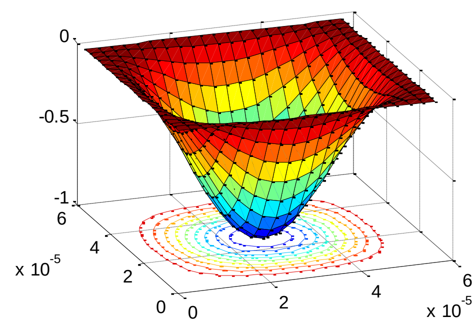


Abstraction to thin single plate [1]





2D-FE-Model



In-Plane-Stress leads to deflection without applied voltage

[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.

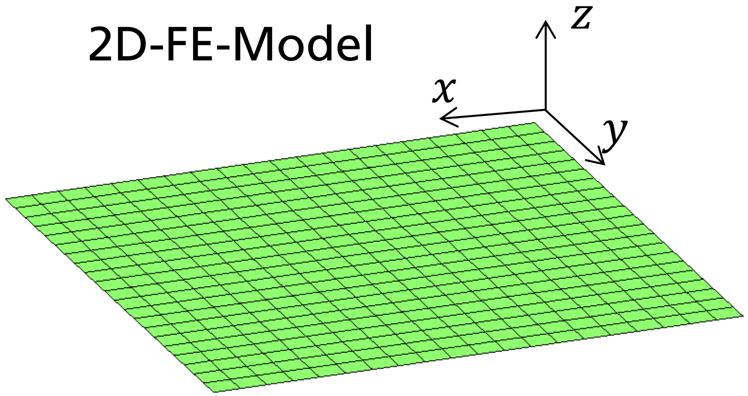
Static Analysis of Plate Deflection

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

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

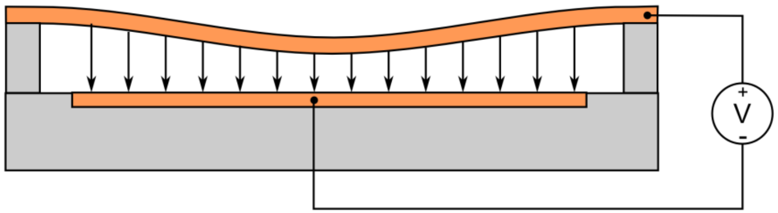
$$\mathcal{K}\begin{pmatrix} w_z \\ \sigma_x \\ \sigma_y \end{pmatrix} = \begin{pmatrix} F_z \\ F_x \\ F_y \end{pmatrix}$$

2D-FE-Model



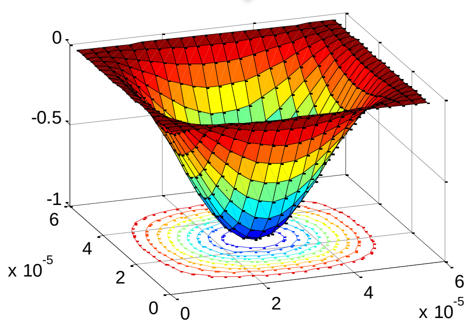
Design condition	Determined/ measured value	Information on
• Plate material • Plate size and thickness • Atmospheric pressure	In plane stress →	Initial deflection
	Centre deflection →	Residual stress

Static Analysis of Plate Deflection

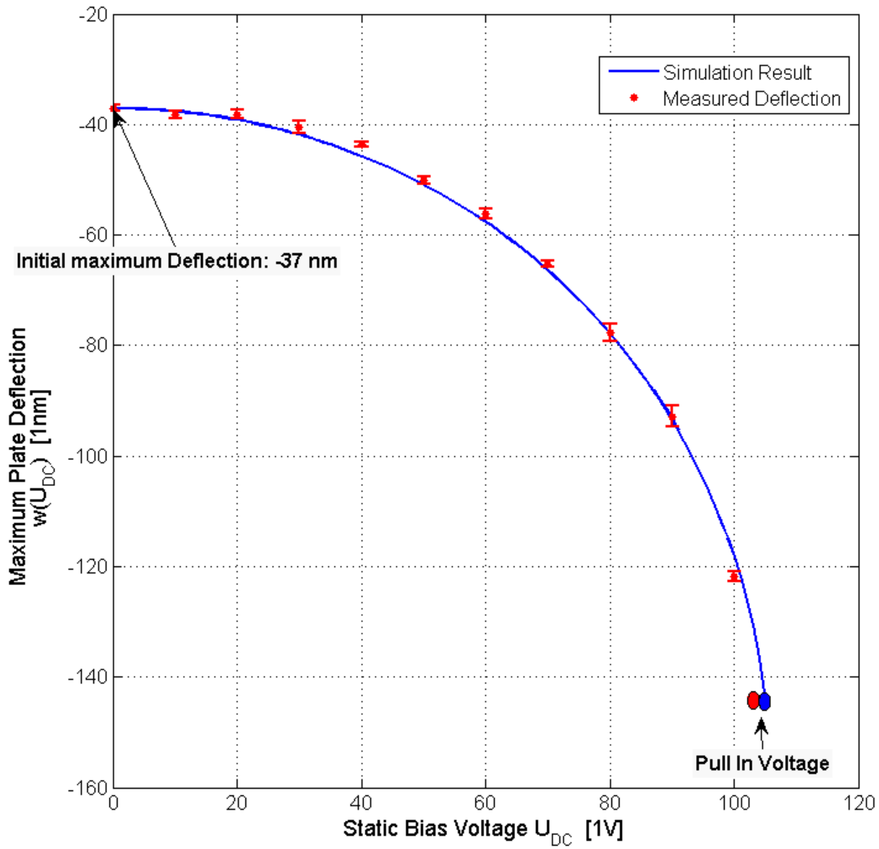


Elektrostatic Force

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



Static deflection $w(U_{DC})$



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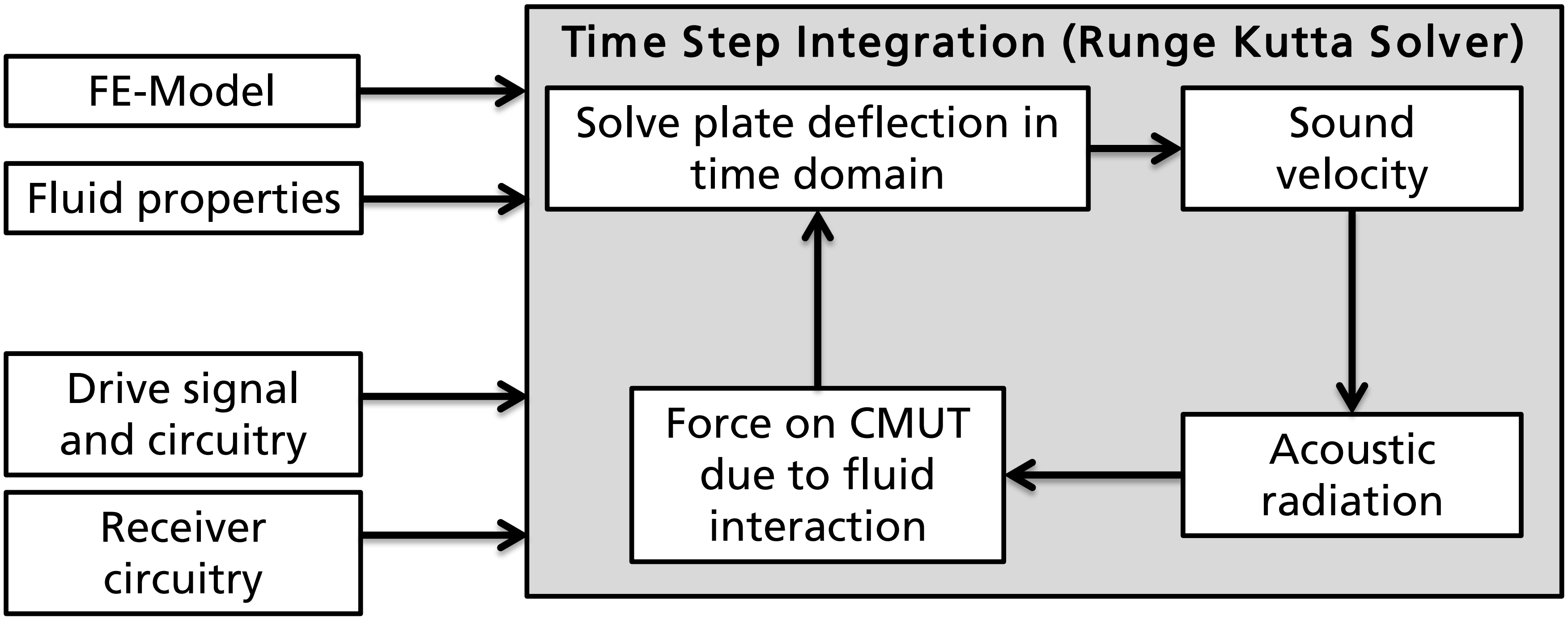
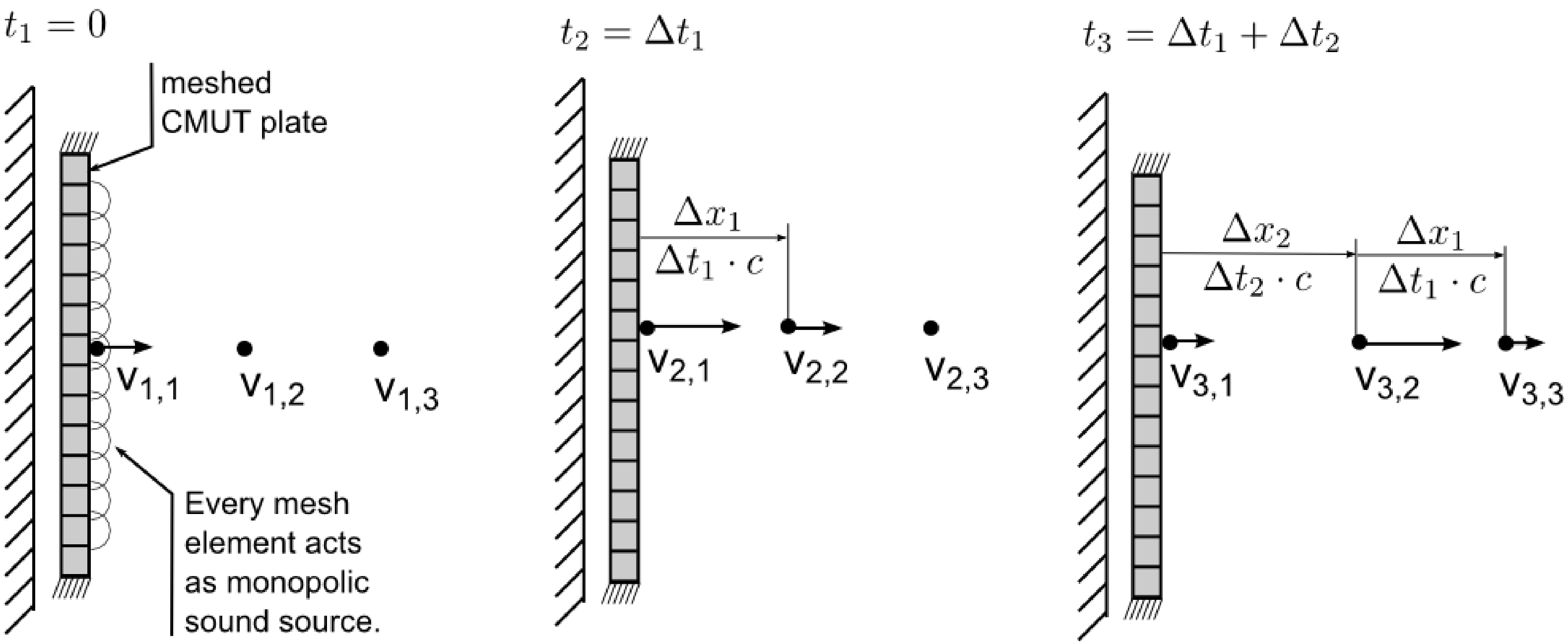
Dynamic Plate Simulation



Structure Fluid interaction



Near field of spheric wave:

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

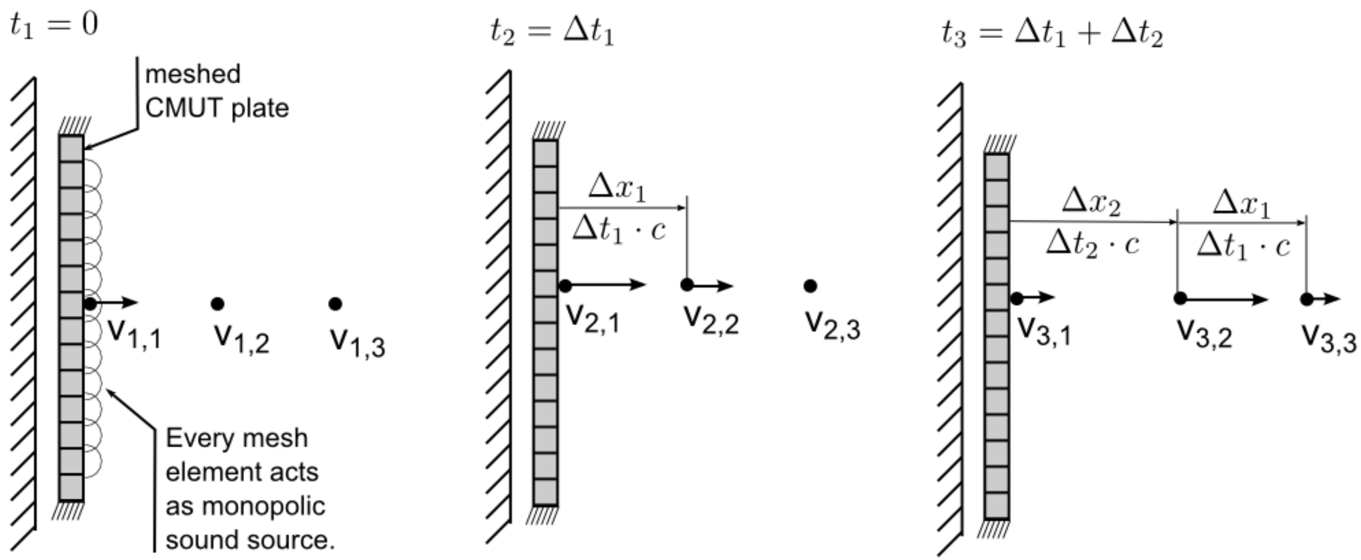
$$p_{2,2} = \frac{p_{1,1}}{\Delta x_1}$$

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:

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

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

→ Sound pressure at surface of CMUT in time domain

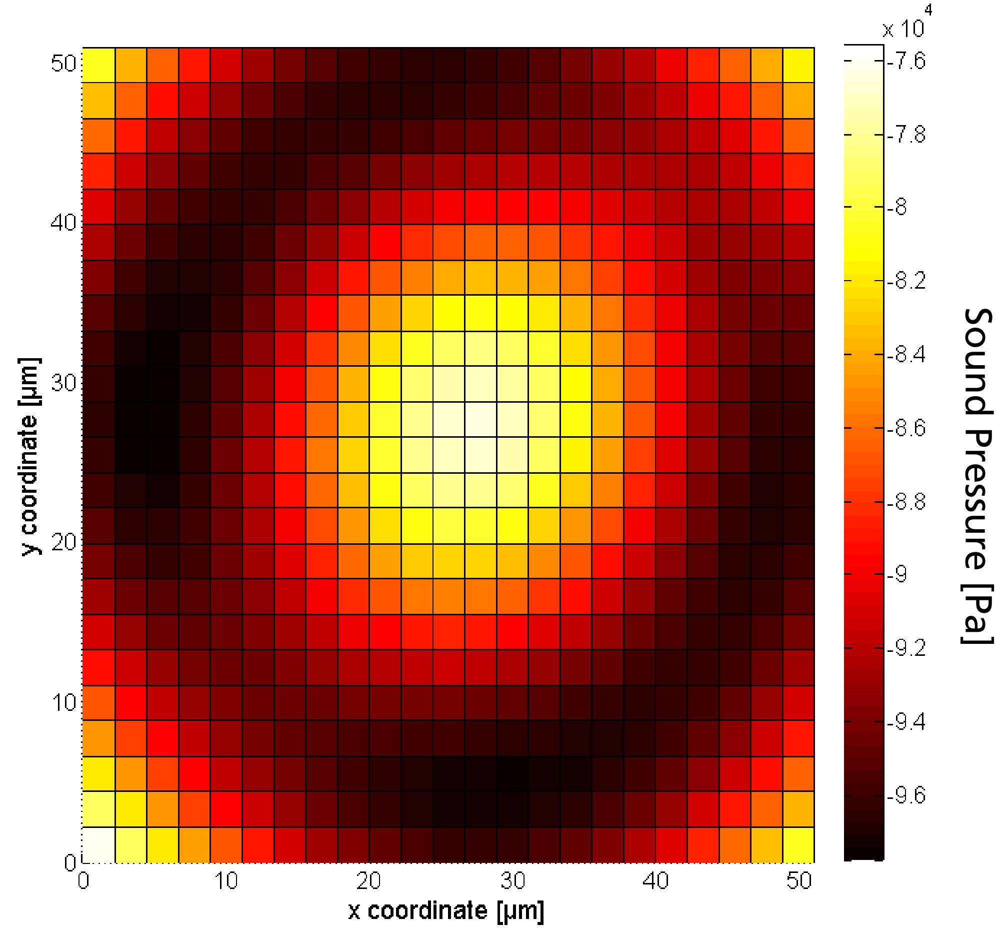
Structure Fluid interaction

Model covers:

- Simulation of sound pressure in front of a CMUT cell

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:

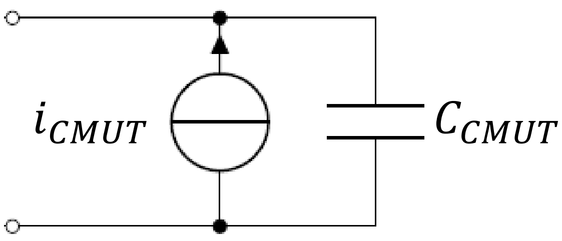
1. Charging of CMUT as Capacitor

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

2. Capacity Change of CMUT

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

Equivalent circuit of CMUT



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Values of interest:

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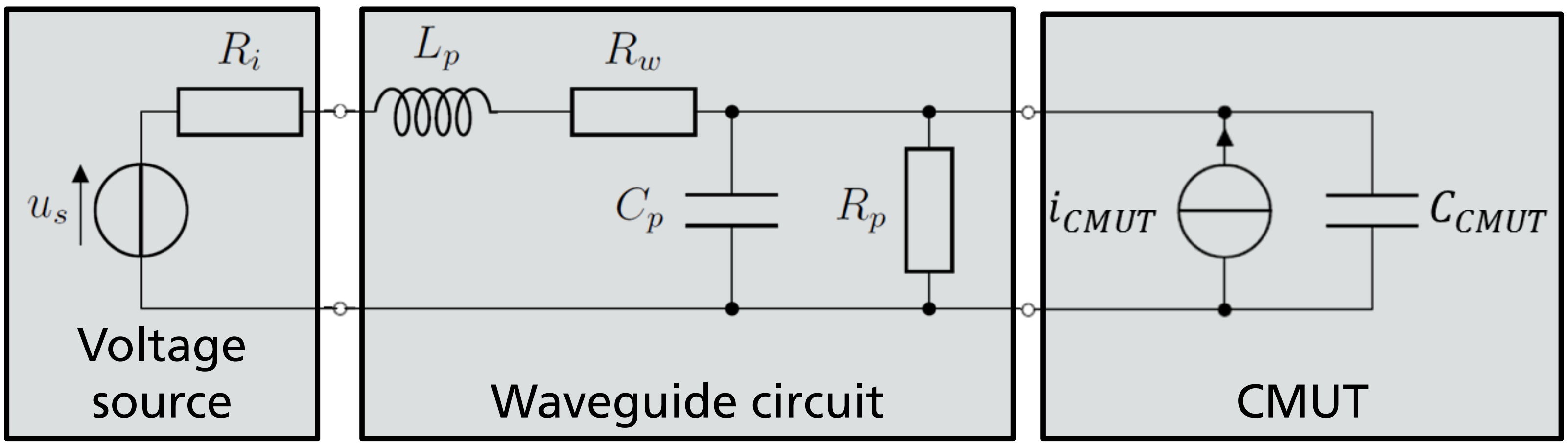
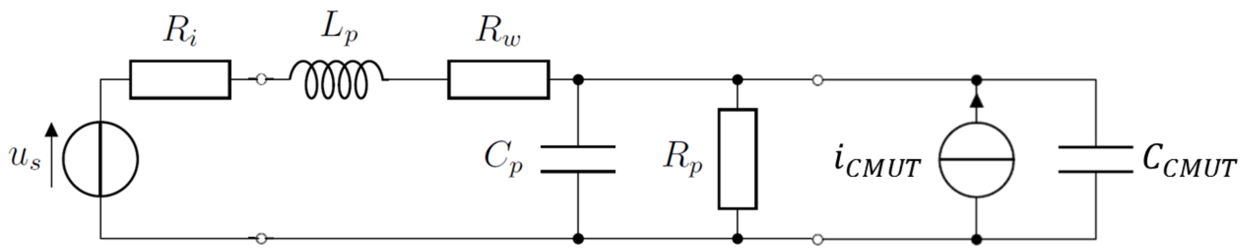


Influence of Electronics: State space representation



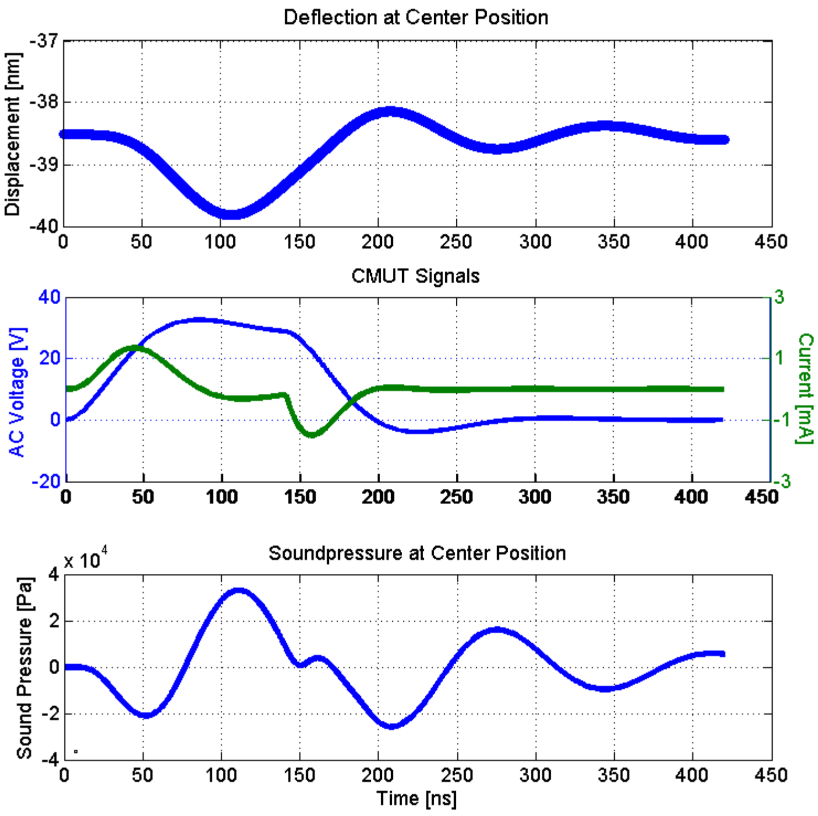
$$\frac{d\vec{z}}{dt} = A\vec{z} + B\vec{x}$$
$$\vec{x} = C\vec{z} + D\vec{x}$$

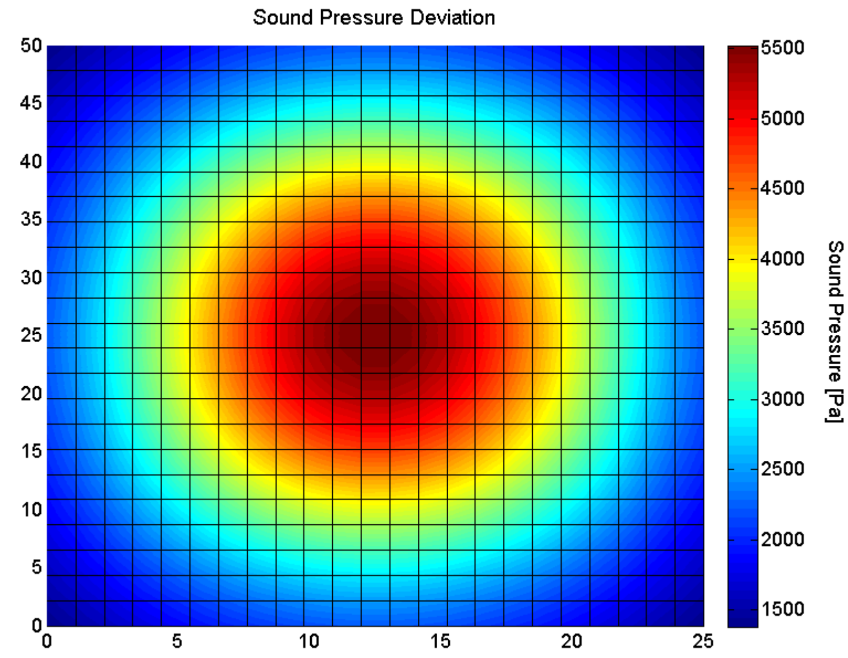
$$\vec{x} = \begin{pmatrix} i_{CMUT} \\ u_s \end{pmatrix}$$
$$\vec{y} = (u_{CMUT})$$
$$\vec{z} = \begin{pmatrix} i_s \\ u_{CMUT} \end{pmatrix}$$

- 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.

Results of Simulation





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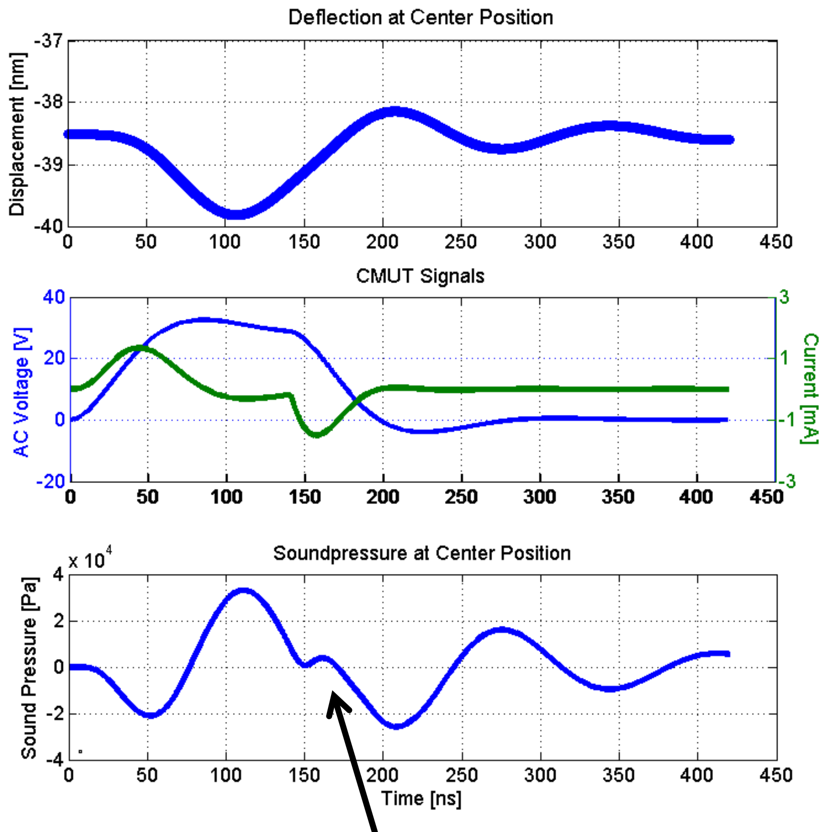

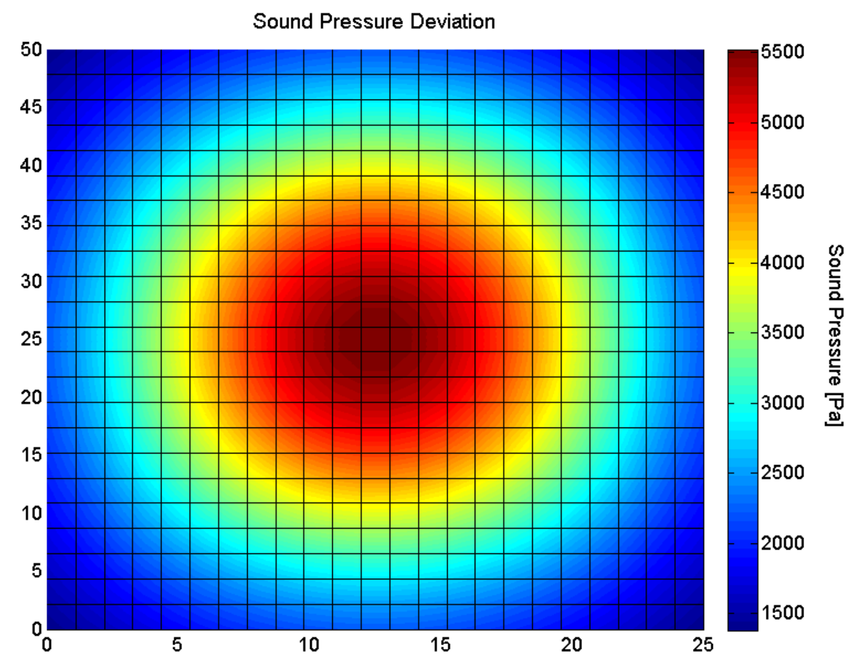

Potential for optimization of driving signal

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!