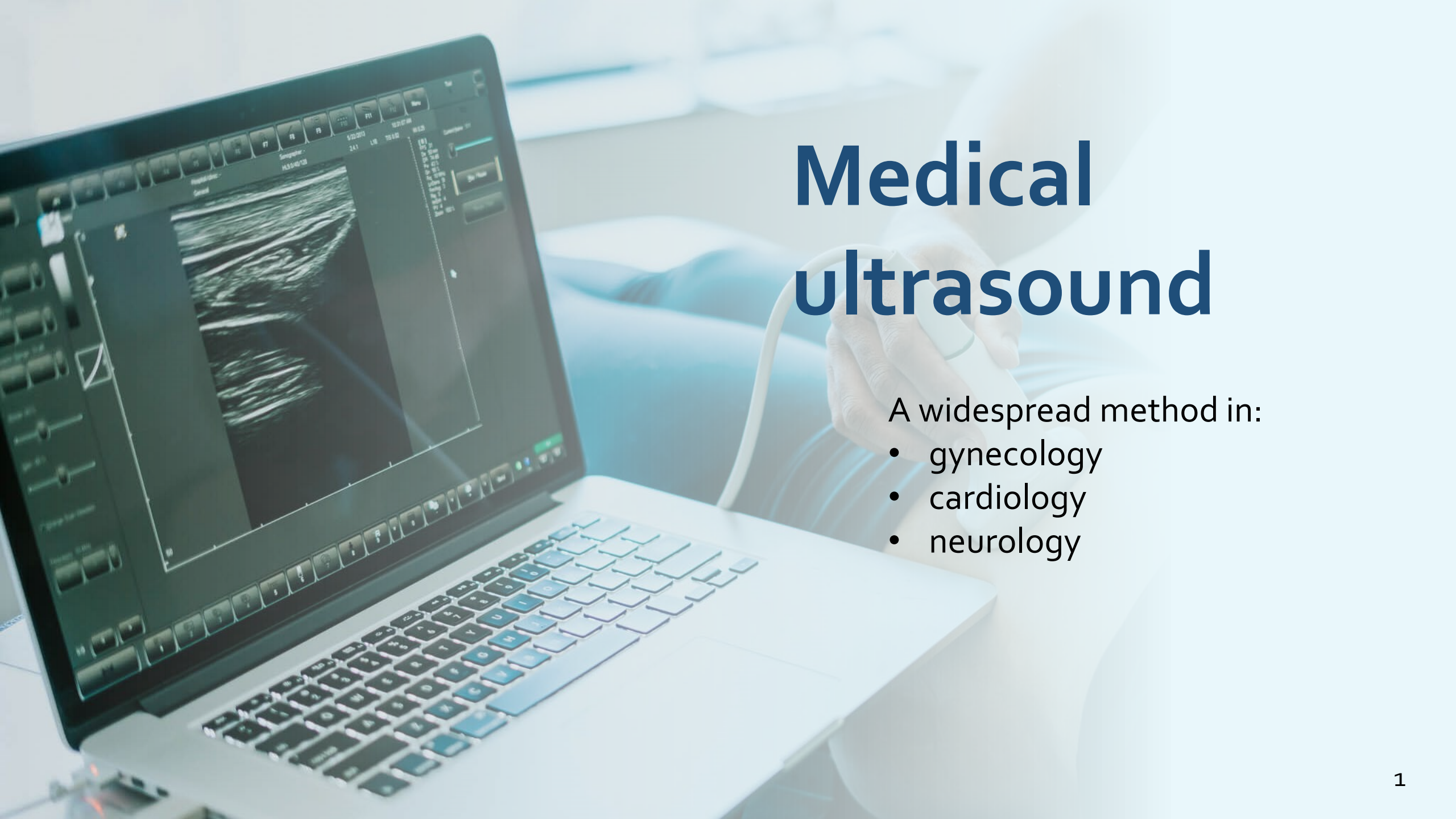
A fast and accurate tool for calculation of characteristics of Capacitive Micromachined Ultrasound Transducers (CMUT)

Biriukov Anton, 1-year PhD student
at Skolkovo Univeristy of Science and Technology

Skoltech

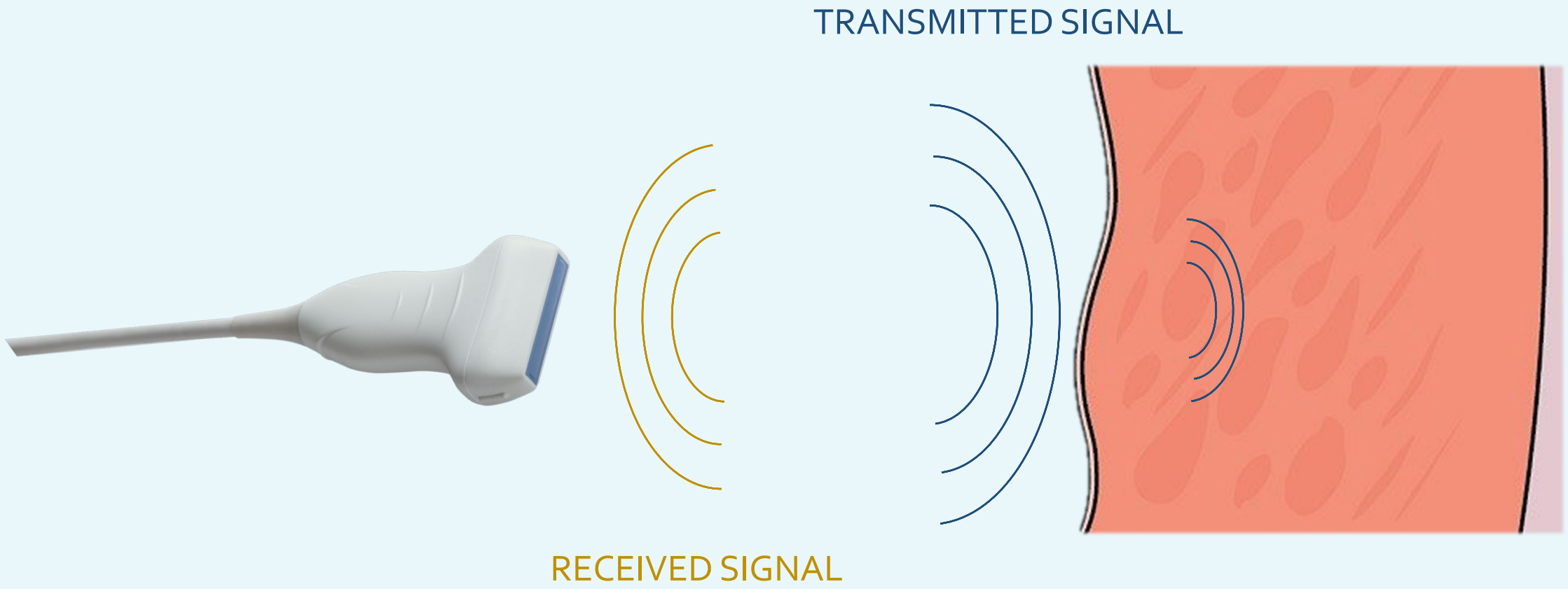


Medical ultrasound

A widespread method in:

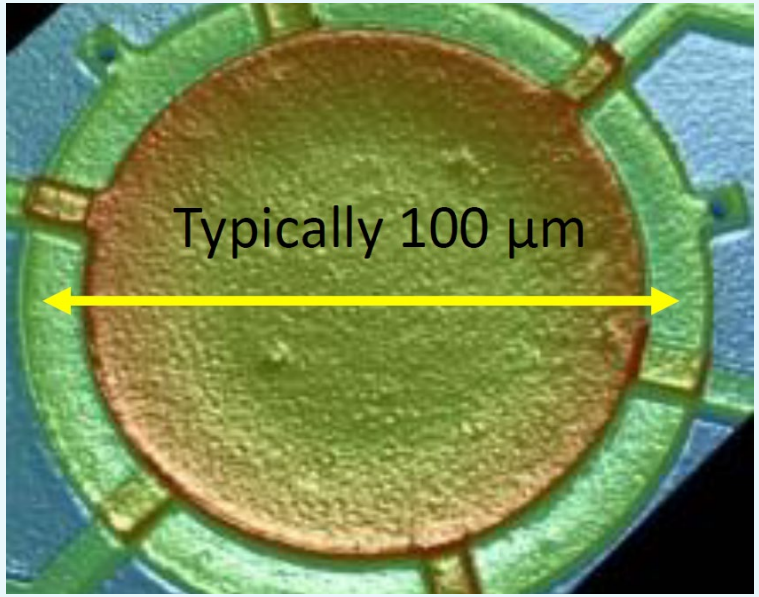
- gynecology
- cardiology
- neurology

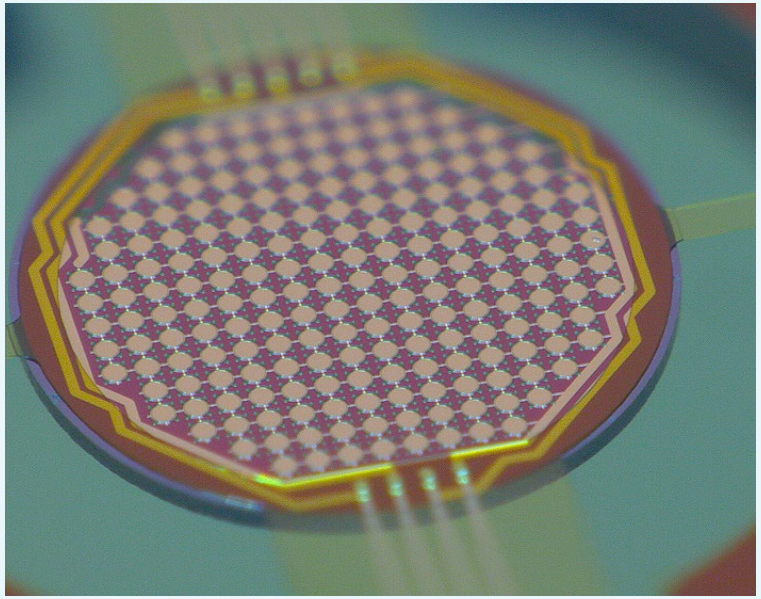
Principle of work

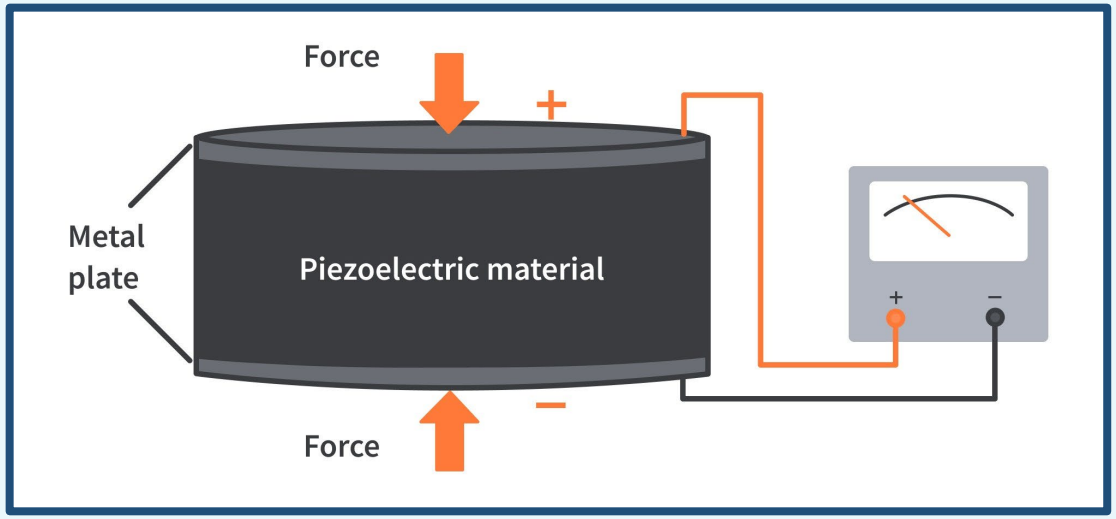


New type

CMUT – capacitive micromachined ultrasound transducers

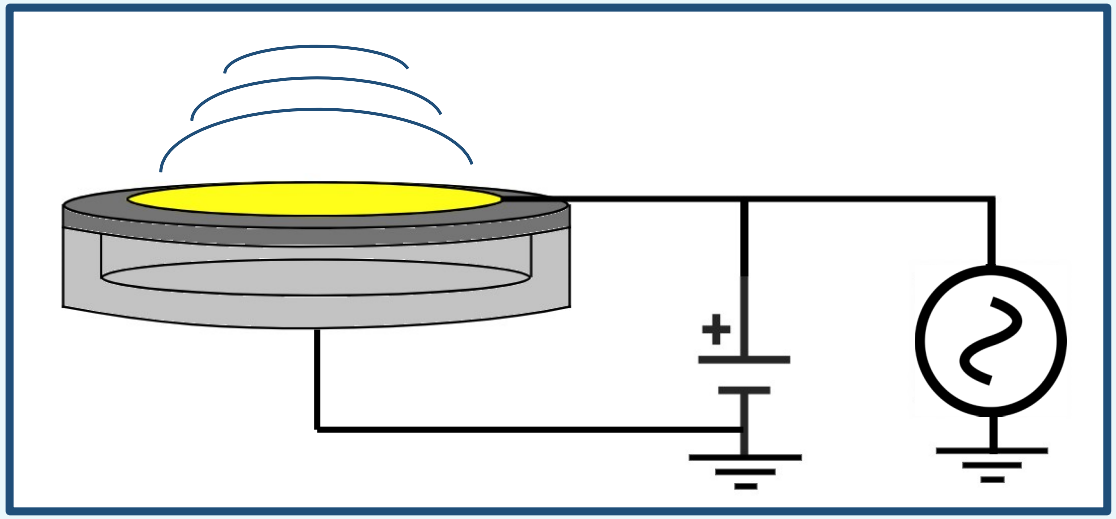


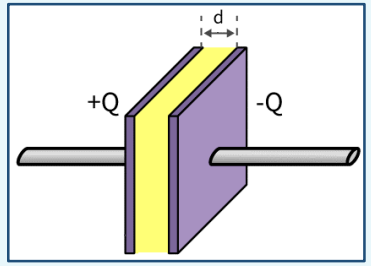




Piezoelectric transducers

- Provide great resolution
- Require high AC voltage (80 – 100 V)
- Hard to integrate into electric circuits

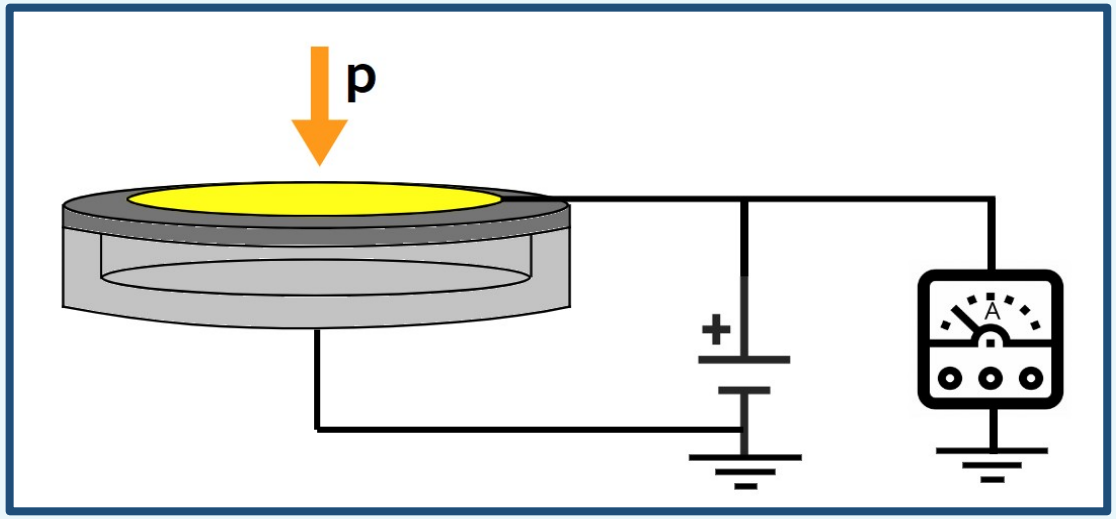




$$F_{Coulomb} = -k\frac{Q_1 Q_2}{d^2}$$

Electrostatic transducers

- Have better linearity
- Have low cost of manufacturing
- Can be easily integrated into electric circuits



Electrostatic transducers

$$I = \frac{\partial Q}{\partial t} = \frac{\partial C}{\partial t} V, \qquad V = const$$

- Have better linearity
- Have low cost of manufacturing
- Can be easily integrated into electric circuits

Development process

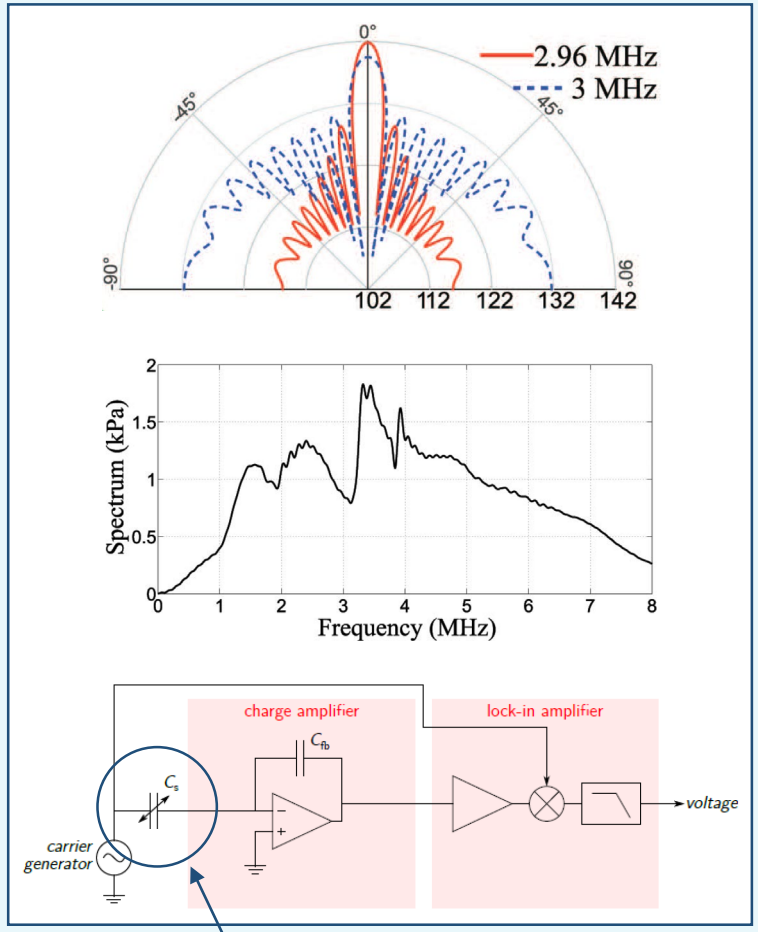
- Specification
- Technical requirements
- **Concept design**
- **Detailed design**
- …

Transducer's parameters:

- Type
- Shape
- Amount
- Width, thickness, …
- Material, etc

Important characteristics

A tool to calculate performance of the product



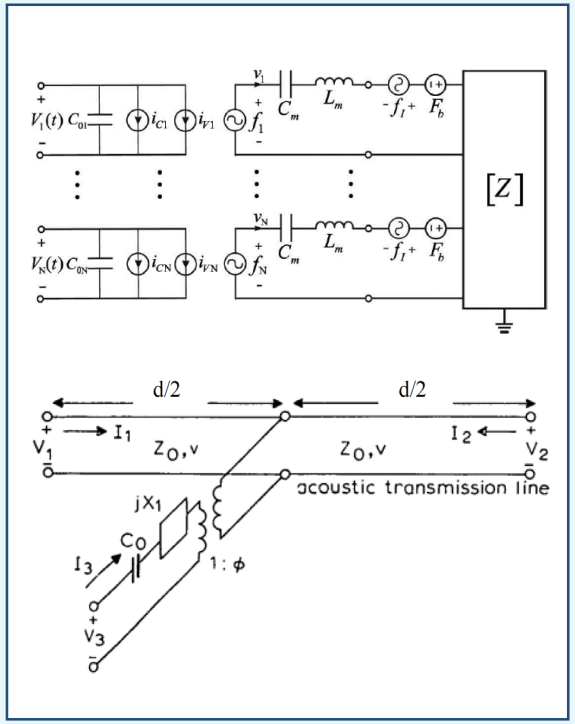
RADIATION PATTERN

FREQUENCY RESPONSE

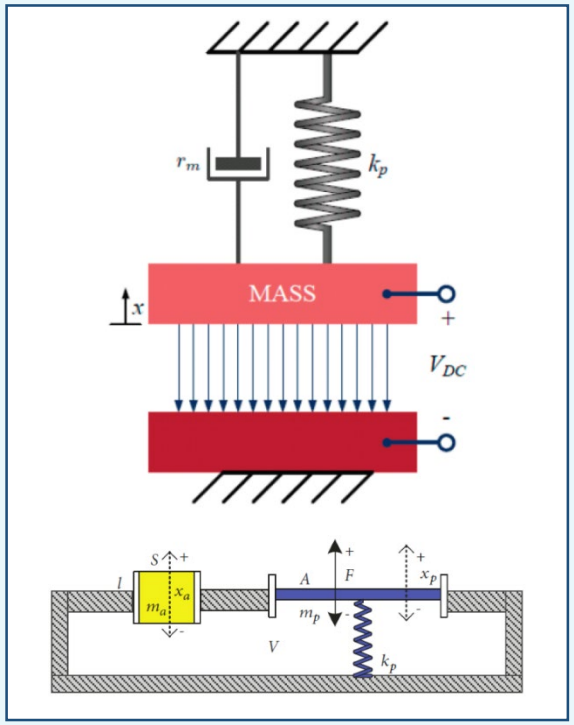
NOMINAL CAPACITANCE, IMPEDANCE, ETC.

Transducer representation

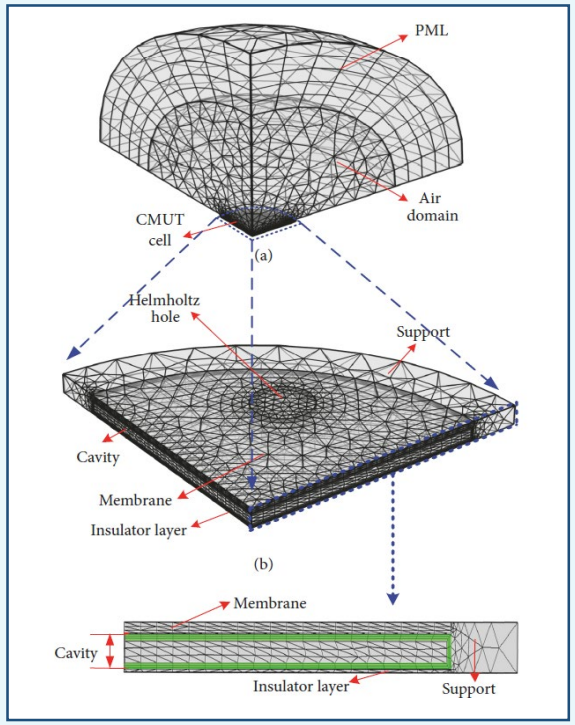
Existing methods



Equivalent circuit



Mass-Spring-Damper system



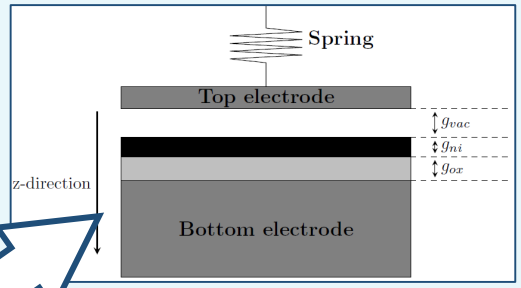
Finite elements

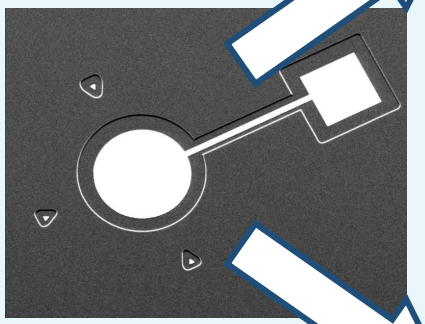
Hayrettin K¨oymen H. Kagan Oguz, ; Abdullah Atalar. Equivalent circuit-based analysis of CMUT cell dynamics in arrays. Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 60(5):1016 – 1024, 2013.

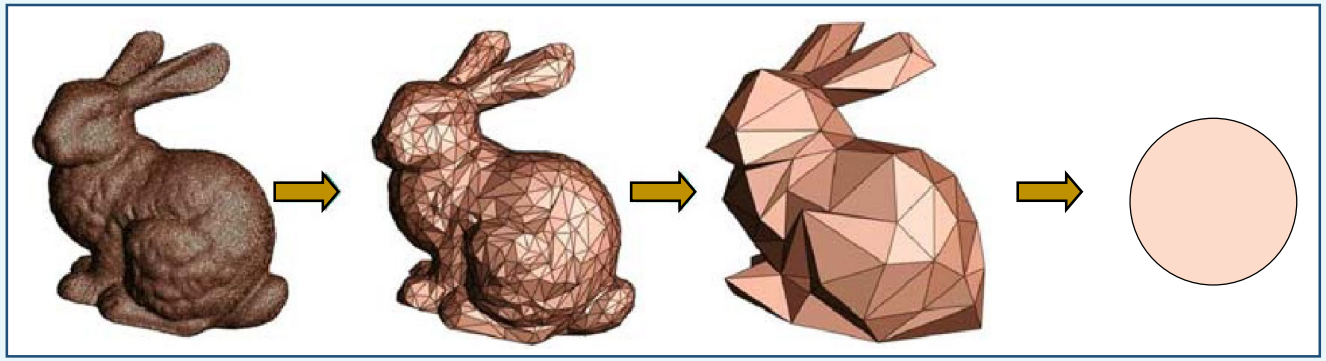
1D methods

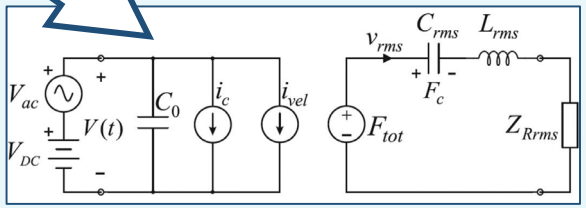
Electrostatic transducer

Mass-Spring-Damper





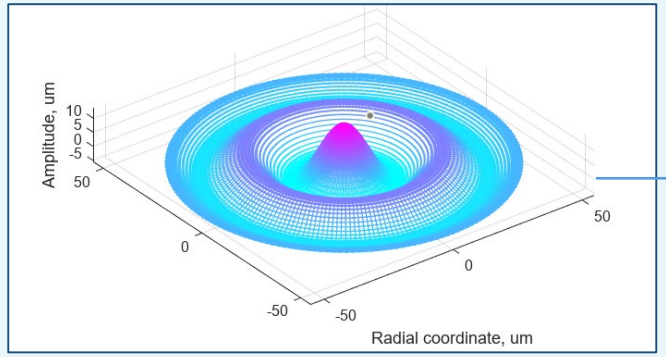


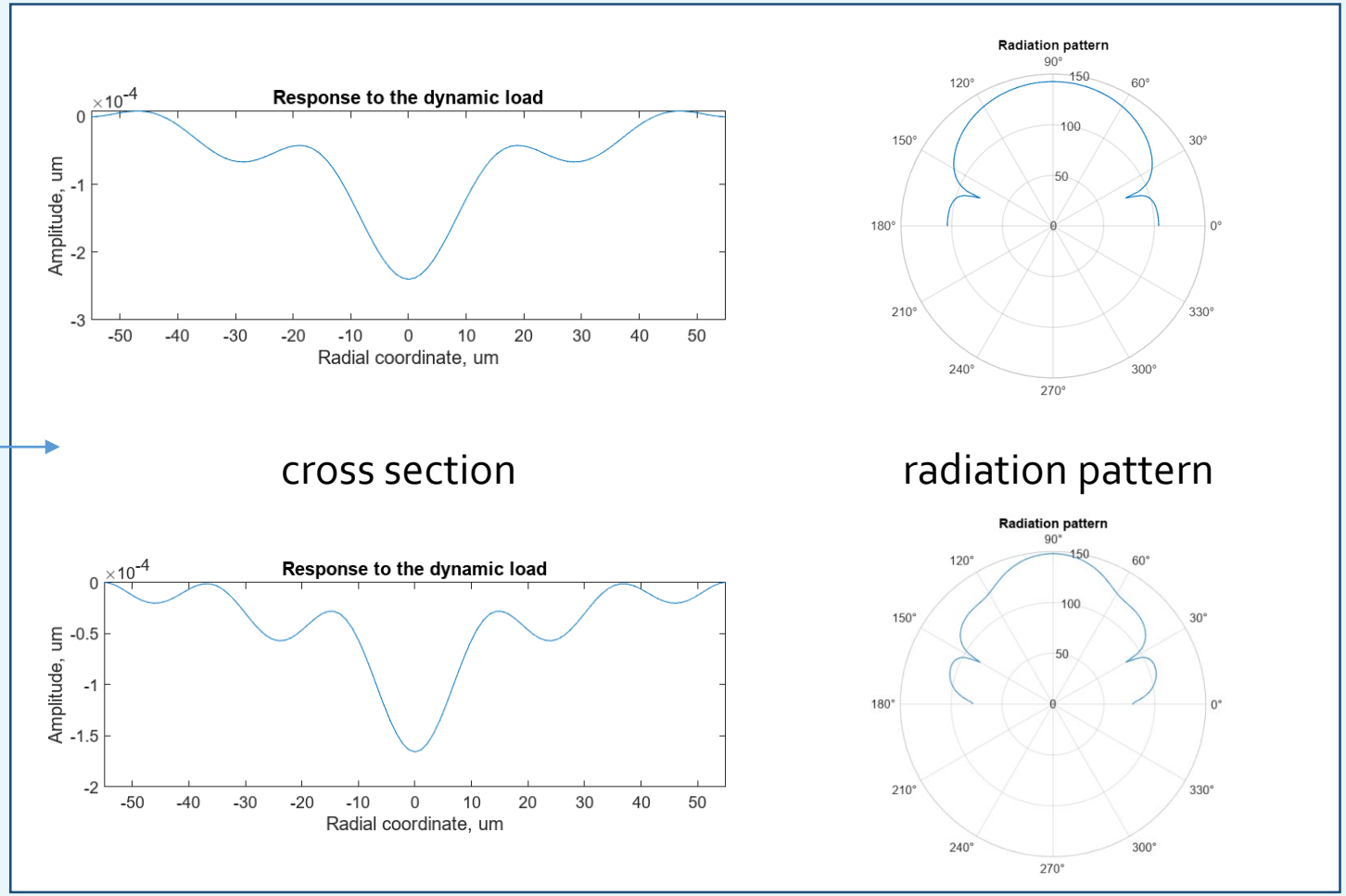


Equivalent circuit

Mette Cour, Thomas Christiansen, Jorgen Jensen, and Erik Thomsen. Electrostatic and small signal analysis of CMUTs with circular and square anisotropic plates. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 62:1563–1579, 08 2015

Considering dependency on coordinate

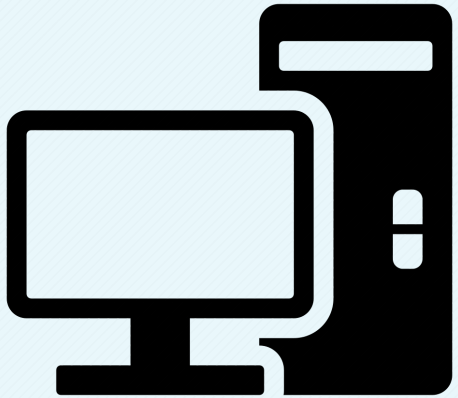




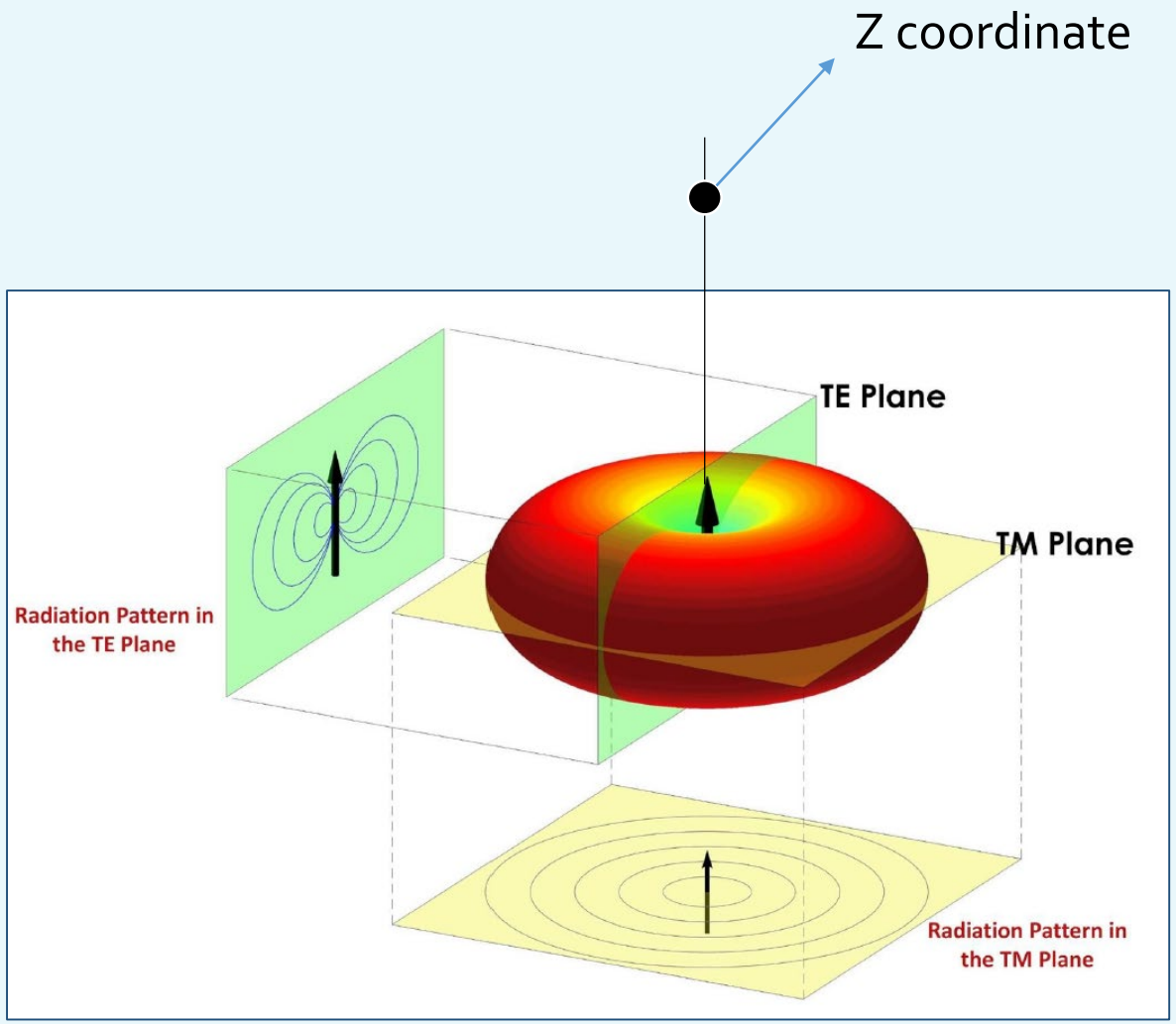
Challenge

Desired geometrical and physical parameters
(size, material, number of transducers, etc…)

Calculated characteristics
(frequency response, radiation pattern)

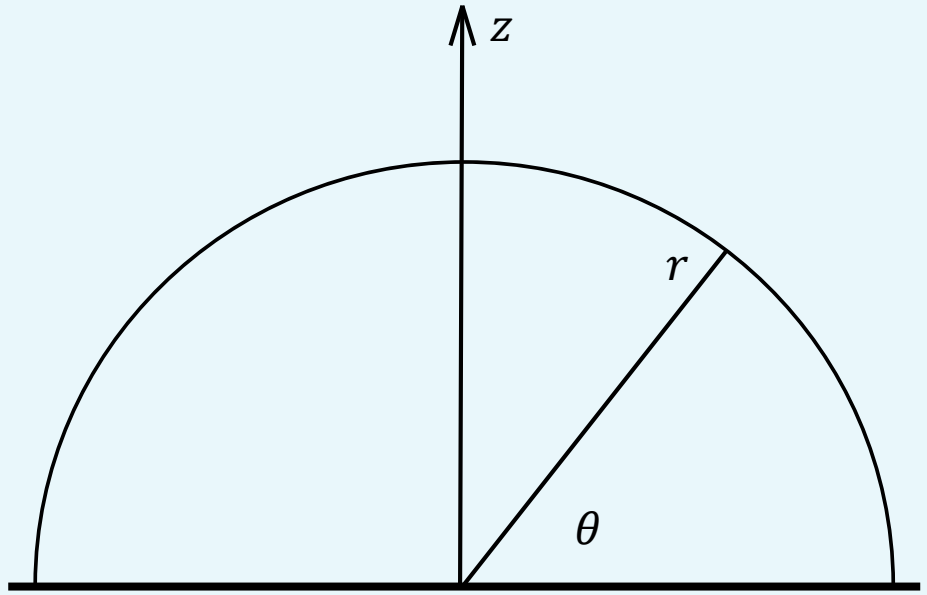


Acoustic field



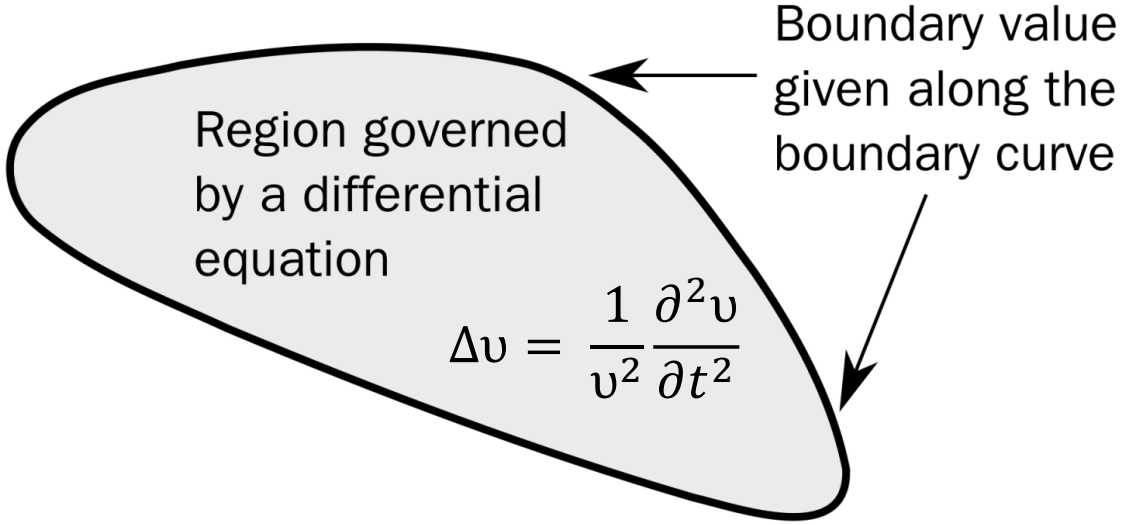
CHARACTERISTICS TO BE CALCULATED

- Radiation pattern: $\mathrm{p} = f(r, \theta)$
- Frequency response: $\mathrm{p} = f(z, \omega)$



Rayleigh integral

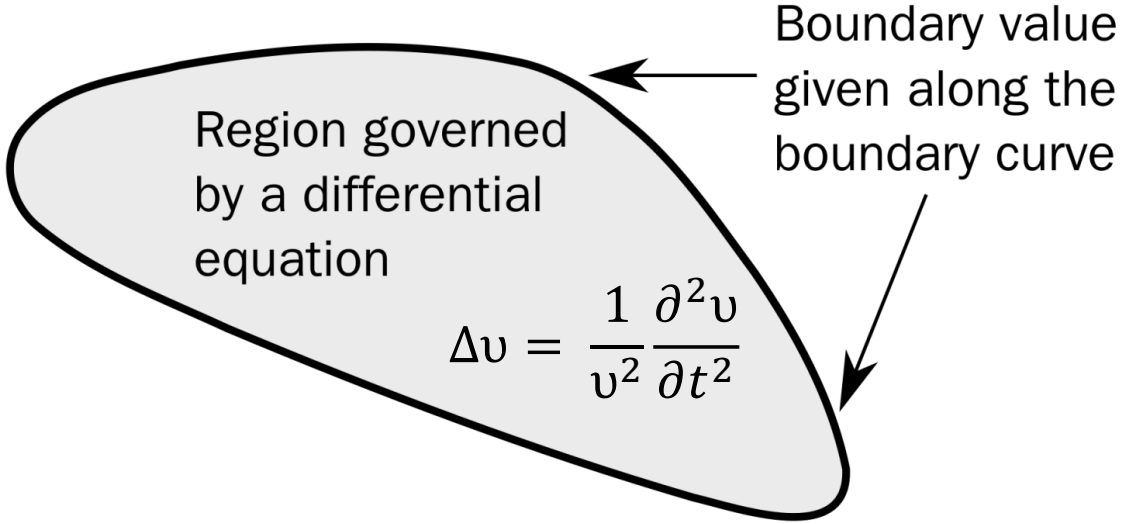
RAYLEIGH INTEGRAL GIVES A KNOWN FIELD AT ANY POINT



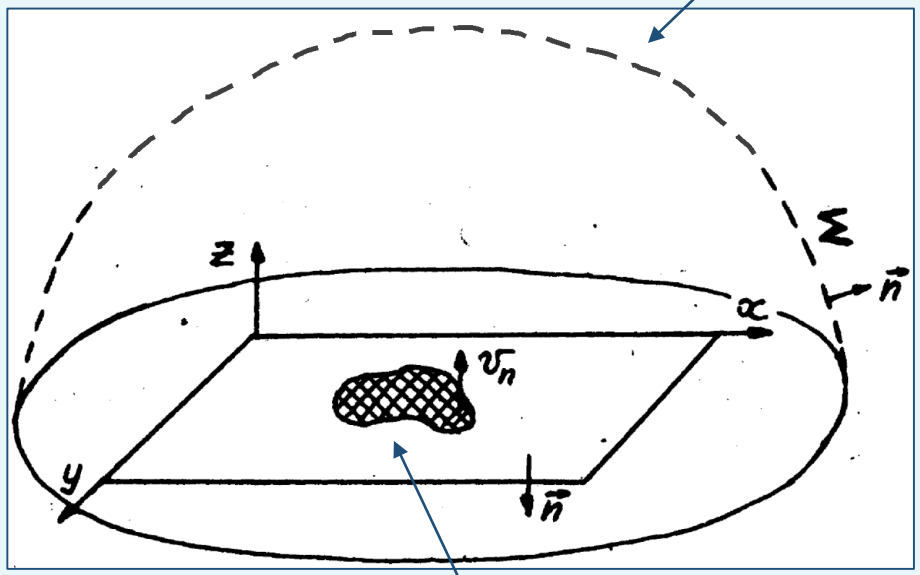
$$\phi(z) = -\frac{1}{2\pi}\int_S \vec{v}_n \frac{e^{ik|\vec{z}-\vec{z'}|}}{|\vec{z}-\vec{z'}|} d\vec{z'}$$

Rayleigh integral

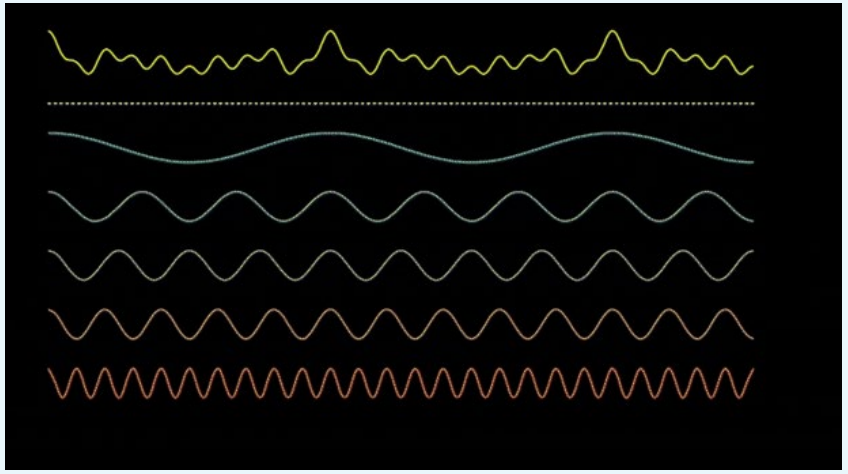
RAYLEIGH INTEGRAL GIVES A KNOWN FIELD AT ANY POINT



$$\phi(z) = -\frac{1}{2\pi}\int_S \vec{v}_n \frac{e^{ik|\vec{z}-\vec{z'}|}}{|\vec{z}-\vec{z'}|} d\vec{z'}$$

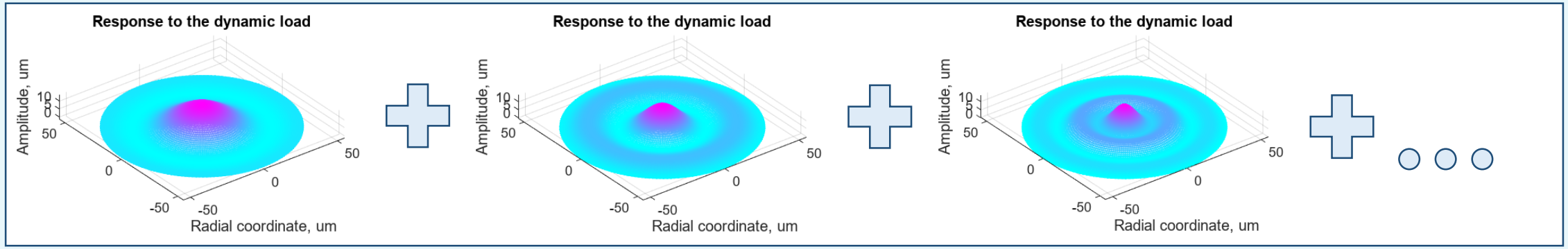


Superposition mode

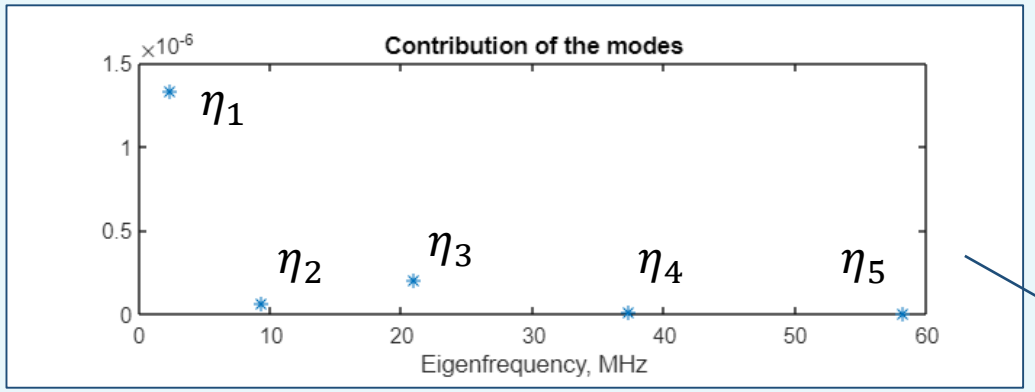


Fourier transform allows to represent an arbitrary signal as a sum of orthogonal functions

$$f(t) = c_0 + \sum_{k=1}^{\infty} c_k \cos(k\omega_0 t + \theta_k) \qquad u(x_j, t) = \sum_{k=1}^{\infty} u_k(x_j)\eta_k(t)$$



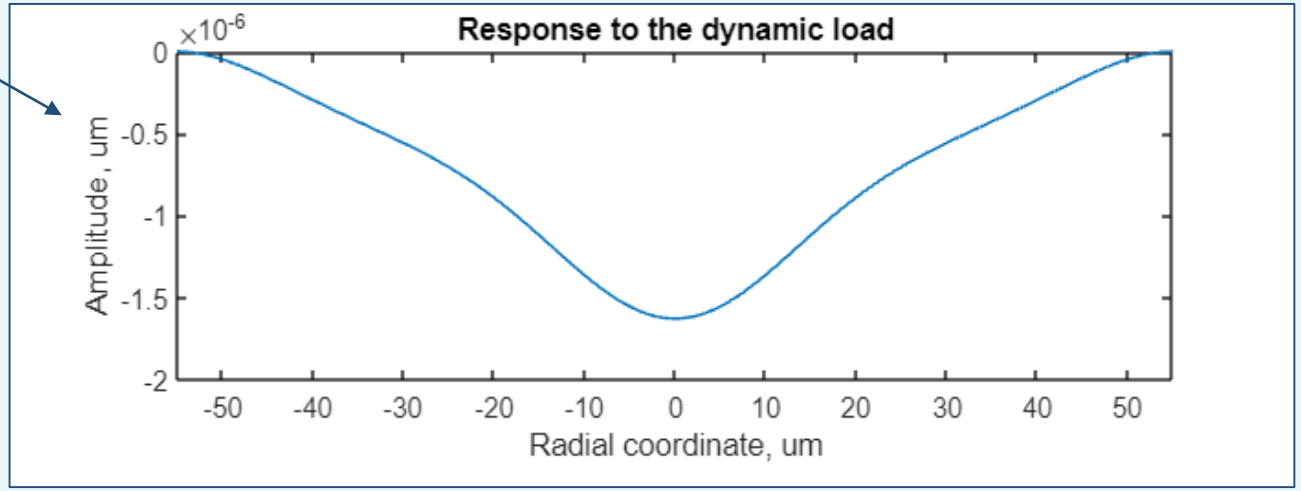
Superposition mode



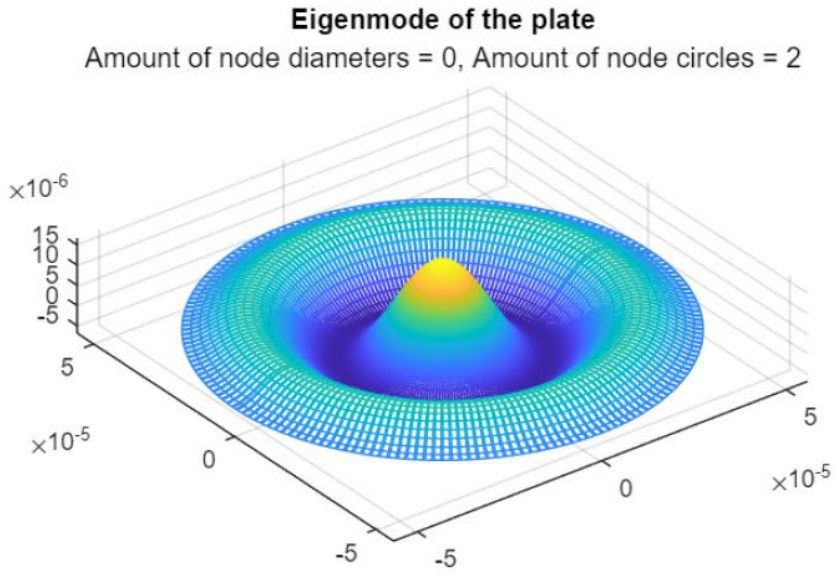
$$\mathbf{u}(x_j,t) = \sum_{s=1}^{\infty} \mathbf{u}_s(x_j)\eta_s(t)$$

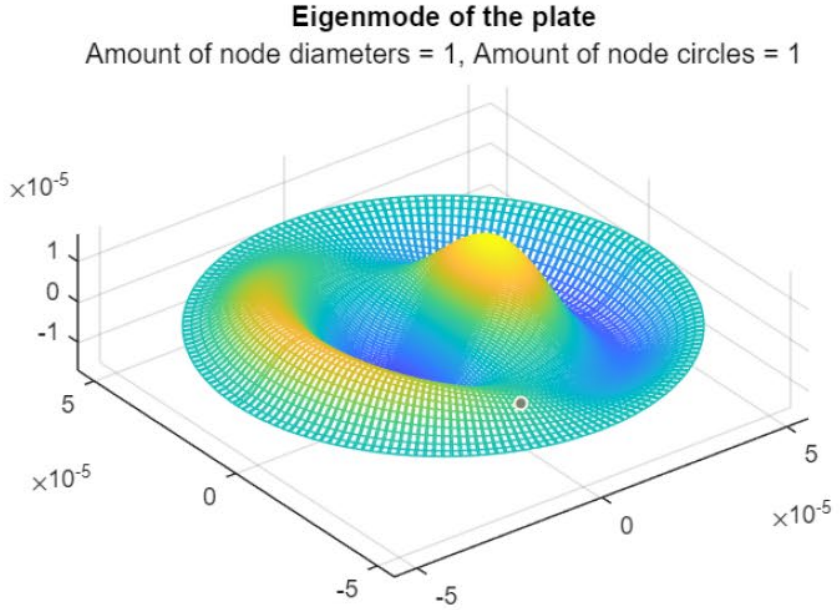
$$\omega_r^2\eta_r + \ddot{\eta}_r = \phi_r$$

$$\phi_r = \int_V \mathbf{u}_r^T \overline{\mathbf{X}} dV$$



Eigenvalue problem





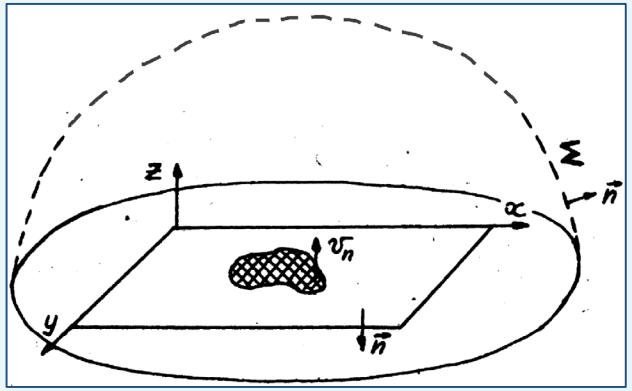
$$w_k(r,\theta) = (J_k(\beta r) - \frac{J_k(\beta a)}{I_k(\beta a)} I_k(\beta r))\,(A_{1k} sin(k\theta) + A_{2k} cos(k\theta))$$

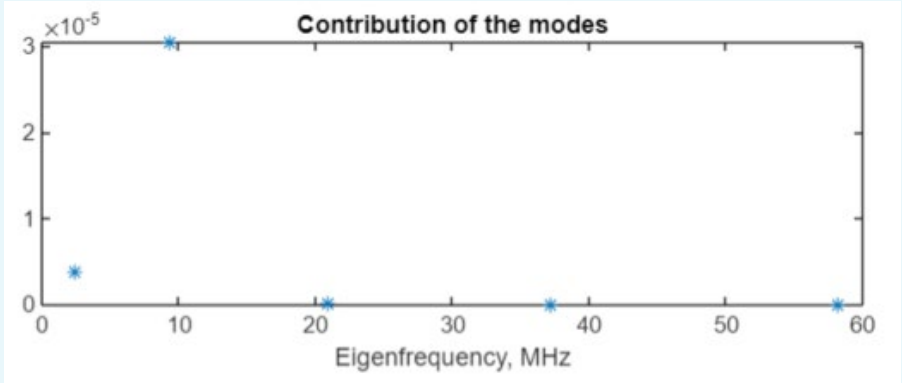
Program based on a methodology

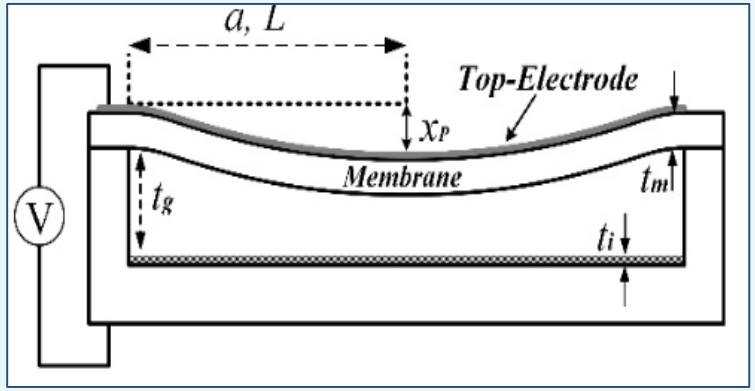
RAYLEIGH INTEGRAL

SUPERPOSITION MODE

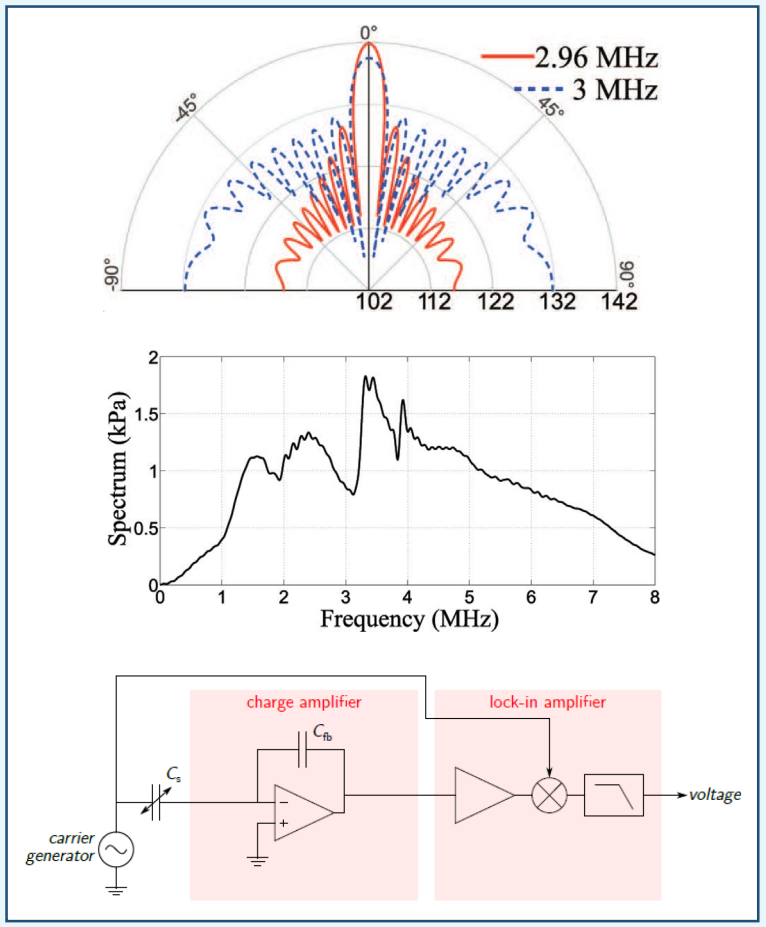
CAPACITOR REPRESENTATION



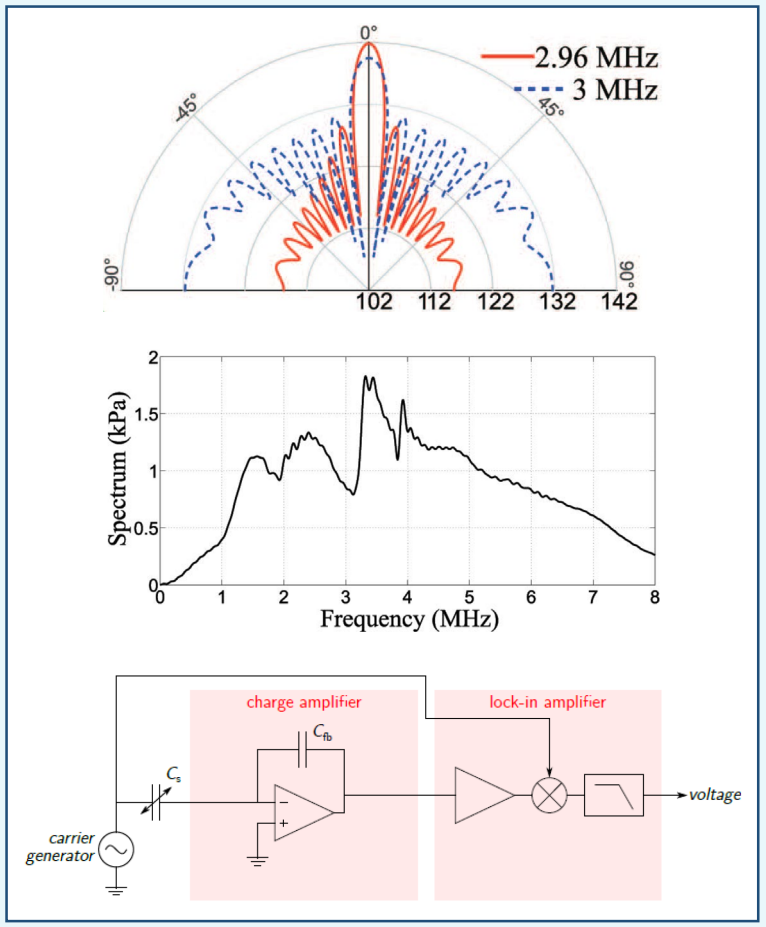


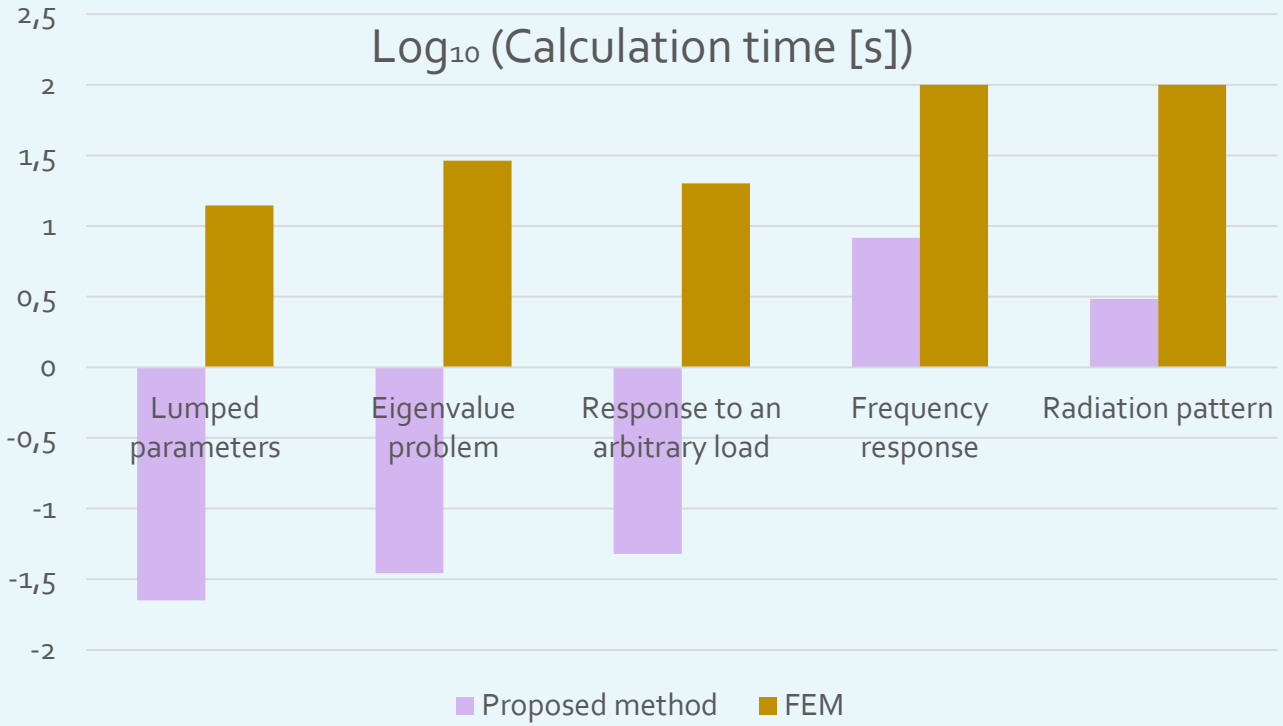


Validation

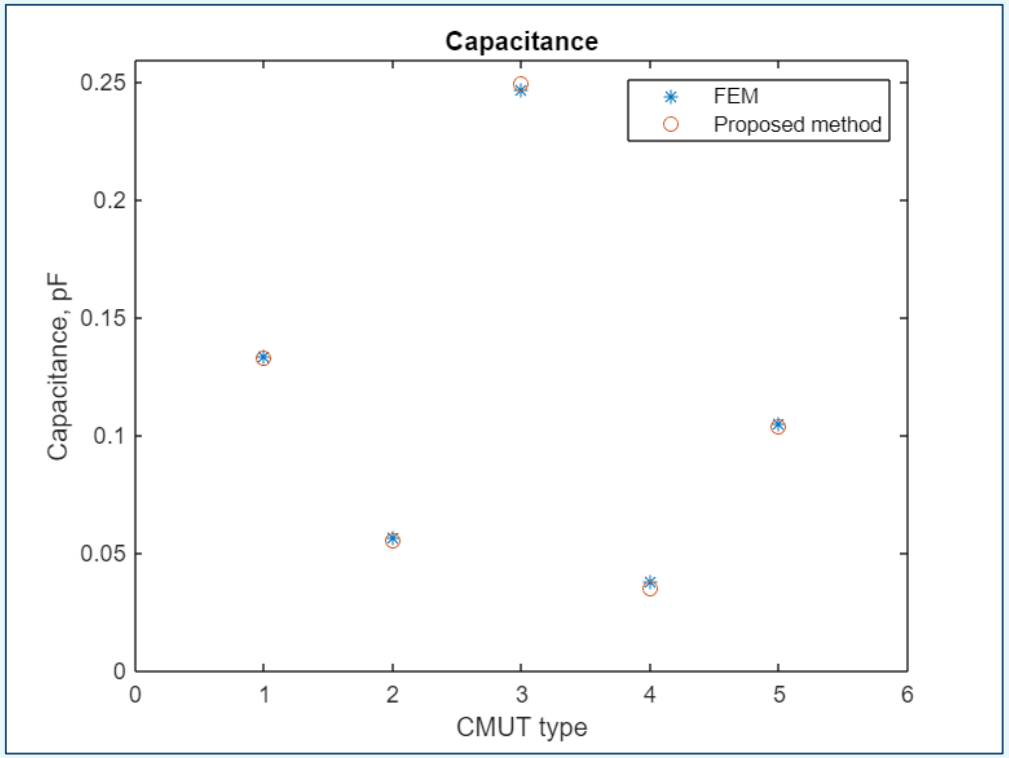

0°
2.96 MHz
3 MHz
45°
45°
-90°
90°
102 112 122 132 142
Spectrum (kPa)
Frequency (MHz)
charge amplifier
lock-in amplifier
C_{fb}
C_s
carrier generator
voltage

Validation

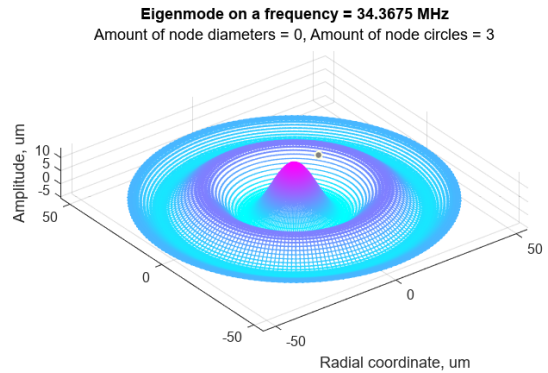

0°
2.96 MHz
3 MHz
-45°
45°
-90°
90°
102 112 122 132 142
Spectrum (kPa)
Frequency (MHz)
charge amplifier
lock-in amplifier
C_{fb}
C_s
carrier generator
voltage


Log10 (Calculation time [s])
2,5
2
1,5
1
0,5
0
-0,5
-1
-1,5
-2
Lumped parameters
Eigenvalue problem
Response to an arbitrary load
Frequency response
Radiation pattern
Proposed method
FEM

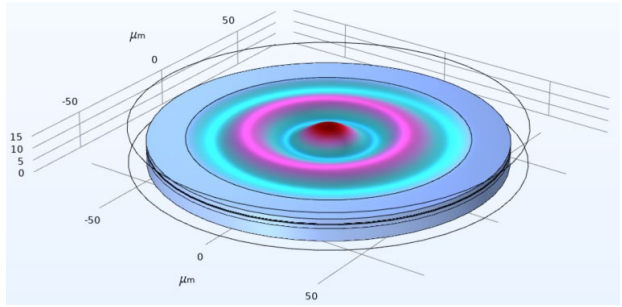
Verification



Five transducers with random geometrical parameters were created

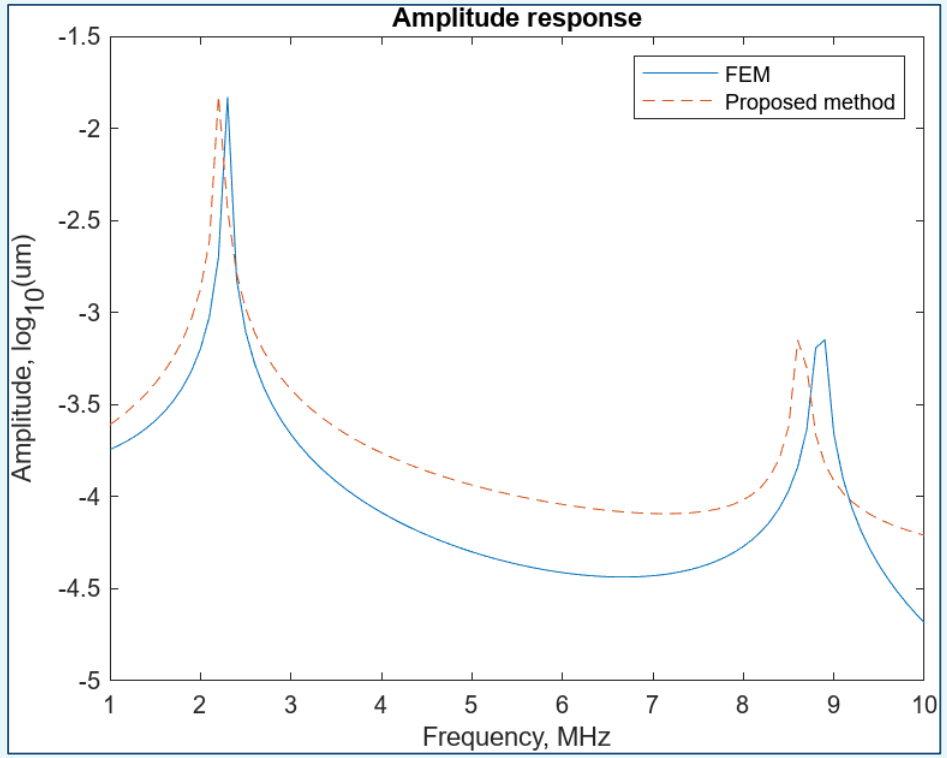


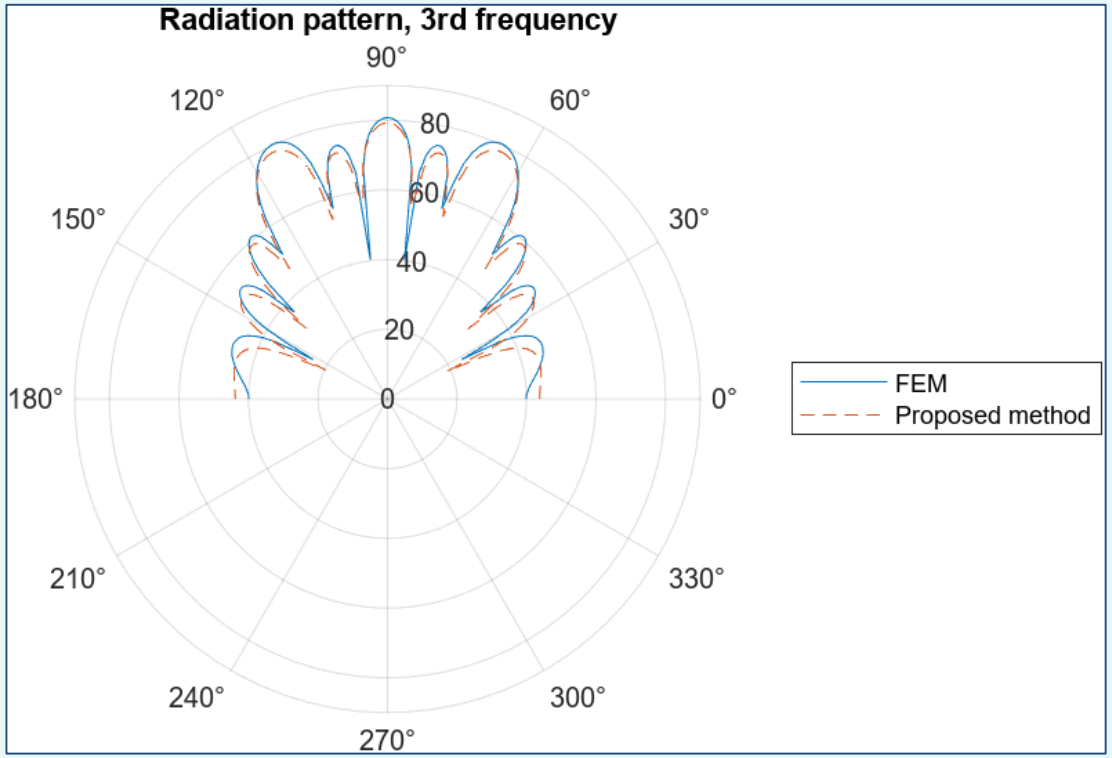
Proposed method
34.3675 MHz



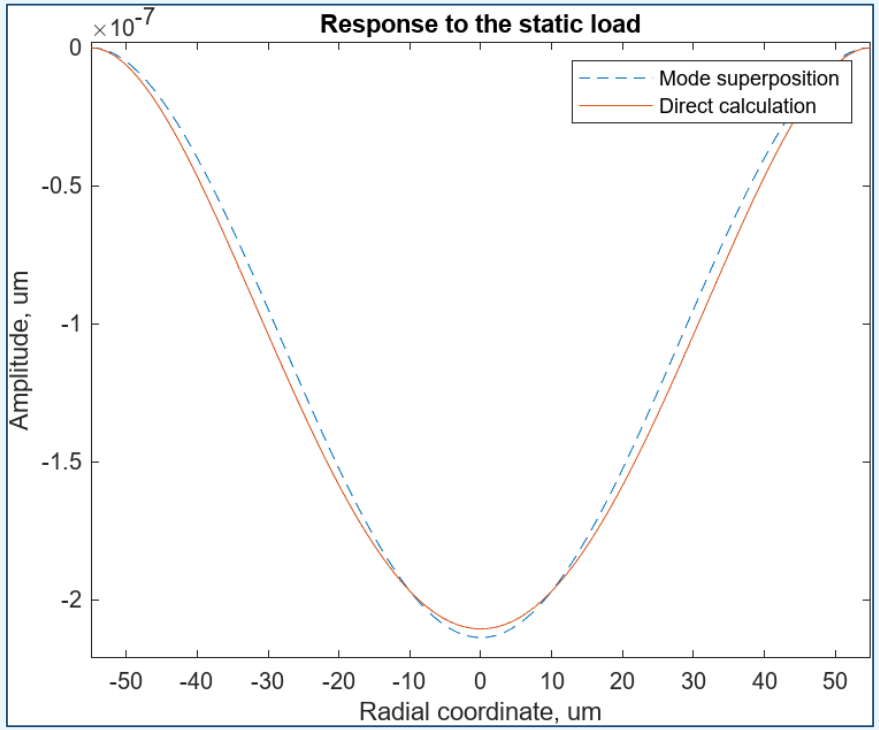
Finite Elements Method
34.395 MHz

Verification

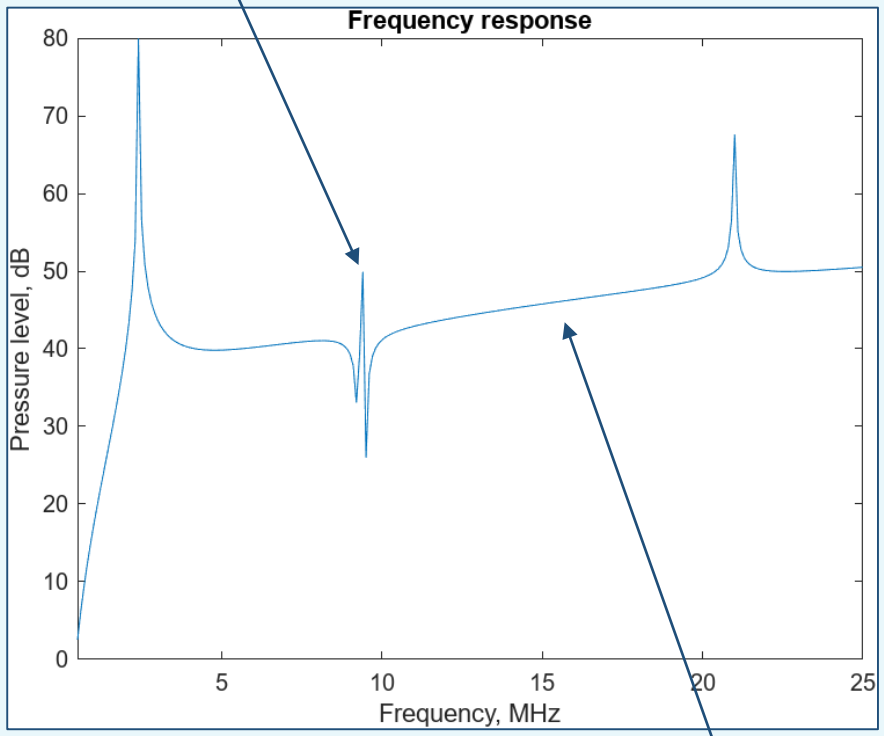




Verification

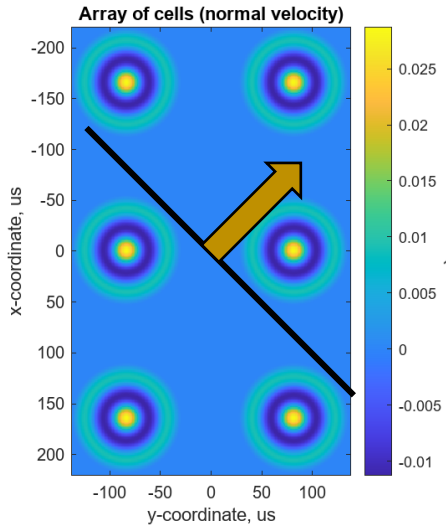


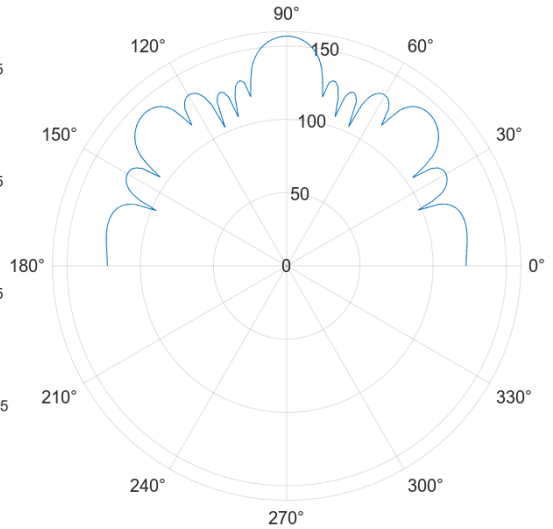
Characteristic peaks of a system with a high quality factor

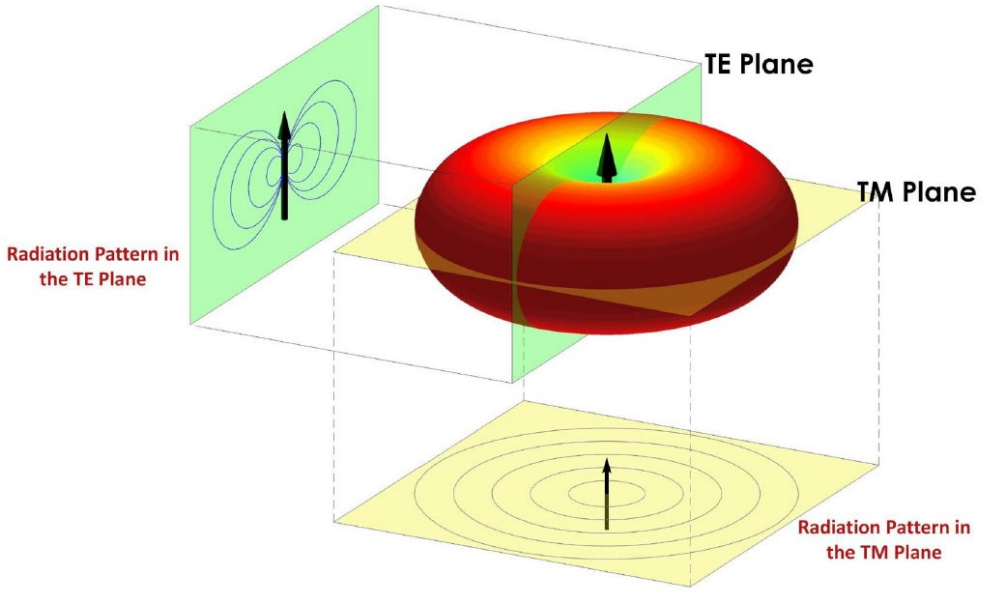


Plateau on other frequencies

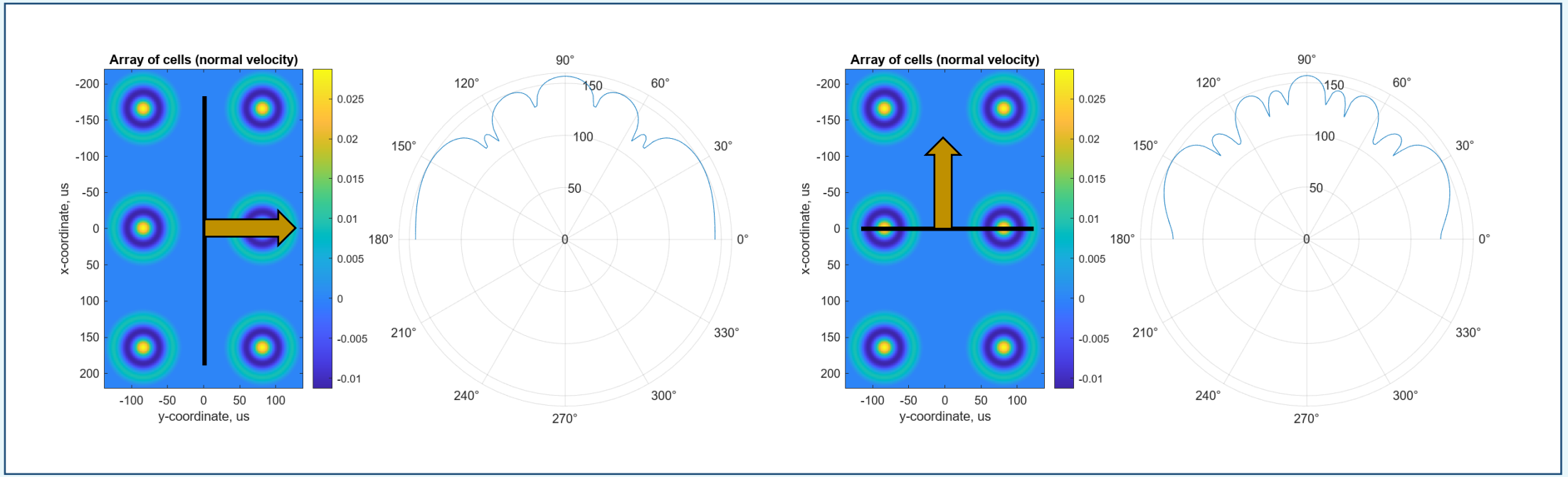
Verification



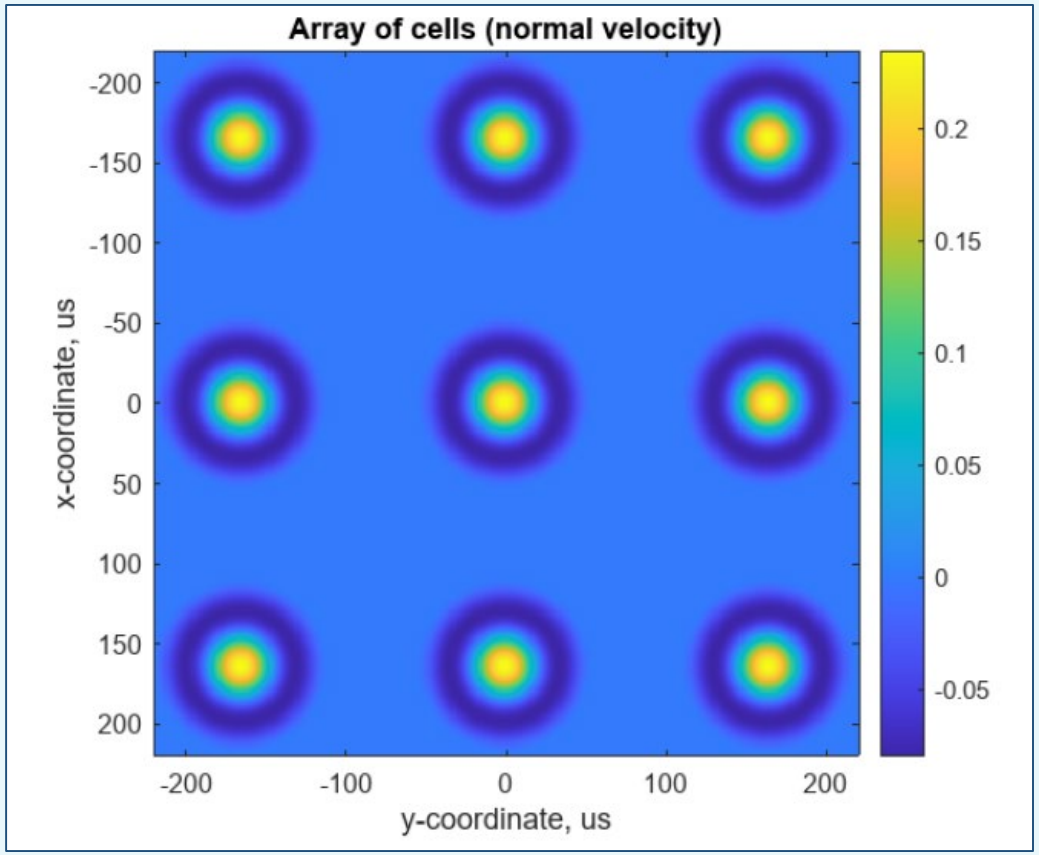




Verification



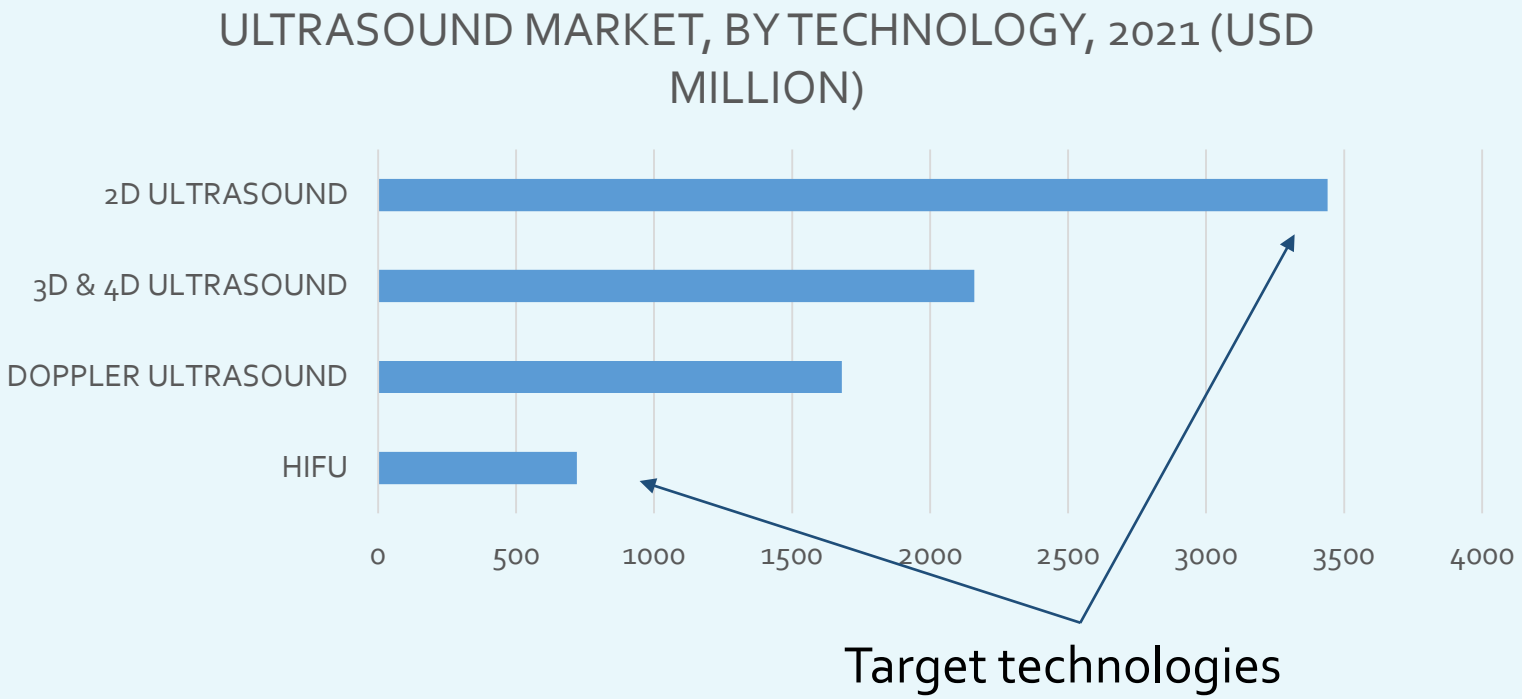
Conclusion



Fast and effective way to calculate arrays

- number of cells in x-direction
- number of cells in y-direction
- distance between the cells

Conclusion



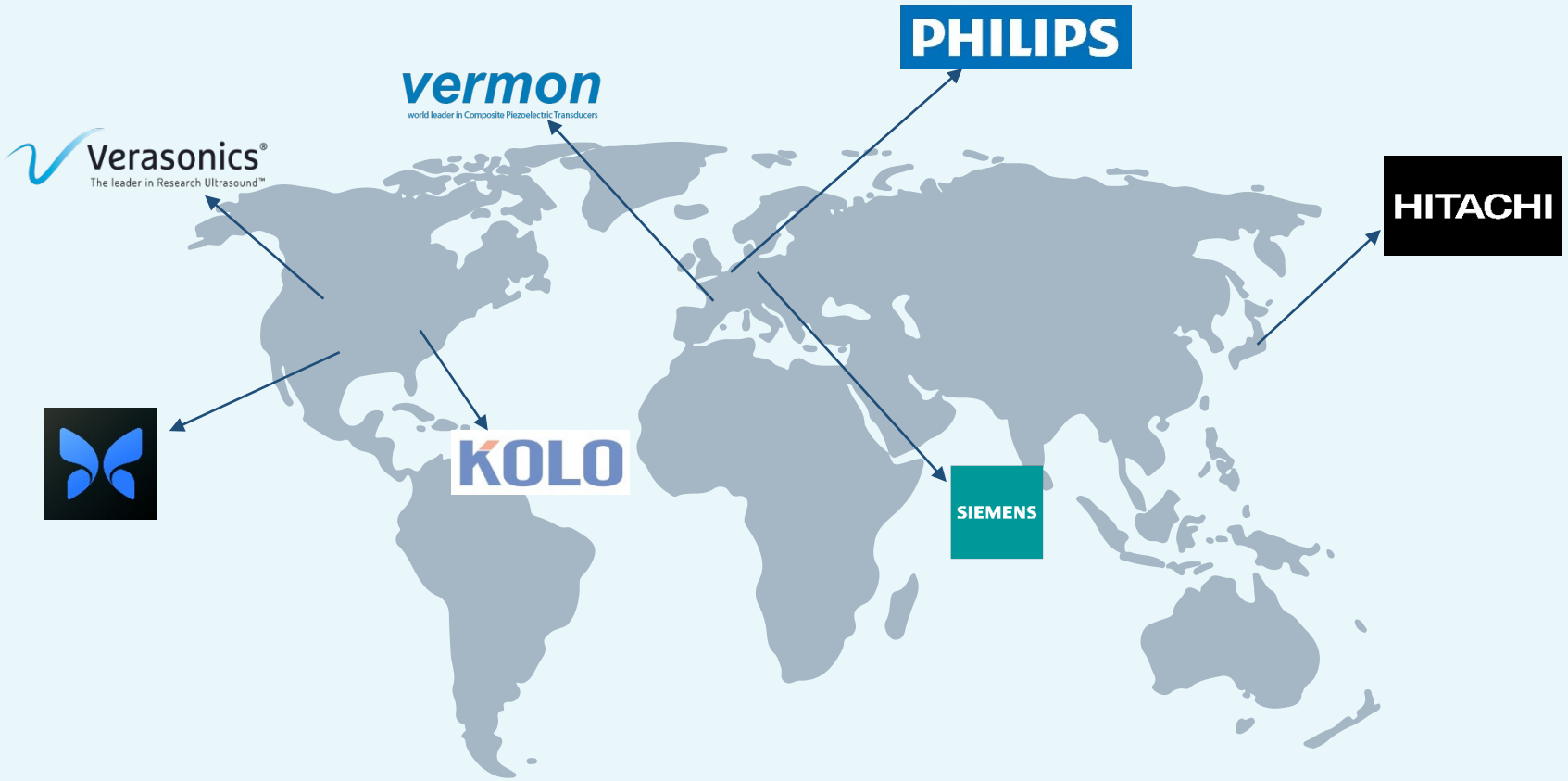
Target technologies

CMUT on the market

< 5% share

x2 growth rate

Conclusion



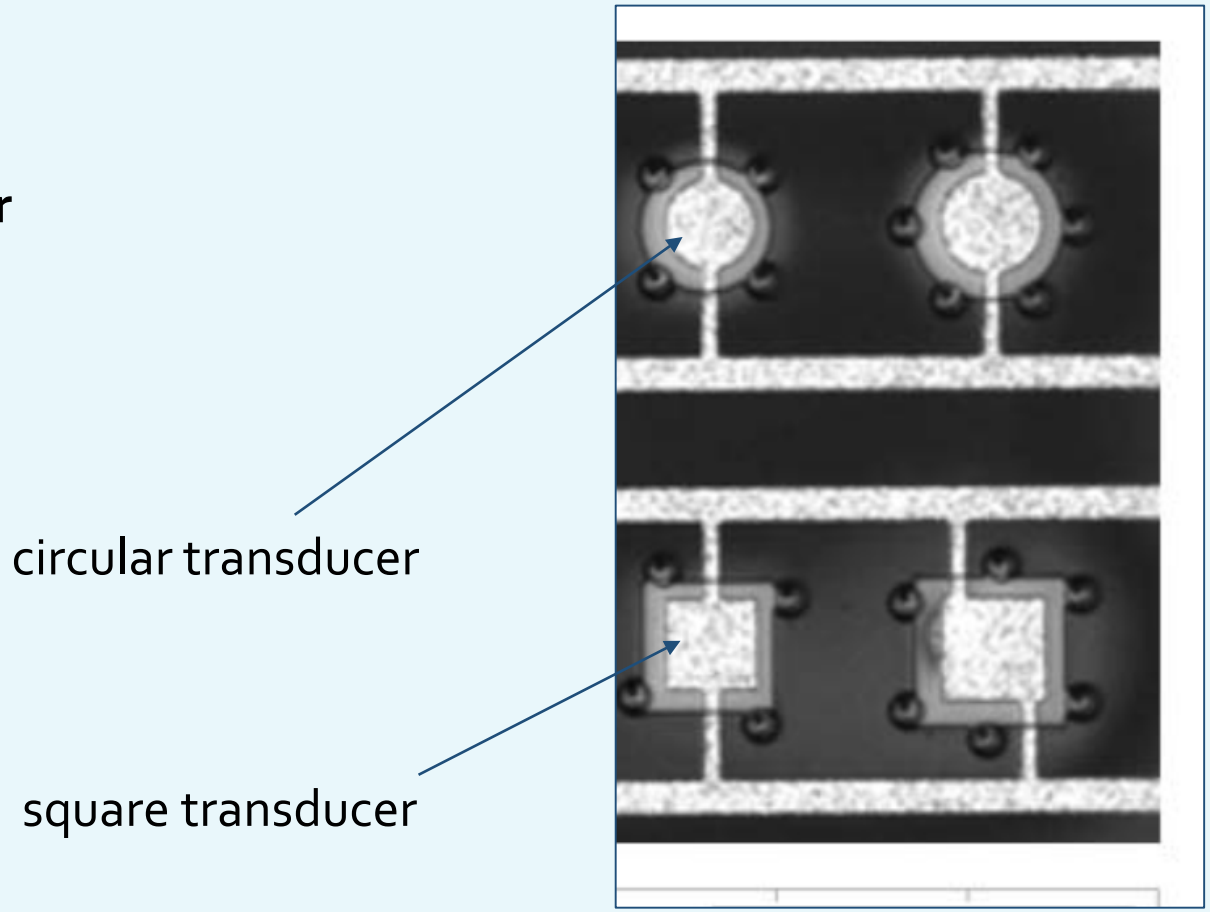
Companies that use CMUT technologies now:

- Butterfly IQ
- Philips
- Siemens
- Hitachi
- KOLO
- …

Outlook

WAYS TO IMPROVE THE METHOD

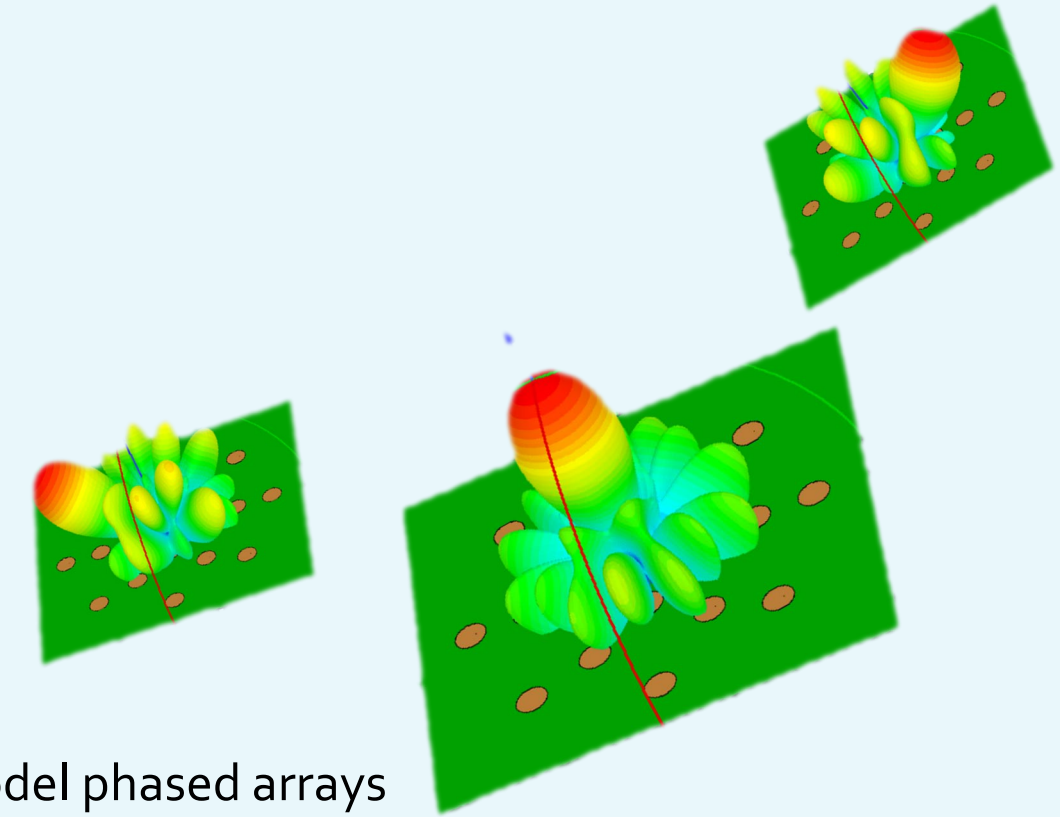
- **Square shape of a transducer**
- Phased arrays
- Losses of different nature



Outlook

WAYS TO IMPROVE THE METHOD

- Square shape of a transducer
- **Phased arrays**
- Losses of different nature

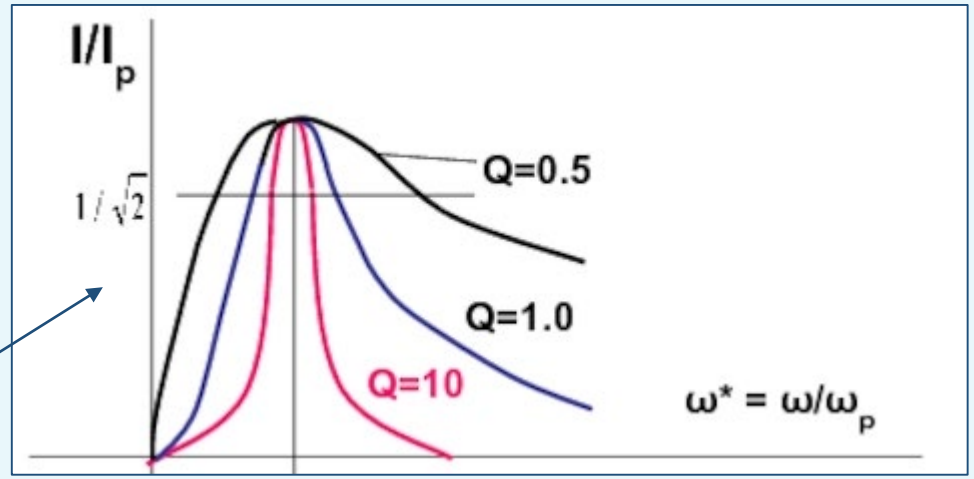


Add phase shift to specific cells to model phased arrays

Outlook

WAYS TO IMPROVE THE METHOD

- Square shape of a transducer
- Phased arrays
- **Losses of different nature**



Thermal losses, friction with fluid, mechanical damping, …

Thank you for your attention!

Biriukov Anton, 1-year PhD student
at Skolkovo Univeristy of Science and Technology

Skoltech