Piezoelectric Transducers and Ultrasound Imaging: Impact of Materials Properties and Multiphysics Aided Design

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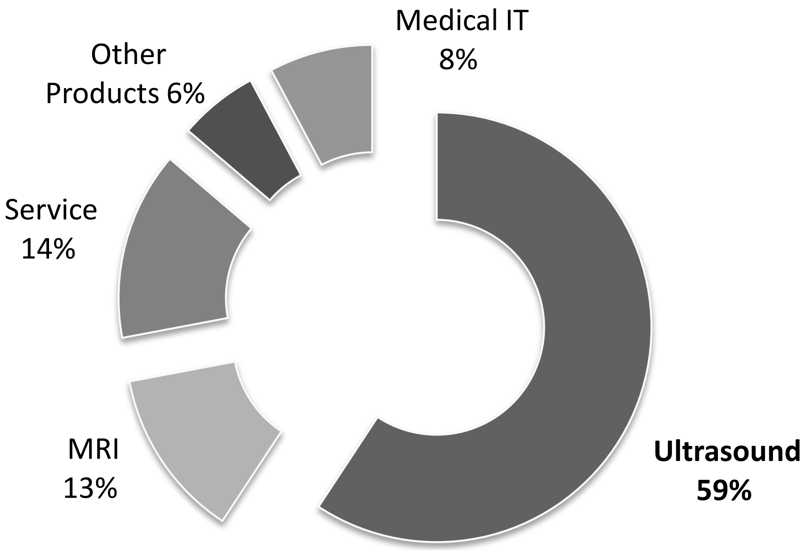
History

- Esaote was founded in Italy at the beginning of the 80's
- More than 30 years of activity
- Extremely successful industrial and technological concern
- Sectors with a high rate of innovation
- About 9% of the turnover allocated in Research and Development
- Top ten biomedical companies in the world

Esaote: products overview

Ultrasounds	Dedicated MRI	Services	Other	Interventional	Healthcare IT
					



Core
Business

Ultrasound products

- Many different kinds and typologies of ultrasound scanners are present nowadays on the Market
  - Portable
  - Wearable
  - Armheld
  - Console-based
  - Examination-Targeted

MyLabAlpha™

MyLabSeven™

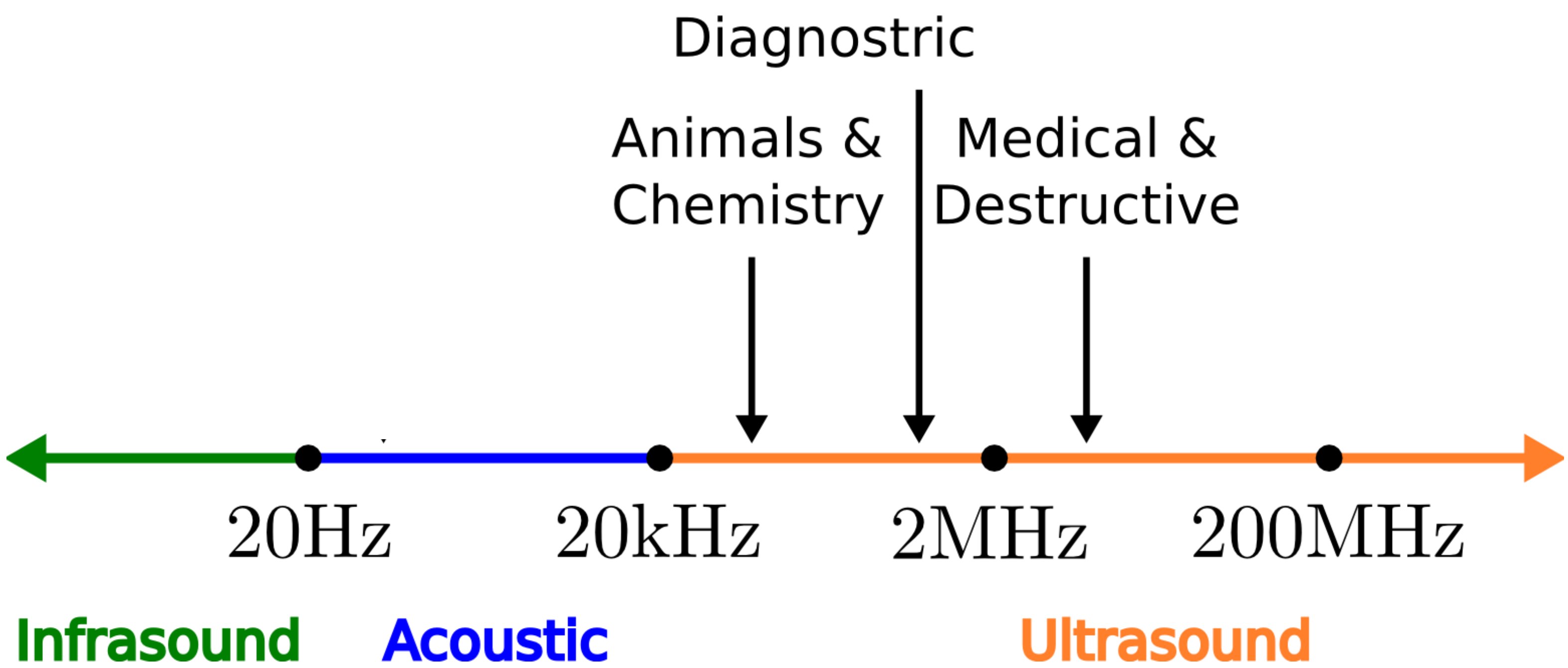
MyLabTwice™ Cardiovascular

esaote

Why ultrasound?

- Ultrasound products have changed a lot their position and diffusion among the Diagnostic Imaging Market
- Ultrasound have now:
  - much lower prices,
  - increased general quality regarding diagnostic capabilities
  - more user friendly interfaces
  - high quality user interfaces
- Ultrasound systems are:
  - more common than some years ago
  - much more present on the field
  - used also by non-sonographers
- All these points have completely changed the approach of the customer to Ultrasound Technology and Devices

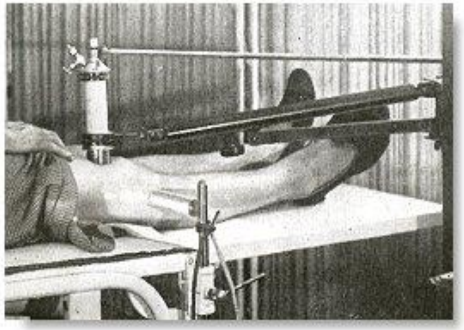
Ultrasound spectra

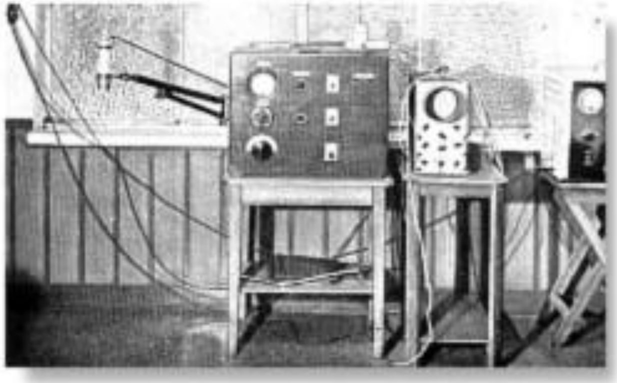


Ultrasounds used in sonography deal with frequencies between 1 MHz and 20 MHz

http://en.wikipedia.org/wiki/Ultrasound

Medical ultrasound in therapy: the beginning ...



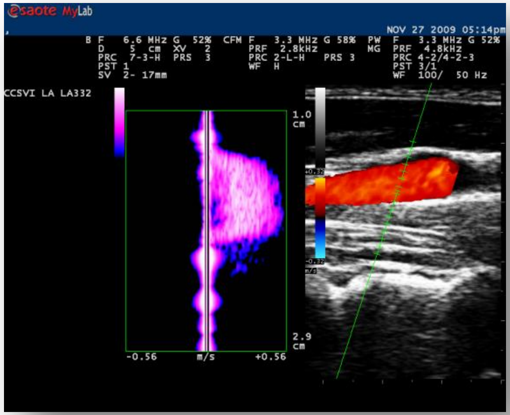


Denier's ultrasonic apparatus in 1946

- Use of ultrasound for physical therapy dates back to the 1940's
- Thermal energy generated from ultrasound is used in ultrasonic therapy
- Once thought – "Ultrasound is a *cure-all* remedy"
- Used to treat conditions such as arthritic pains, gastric ulcers, eczema, asthma, thyrotoxicosis and so on.....!

Medical ultrasound in imaging: timeline

1950	1D - Imaging (A-Mode)
1954	Echocardiography (M-Mode)
1955	2D - Image of Abdomen (B-Mode)
1958	2D - Imaging In Obstetrics
1958	2D - Imaging In Ophthalmology
1968	Transrectal Examination
1968	First Contrast Imaging (Saline)
1978	Transesophageal Examination
1990	Broad-Band Transducers
1992	3D - Imaging In Ob/Gyn
1992	Transpulmonary Echocontrastagents
1996	Native Harmonic Imaging
1998	4D (3D - Imaging in Real Time)
…….	



Ultrasound image quality

- “Old” type of diagnostic imaging exam: low info, few requirements
- “New” type of diagnostic imaging exam: detailed info, lot of new requirements

- Spatial improvements
- Contrast resolution
- Background noise reduction
- Dynamic range improvements
- Near and far field visualization

http://www.ob-ultrasound.net/history-realtime.html

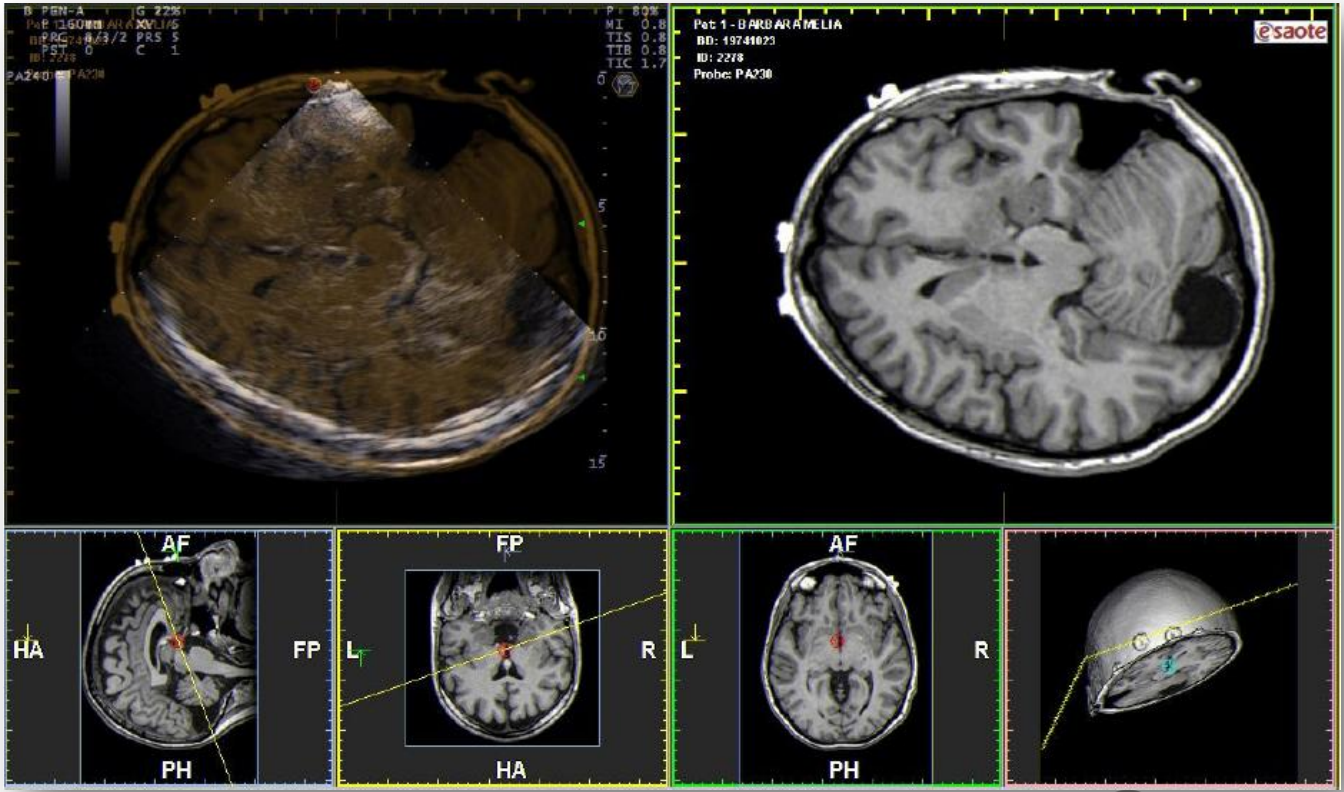
Present and near future

- New ultrasound technologies & methods
  - XView
  - MView
  - XStrain
  - 3D/4D
  - QDP
  - QDP DIR
  - Elastosonography
  - QIMT
  - QAS
  - FWI
  - Virtual Navigator

Virtual Navigator

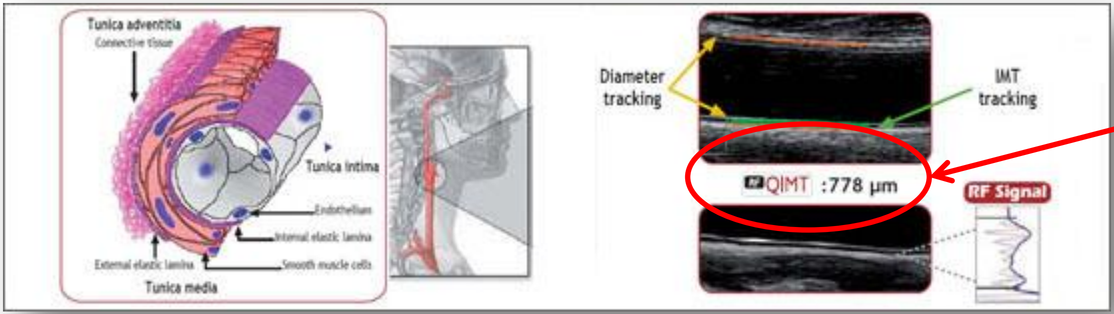
- The Virtual Navigator advanced system allows the real-time visualization of enhanced Ultrasound Images thanks to the correlation with CT/MR gold-standard images. The combination of US with CT/MR reference modalities has as final result the data fusion of US and CT/MR images allowing to gain confidence in assessing the morphology in US images, specially in difficult-to-scan patients .

Fusion Imaging
Virtual Navigator



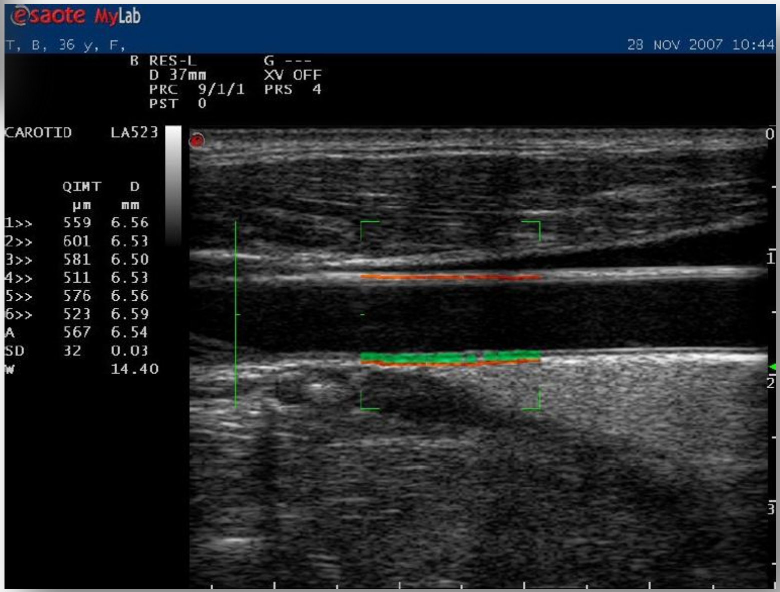
QIMT

- RF-based Quality Intima Media Thickness - RFQIMT method is the next generation IMT real-time measurement for high accuracy and reproducibility in early detection of cardiovascular diseases (e.g. diabetes, hypercholesterolemia, hypertension, etc.) and for detecting early atherosclerosis.

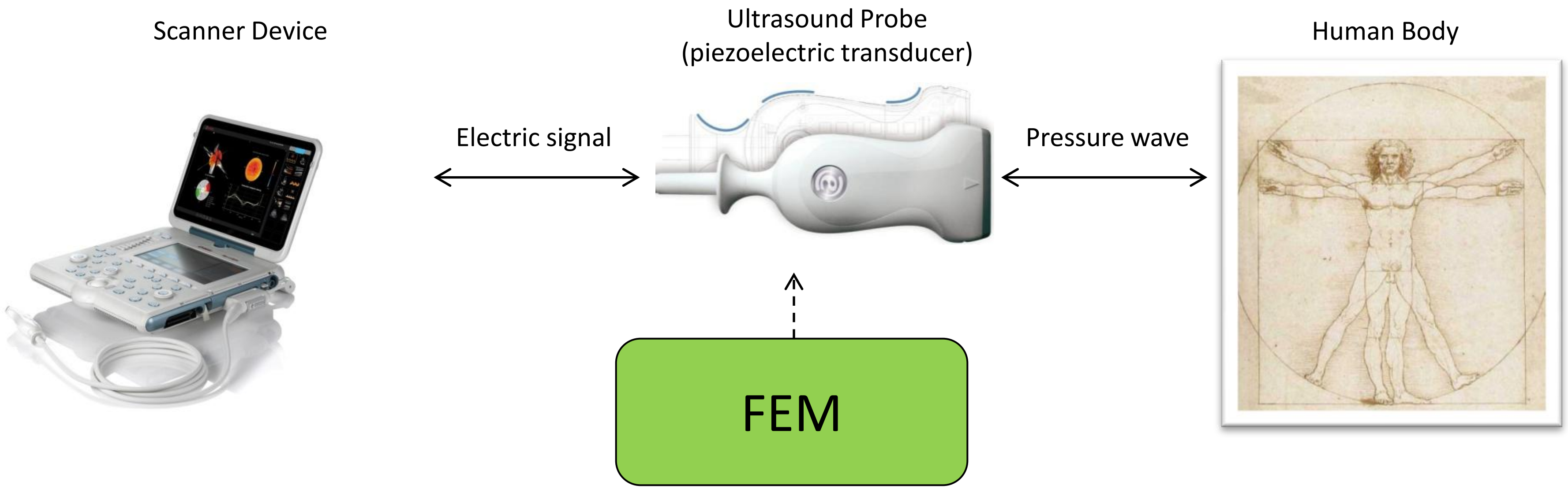


µm !!

- Based on the direct analysis of the radio-frequency signal, this technique is a gold standard for diameter, changes in diameter and wall vessel measurements with high spatial resolution



The role of computer aided simulation



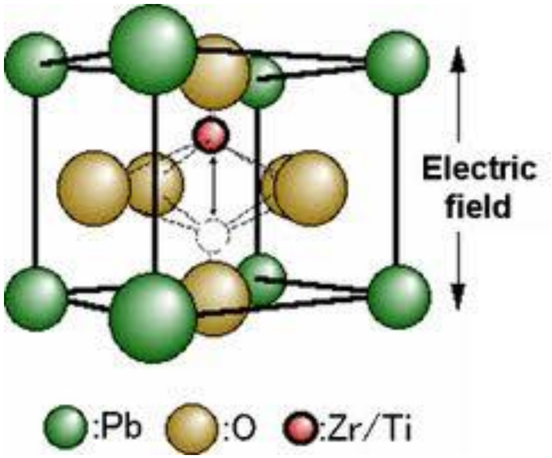
- Ultrasound imaging transducers generate a pressure field into the human body
- Differences in acoustic properties of different types of tissue allow the scanner to generate an image
- Quality of the resulting image is strictly related to:
  - technology level of the materials involved in the transducer manufacturing
  - understanding of their interactions
- Simulations greatly help in the study and optimization of transducer electroacoustical performances and image quality improvement

Design issues and solutions

- Which are the problems that a probe designer has to face?
  - Material parameters
  - Multiphysics approach
    - ✓ Mechanics
    - ✓ Piezoelectricity
    - ✓ Acoustic
    - ✓ Heat transfer
  - Model with large number of DOF (Degrees of Freedom)
    - ✓ High frequency
    - ✓ Large acoustic domain
- …and how to solve them?
  - Experience & study
  - Approximations, symmetries and model simplification
  - Inverse simulation

Piezoelectricity in COMSOL

The constitutive equations for a piezoelectric material are (*stress-charge* form):
(the superscripts indicates a zero or constant corresponding field)



$$\begin{cases} \mathbf{T} = \left[\mathbf{c}^{E}\right] \mathbf{S} - \left[\mathbf{e}^{t}\right] \mathbf{E} \\ \mathbf{D} = \mathbf{e}\ \mathbf{S} + \left[\boldsymbol{\varepsilon}^{S}\right] \mathbf{E} \end{cases}$$

T: stress vector,
c : elasticity matrix,
S : strain vector,
e : piezoelectric matrix,
E : electric field vector,
D : electric displacement vector,
ε **:** dielectric permittivity matrix.

- Elasticity, piezoelectric and dielectric permittivity matrices must be specified to build the model in COMSOL
- <u>Manufacturer data are often incomplete and should be checked for the particular operating condition of the piezoelectric material</u>
- <u>Physical insight is the starting point for the model</u>
- Optimization procedure should be used

"Step approach"

- **Suggested for whatever complex device**
- The FEM design **MUST** follow an inverse simulation *"step approach":*
  - Development of the model along with the transducer manufacturing stages (starting from the choice of piezoelectric material, up to the complete transducer assembly).
  - Inverse simulation with measurement comparison
  - Optimization procedure for each stage

Ultrasound Piezo-Disk Transducer Model for Material Parameter Optimization

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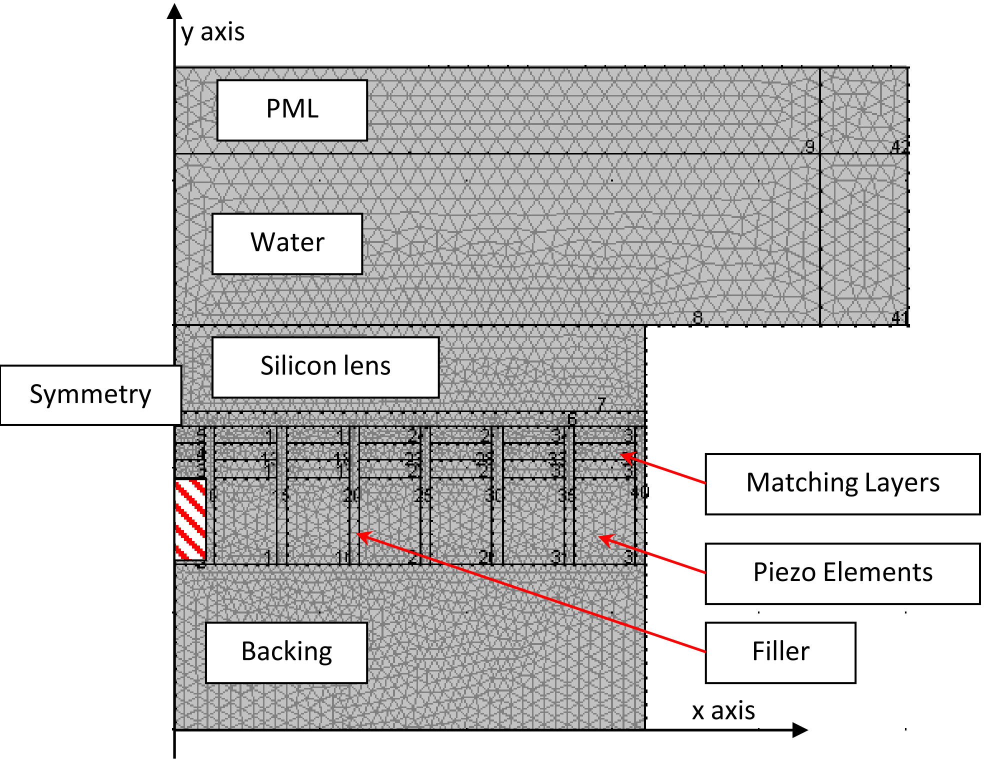
Electro-acoustical measurements

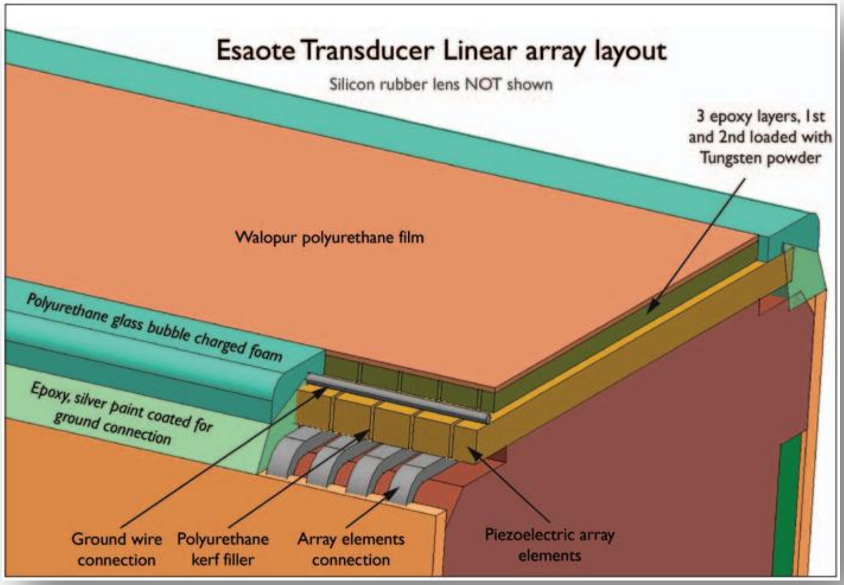
- The most important measurements to determine the quality of the transducer and its consequent imaging performances are:
  - **Electrical impedance**
    (performed with Network Analyzer):
    - Determines resonance frequency of principal vibration modes
    - Determines piezoelectric coupling efficiency
  - **Emitted pressure bandwidth**
    (performed with Pulser-water tank-hydrophone-oscilloscope system):
    - Determines transducer spatial resolution
    - Determines transducer sensitivity for different frequencies

Corresponding Simulation: a FEM frequency response analysis is to be performed in order to compare simulation results with measurements above and perform an optimization procedure

Transducer 2D FEM

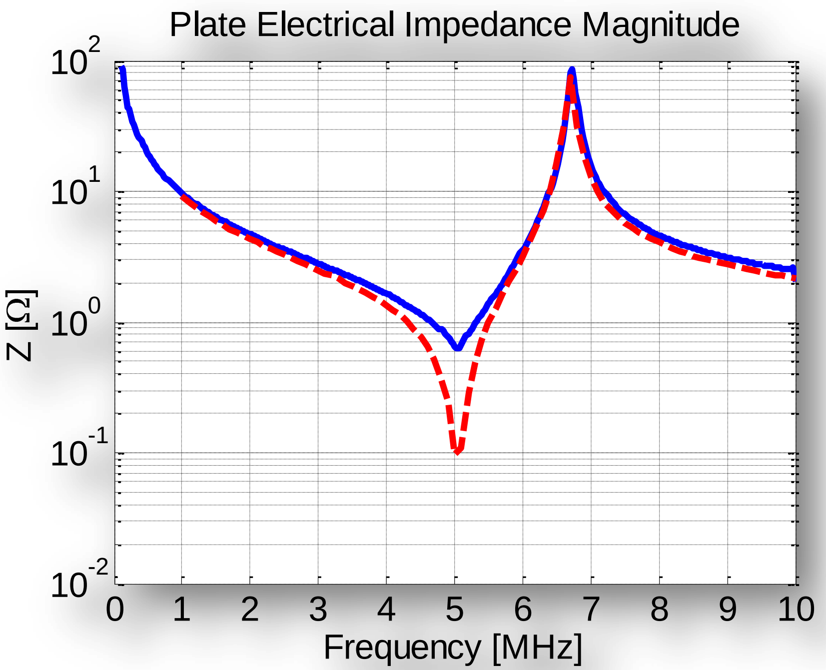
- Transducer COMSOL 2D FEM (complex model).
- Red striped block: active piezoelectric element.
- Acoustic domain reduced to a small region surrounded by Perfectly Matched Layer (PML), which simulate the zero reflection condition.

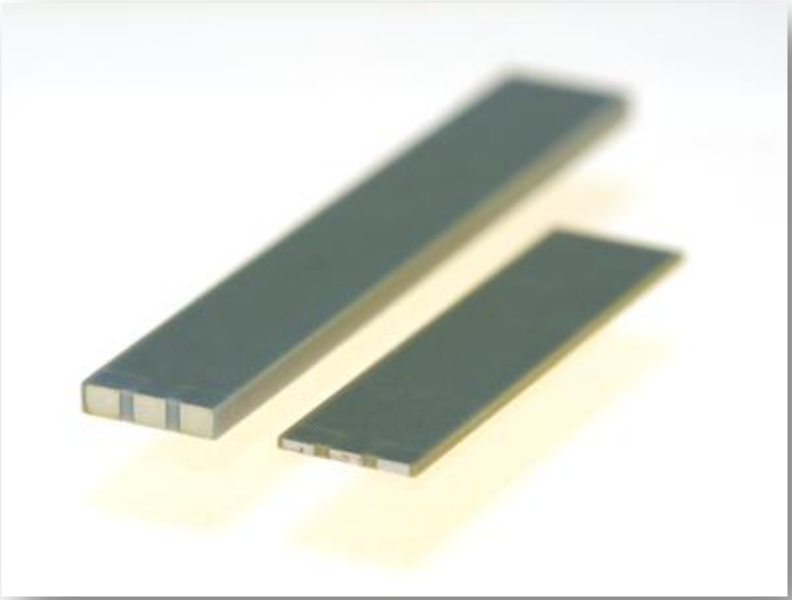




Electric: first stage design results

- Piezoelectric plate alone
- Electrical impedance comparison between measurement (solid) and simulation (dashed)
- Determination of matrices [c], [e] and [ε] from FEM analysis

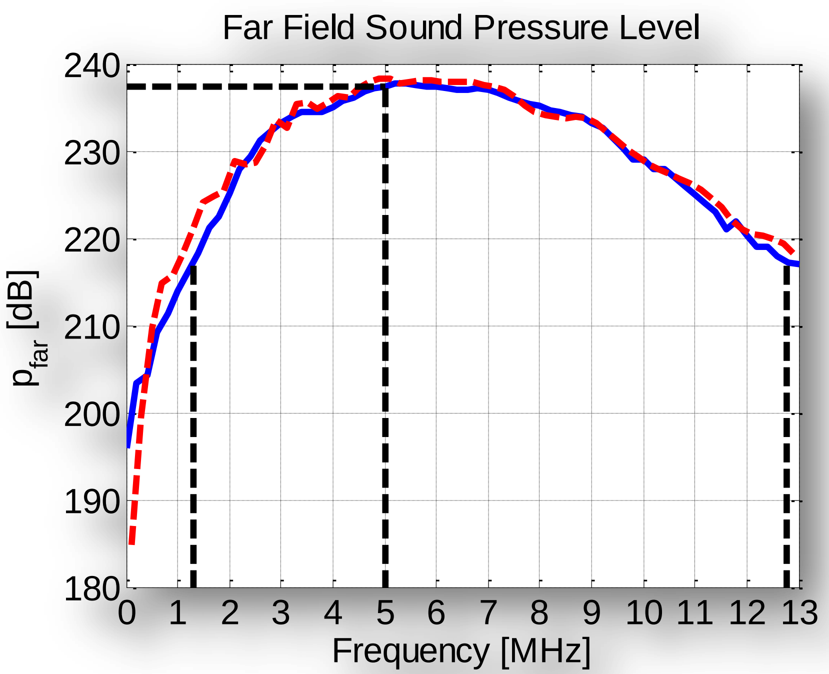




Agreement between FEM simulation and measurements are excellent (error less than 3% in frequency at resonance and anti-resonance frequencies)

Acoustic: final stage design results

COMSOL Simulation Vs. Measurement

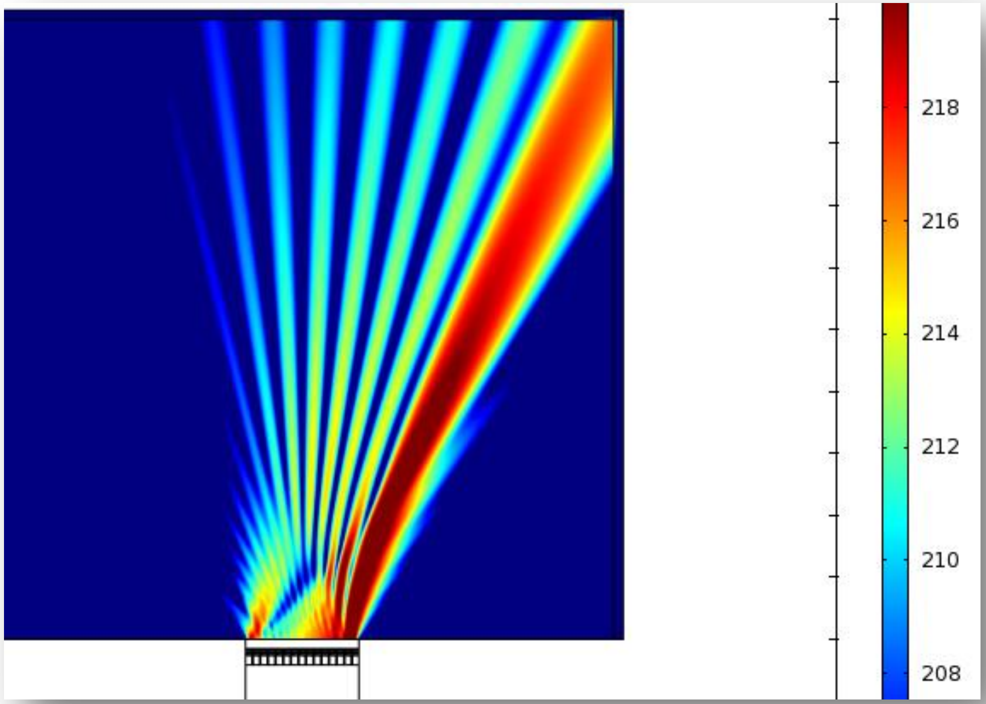


Measurement Set-Up

Agreement between FEM simulation and measurements are very good (error less than 1dB in amplitude at center frequency)

Acoustic: Beam Steering Capability

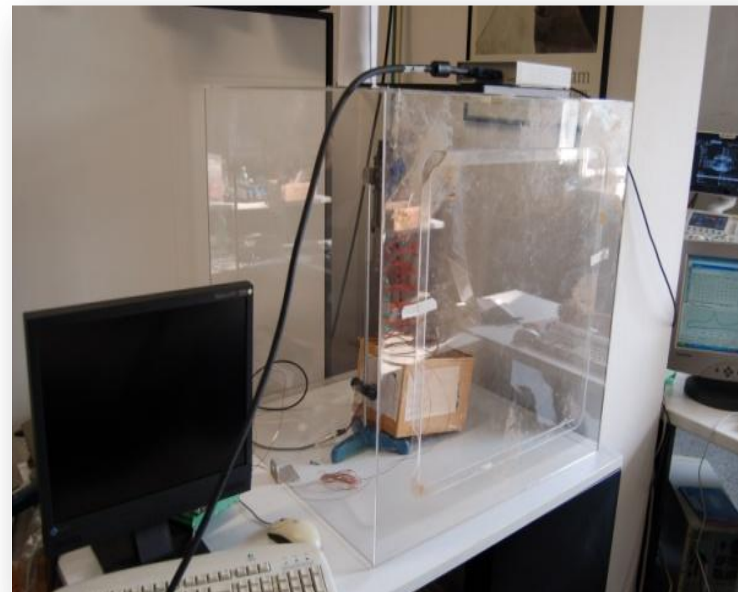
- Used for Doppler exams
- Performance strictly related to:
  - material parameters,
  - geometrical design,
  - electrical excitation



Simulation gives more… Thermal piezo-disk analysis (1)

Measurement Set-Up

Measurement Set-Up



Thermal Analysis of a piezo-disk ultrasound probe

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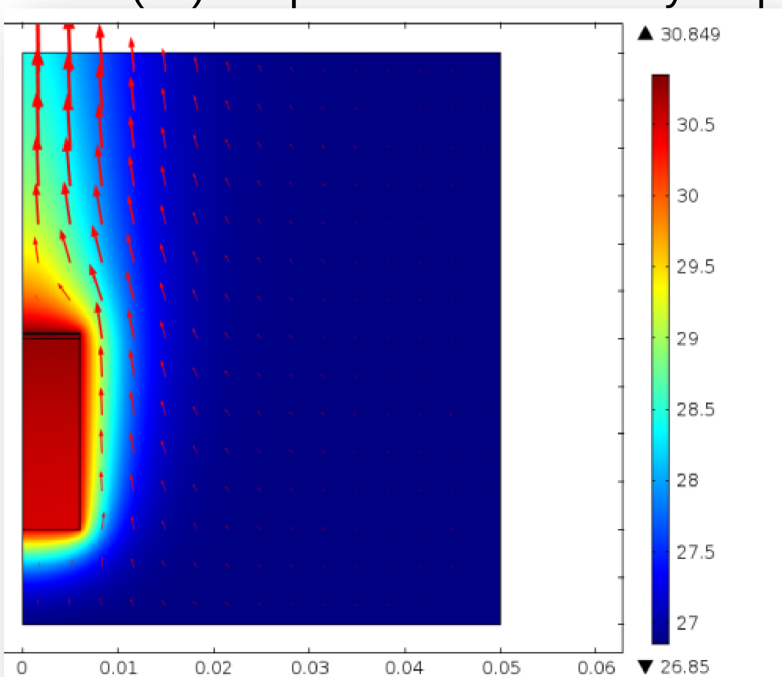
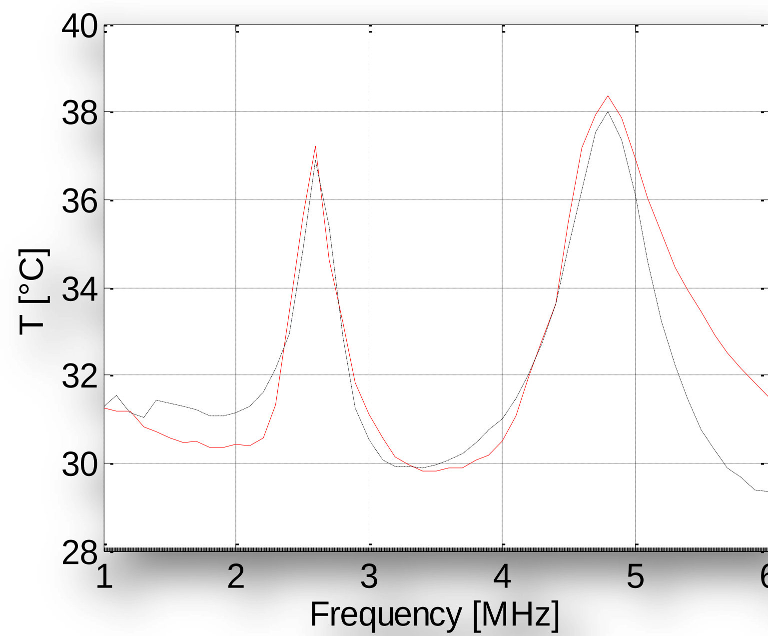
ACOUSTICS & VIBRATIONS II
Thursday, October 11, 4:45pm - 5:45pm
Room: *Gazebo*
Moderator: *Ysbrand Wijnant, University of Twente*

Simulation gives more...
Thermal piezo-disk analysis (2)

COMSOL Simulation
Fluid (air) temperature and velocity map



Transducer front face
equilibrium temperature



FEM can predict the temperature rise of the probe front surface under a given operating condition, in order to fulfill the International standard (IEC 60601-2-37) limit of 43 C in contact with patient skin (50 C in air)

Conclusions

- COMSOL is very a user friendly tool that greatly help the design of multi-physics complex problems

but…

- Experience
- Physical insight
- Measurement accuracy
- Teamwork
- Multi-disciplinary approach

…are necessary in order to obtain reliable COMSOL FEM results exploitable in industrial process design.

Thanks for your kind attention