# FEM simulation for ‘pulse-echo’ performances of an ultrasound imaging linear probe

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# Goal

Validate a 2D FEM for ‘pulse-echo’ probe response, for Esaote LA533 linear probe

Summary :

1. Complexity of the analysis
2. Pulse-echo measurement
3. Model design
4. Model optimization tools
5. Important material parameters
6. Final results : frequency response and pulse-echo waveform
7. Conclusions

# 1. Complexity of the analysis

Pulse-echo response FEM simulation is seldom found in literature for ultrasound imaging array probes. Indeed the complete modeling of such device is extremely complicated for several reasons :

1) A complete knowledge of acoustical material properties is requested

2) Multiple vibration modes of the array elements are present

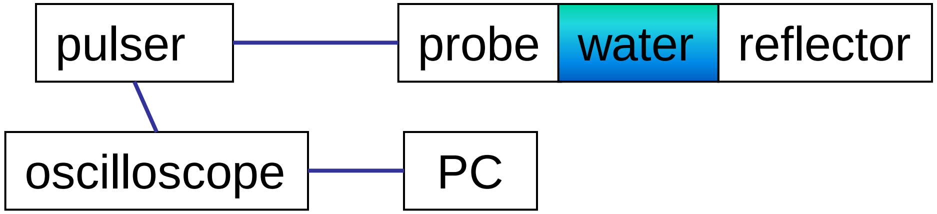
3) Acoustic/structural domain interface need to be handled

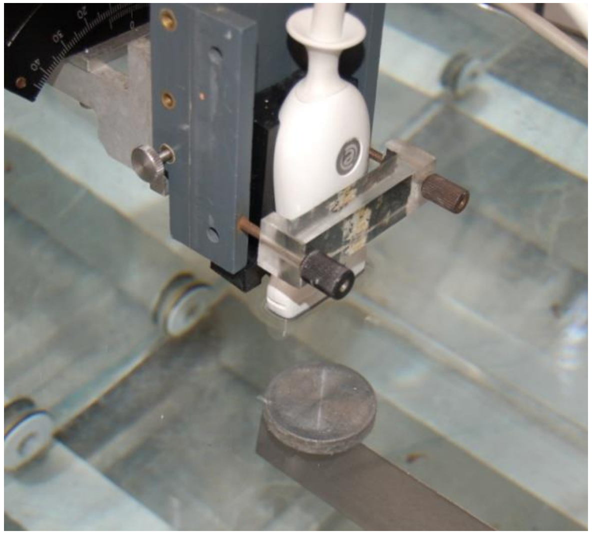
4) Model dimensions must be limited : approximations are needed

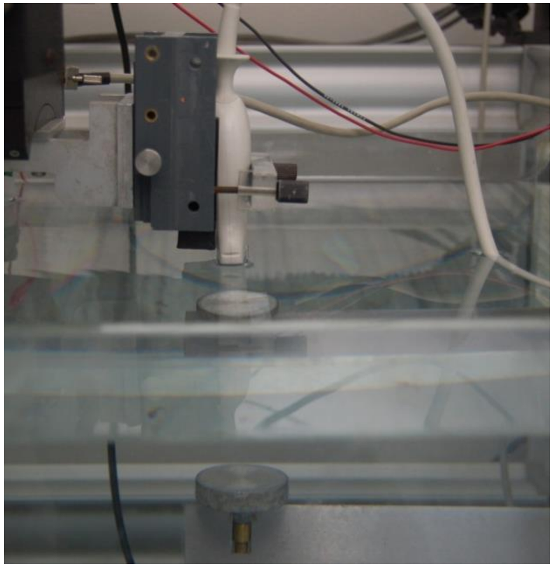
5) IFFT algorithm must be performed separately if FEM runs in the frequency domain

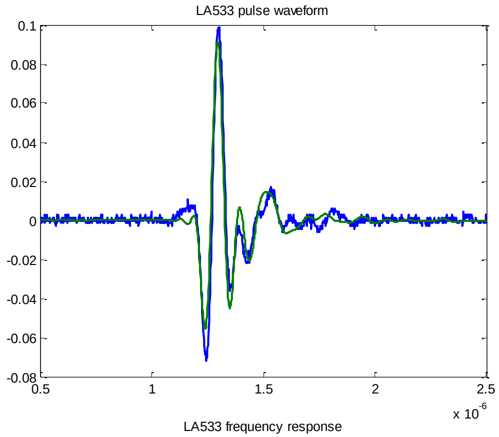
# 2. Pulse-echo measurement

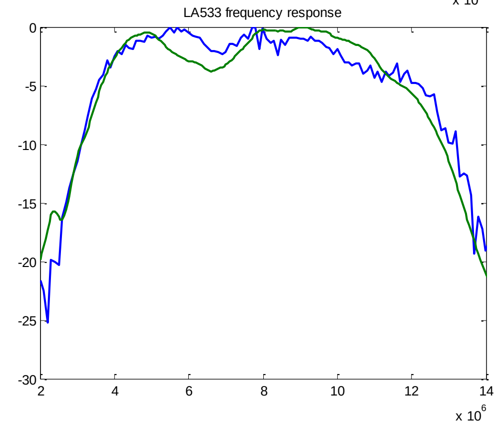
Pulse-echo measurement from a reflector in a specialized water tank is the most important measurement to determine the ultrasound imaging probe performances







# 2. Model design

After many trial models for many different types of ultrasound transducers and arrays, enough knowledge was gained to design a FEM Comsol model for a high-frequency linear probe.
The design procedure, along with the transducer layout, is the following :

1) 2D geometry , running in frequency domain

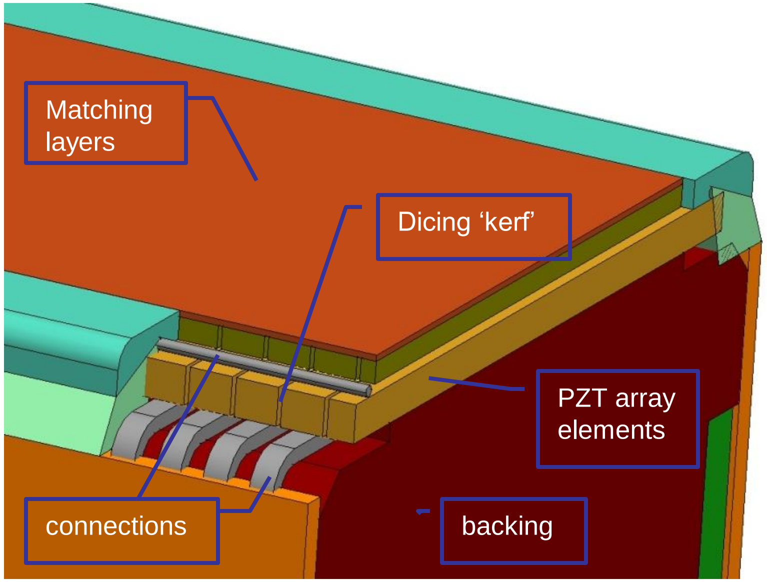
2) Acoustical/mechanical parameters for piezomaterial, array kerf filler, backing, matching layers and silicone lens need to be optimized

3) Far field pressure integration is needed to limit the acoustic domain dimensions

4) <u>Far field pressure data must be exported from the 'transmit' model and input as amplitude of an incident plane wave (back-travelling) on the boundary of the acoustic domain of the 'receive' model, to get the final echo-voltage on the array piezoelement</u>

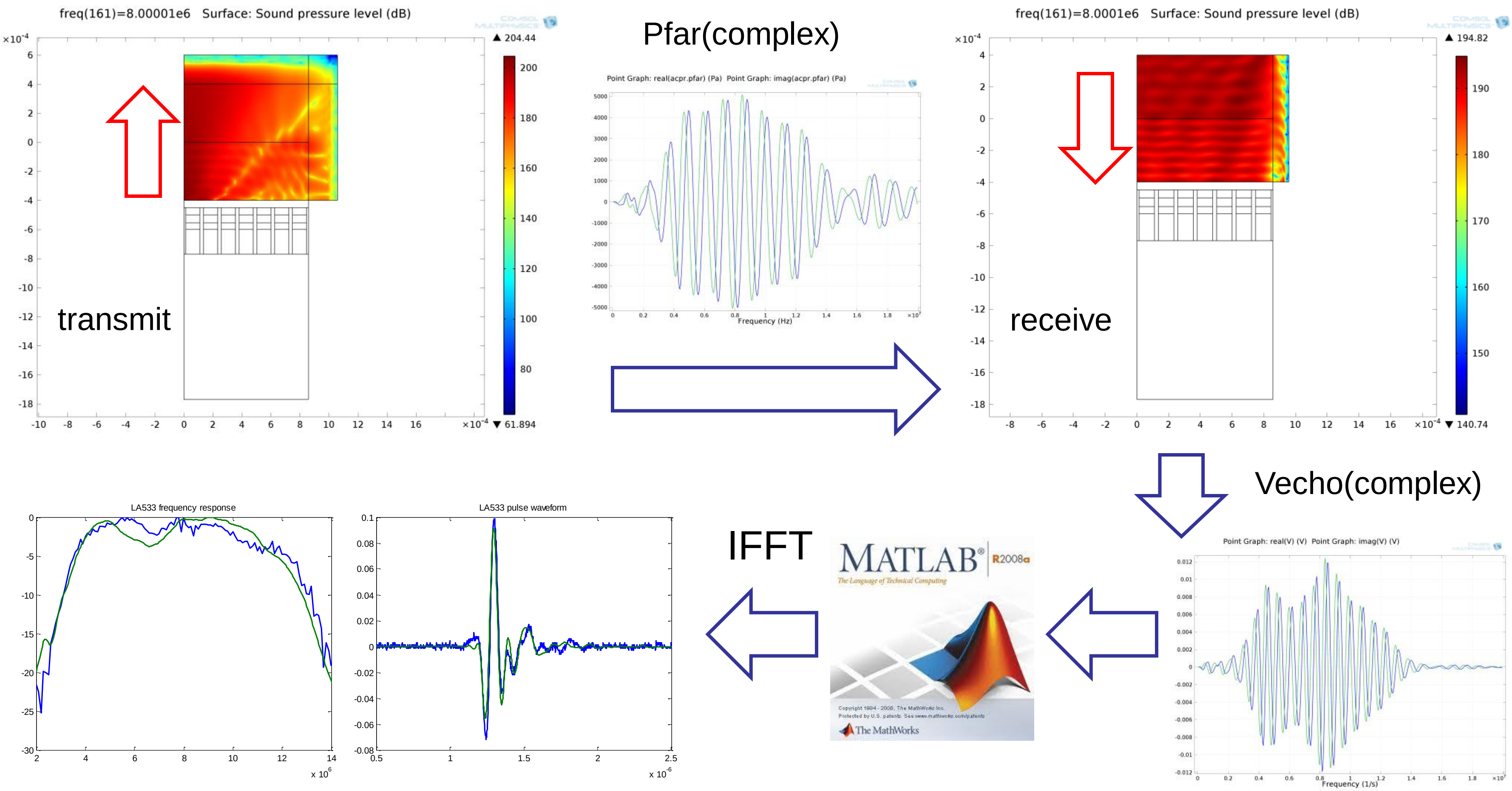
5) IFFT algorithm (Matlab) is used to recover the pulse-echo voltage waveform

## Typical linear array transducer



# 2. Model design sketch

The simulation layout is outlined below :



# 3. Model optimization tools

Inverse simulation 1 : measurements of the electrical impedance frequency response for the piezoelectric transducer (not reported here) allow to optimize piezo and other materials.

Speed velocity measurements : for elastic materials, measurements of longitudinal and shear wave speed can be converted (along with density) to Young modulus and Poisson ratio coefficient :

Poisson's Ratio $(\nu) = \dfrac{1-2\,(V_T/V_L)^2}{2-2\,(V_T/V_L)^2}$

Where
$V_T$ = Shear (transverse) velocity
$V_L$ = Longitudinal velocity

Young's Modulus $(E) = \dfrac{V_L^2\,\rho(1+\nu)\,(1-2\nu)}{1-\nu}$

Where
$V_L$ = Longitudinal velocity
$\rho$ = Density
$\nu$ = Poisson's Ratio

Direct measurements of elasticity : Young modulus measurements were performed for some of the matching layers.

Silicone rubber lens was considered as part of the acoustic domain, so that only density, sound speed and attenuation (easily measured) were needed to model such material.

Inverse simulation 2 : final measurements of on-axis pressure and pulse-echo voltage can be compared to the complete simulation results, to validate the FEM

# 4. Important material parameters (1)

It can be useful to report some of the material values that was determined, as starting point for future works.

CTS 3257 HD piezoceramic, cut into 0.1225 X 6mm elements (subdicing) :

Elasticity matrix :

$c^E =$

| | | | | | |
|---|---|---|---|---|---|
| 12e10 | 8e10 | 8.8e10 | 0 | 0 | 0 |
| | 12e10 | 8.8e10 | 0 | 0 | 0 |
| | | 11e10 | 0 | 0 | 0 |
| | | | 2e10 | 0 | 0 |
| | | | | 2e10 | 0 |
| | | | | | 3e10 |

Coupling matrix :

$e^E =$

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 30 | 0 |
| 0 | 0 | 0 | 30 | 0 | 0 |
| -10 | -10 | 28 | 0 | 0 | 0 |

Relative permittivity matrix :

$\varepsilon^E =$

| | | |
|---|---|---|
| 2500 | | |
| | 2500 | |
| | | 2000 |

Density : 8200 $Kg/m^3$

# 4. Important material parameters (2)

Backing : ILPEA F02-BR4 hard rubber

Density : 3500 Kg/m$^3$
Young's mod.: 4 GPa
Poisson ratio : 0.45

Matching layers :

1st : RPW10 (epoxy resin loaded with 10/1 parts (weight) of Tungsten powder (3-5$\mu$m)

Density : 8000 Kg/m$^3$
Young's mod.: 10GPa
Poisson ratio : 0.42

2nd : RPW3 (epoxy resin loaded with 3/1 parts (weight) of Tungsten powder (3-5$\mu$m)

Density : 3500 Kg/m$^3$
Young's mod.: 4.4GPa
Poisson ratio : 0.44

3rd : RP055 (epoxy resin)

Density : 1100 Kg/m$^3$
Young's mod.: 2GPa
Poisson ratio : 0.45

4rd : Walopur (polyurethane film)

Density : 1100 Kg/m$^3$
Young's mod.: 0.9GPa
Poisson ratio : 0.45

# 4. Important material parameters (3)

Dicing kerf  filler : TriasChem APT8 polyurethane

Density : 1000 $Kg/m^3$
Young's mod.: 0.35GPa
Poisson ratio : 0.485

Acoustic lens : Nusil MED 6016-11 RTV type silicone rubber (acoustic domain)

Density : 1100 $Kg/m^3$
Sound velocity : 1060 m/s

Damping :
Rayleigh Damping was set for all the materials of the mechanical domain except PZT ceramic, with the following parameter values :

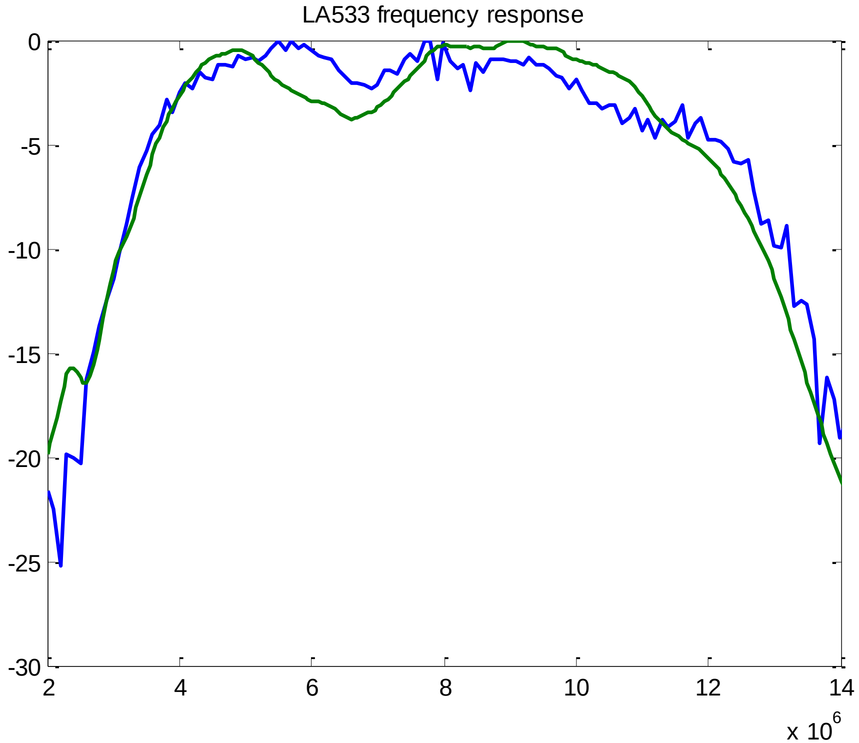
alpha : $7\ 10^{6}\ s^{-1}$
Beta : $1\ 10^{-9}$ s

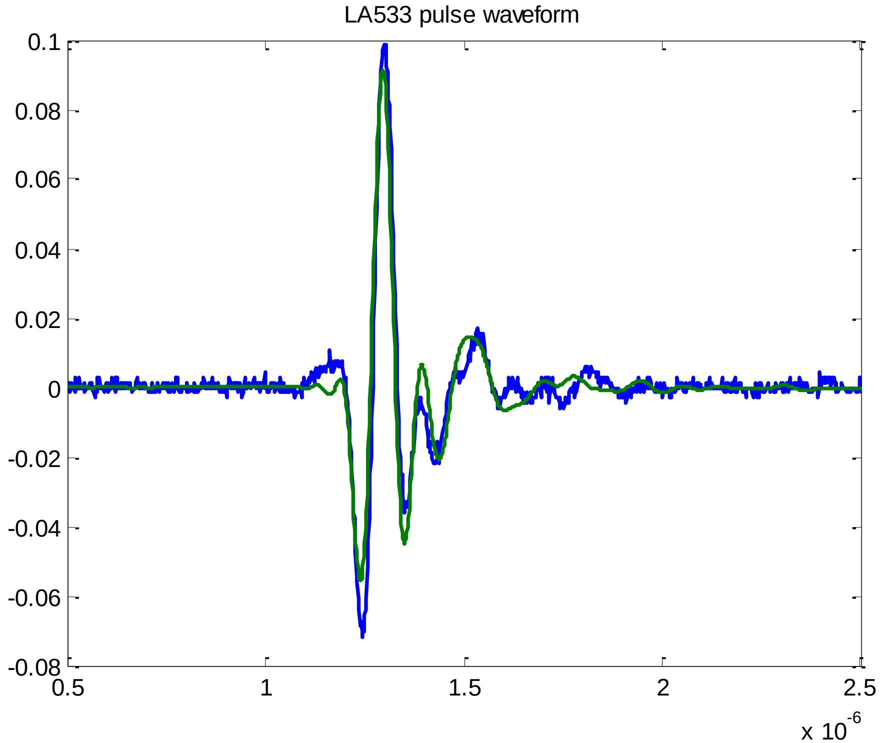
Attenuation of acoustic waves in the silicone rubber domain was set as :

alpha : ($8\ 10^{-4}$ dB/m) * frequency

# 5. Final results

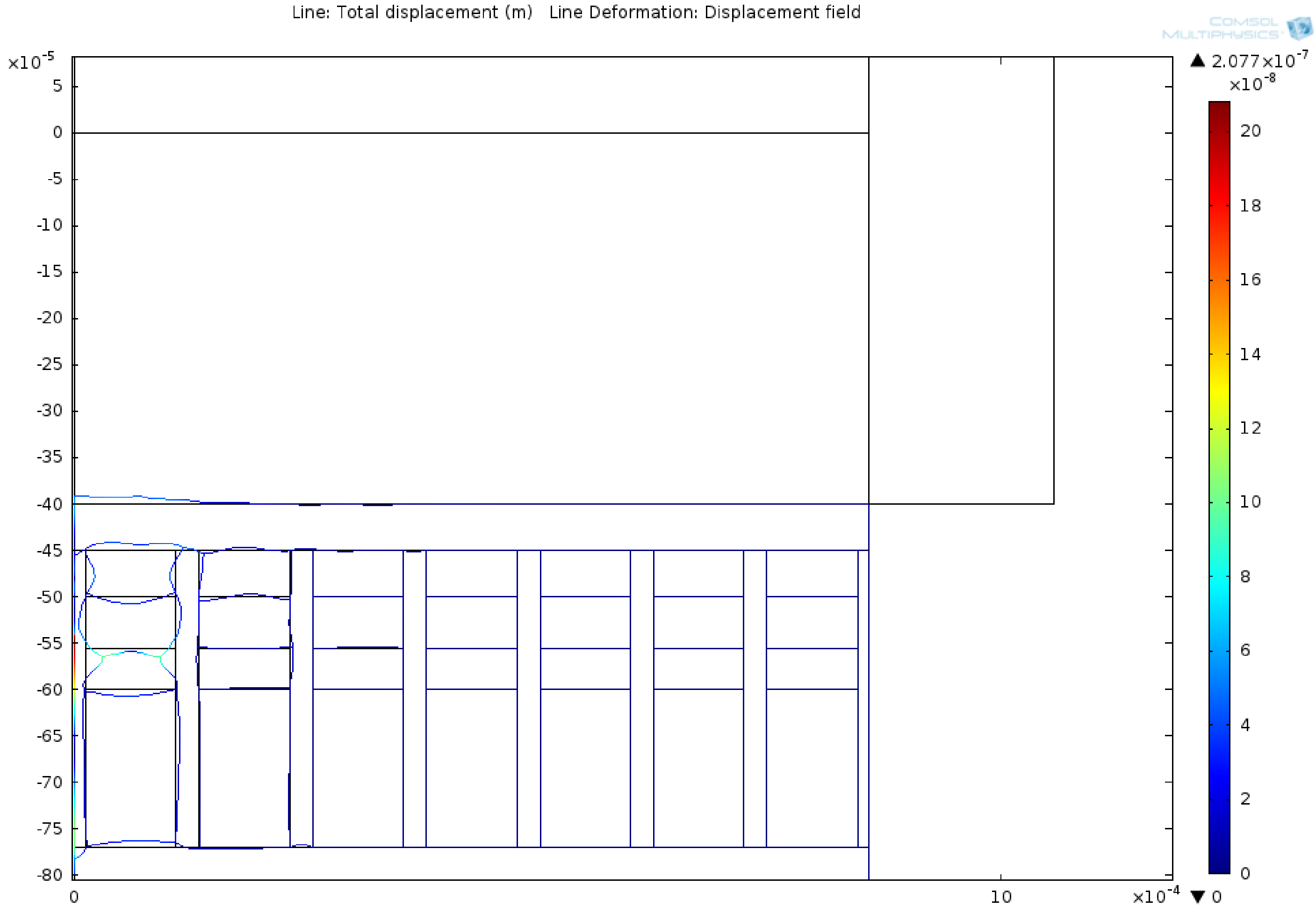
The following plots show a comparison of the simulation results (GREEN) with the pulse-echo measurements (BLUE).



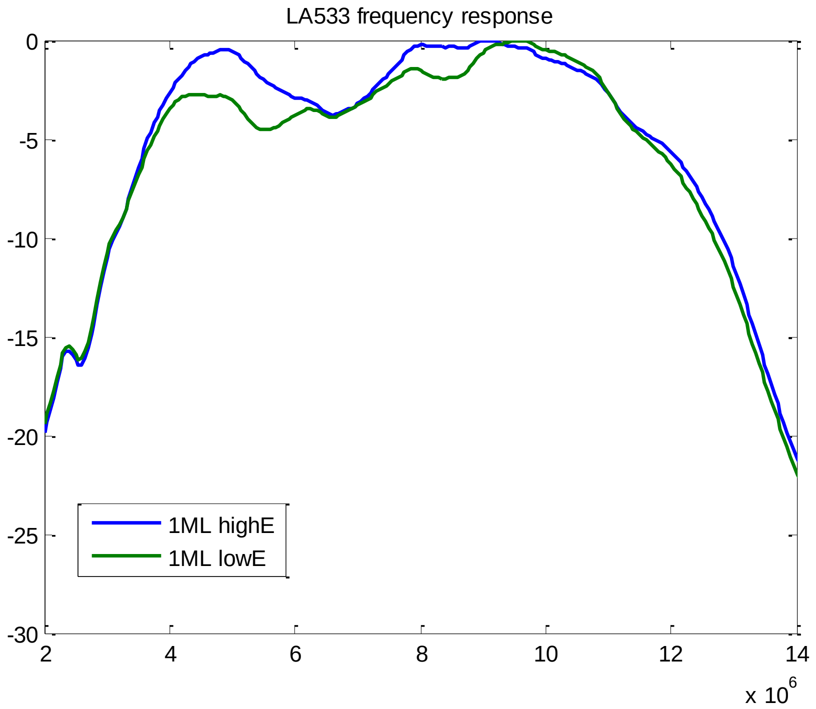



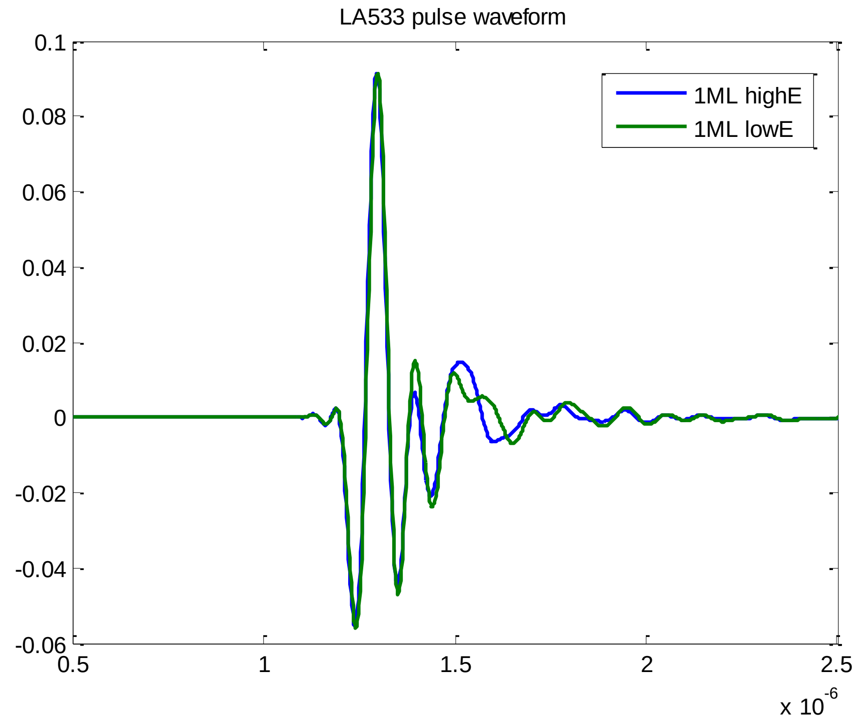

Simulations are the final results from the optimized model while measurements are performed with a standard pulser/water tank/reflector/oscilloscope setup

Deformed shape at 8MHz , on axis element



Test of different design 1 : $1^{st}$ Matching Layer with lower density and Young modulus

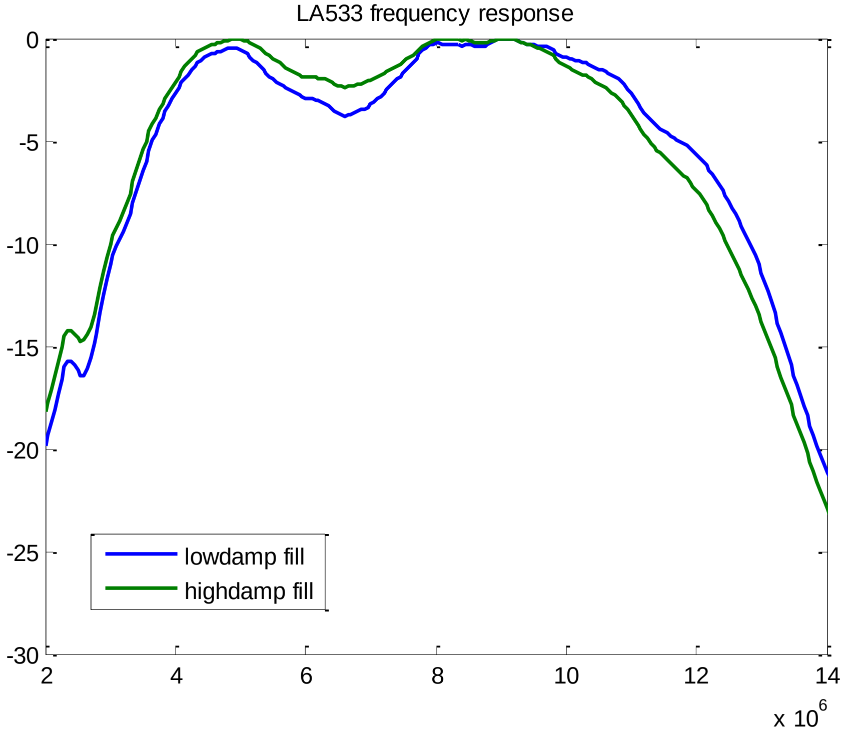


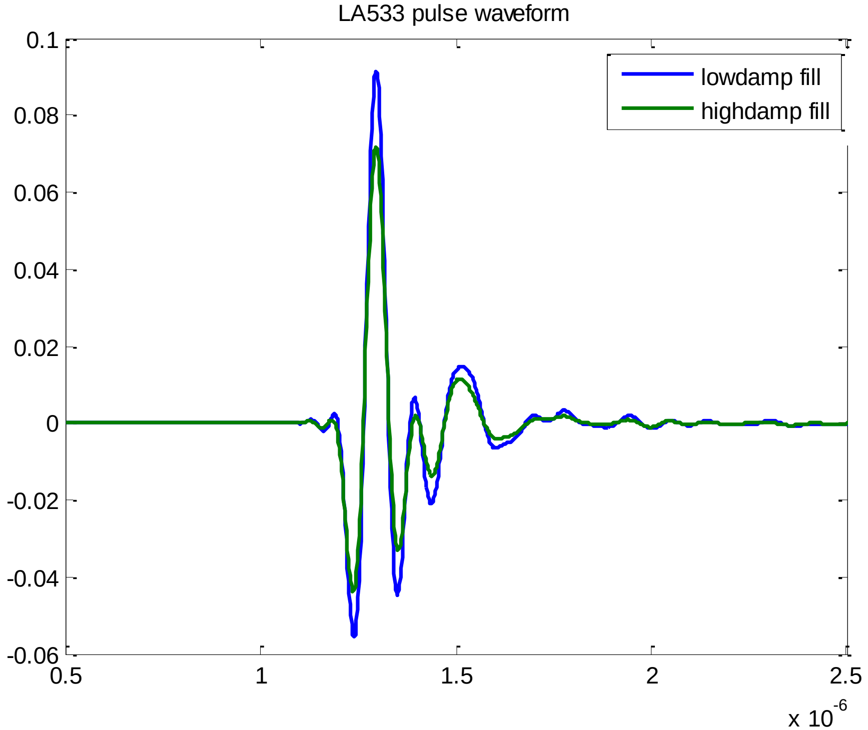




1ML high E : density = 8000 $Kg/m^3$ , Young modulus = 10GPa
1ML low E : density = 6000 $Kg/m^3$ , Young modulus = 7GPa

No great improvement …

<u>Test of different design 2</u> : higher damping kerf filler




Higher damping (Raileigh) kerf filler : alpha = 7 $10^6$ $s^{-1}$ , beta = 1 $10^{-9}$ s
Lower damping (Raileigh) kerf filler : alpha = 8 $10^6$ $s^{-1}$ , beta = 1.5 $10^{-9}$ s

⇨ Slight improvement

# 6. Conclusions

➢ The agreement between measurements and simulation results can be considered quite good and the model is validated for further applications and probe performance prediction

➢ Slight discrepancies between simulation results and measurements could be the result of the approximations that were made to develop a fast and simplified 2D FEM

➢ Many different design can be simulated, varying the material parameters or geometrical design, to study the change in probe pulse-echo performances. The latter is essential to limit the cost of development for a new design ultrasound imaging probe

Note : The time for complete simulation of probe pulse-echo performance (run of 2 Comsol models, Matlab calculation time is neglectable) is approximately only 18min (on a Dell T3500 workstation, 8GB).

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