# FEM Simulation for 'Pulse-Echo' Performances of an Ultrasound Imaging Linear Probe

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**Abstract:** The design of a high performance ultrasound imaging probe needs a reliable model to provide performance estimates related to different design options. Finite Element Model (FEM) is the most powerful and comprehensive tool available for this application, but needs a deep physical insight of the device and a complete validation process [1].

Moreover, the most important and characterizing electroacoustic measurement for an ultrasound imaging probe consists in the so called 'pulse-echo' measurement from a single array element, that is not easily configurable in a FEM. Indeed, such measurements can be described as follows :

- Short pulse electric excitation of one piezoelectric element of the probe
- Pressure signal emission into a water tank, through piezoelectric effect
- Complete reflection from a flat plate
- Back-traveling of the pressure signal
- Reception of the pulse-echo electric signal through inverse piezoelectric-effect

It's clear that such measurement is not easy to design into a simple and efficient FEM, mainly because the reflector is placed in the far field region of the transducer, so the acoustic domain should be very large, compared to the required finite element size.

In the present work a fast and efficient 'duplex-FEM system' is reported, where the ultrasound transmission and reception stages are separated. The system was validated and is capable of accurate probe performance simulations.

**Keywords:** ultrasound, imaging, piezoelectric, FEM, COMSOL, pulse-echo.

## 1. Introduction

Imaging probes for diagnostic ultrasonography are devices that generate a pressure field into the human body, according to an electrical signal [2]. The differences in acoustic properties of different types of tissue allow the scanner to generate an image of a part of the body, based on the echo signals. The quality of the resulting image is strictly related to the technology level of the materials involved in the transducer manufacturing and the understanding of their interactions. This is why a complete Finite Elements Model (FEM) for such a device can greatly help in the study and optimization of its electro-acoustical performances [3].

In the present work, a wide band 8 MHz linear array probe, consisting of an array of 192 piezoelements with 245 µm pitch, is designed and manufactured. The transducer design consists in a standard piezoelectric ceramic, a hard rubber backing substrate, four acoustic matching layers and silicon rubber lens.

A sketch is reported below :

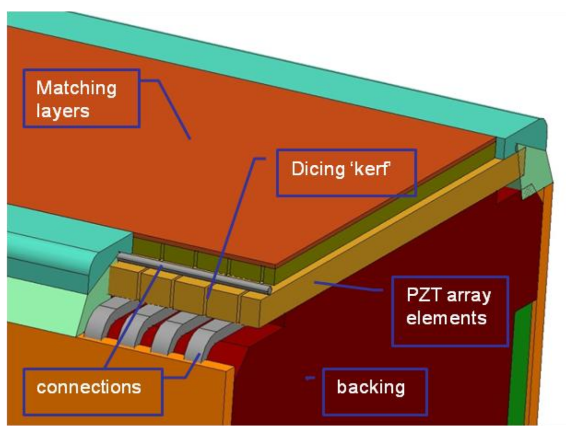


**Figure 1:** transducer sketch

For more details on the probe layout and the optimization of the FEM, a reading of the previous work [4] is suggested.

Rather the present work is focused on the development of a complete model for the pulse-echo performances of the probe, that is described in the followings.

## 2. Pulse-echo measurement and simulation

The most important and characterizing electroacoustic measurement for an ultrasound imaging probe consists in the pulse-echo measurement from a single array element, which allows to get information on pulse waveform and bandshape quality and amplitude. Many importants aspects of the imaging probe final performances can be tested, such as : image quality (SNR), maximum depth of diagnostic applications, multiple frequencies of operation and many others. A picture of a typical pulse-echo measurements is shown below.

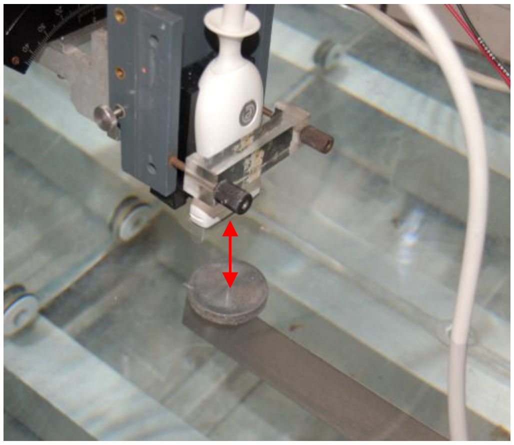

**Figure 2:** pulse-echo measurement

The pulse echo measurement is simply the reception of an ultrasound pulse sent into a water tank from the probe, driven by a specialized pulser/receiver device. The pulse waveform is typically displayed on an oscilloscope and analyzed on a PC. Water mimic some body tissue acoustic properties and is considered the standard for such kind of measurements.

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 :

- A complete knowledge of acoustical material properties is requested and it's not often available from technical specification and literature
- Multiple vibration modes of the array elements complicate the analysis of principal 'thickness' mode response
- Acoustic/structural domain interface needs to be handled, for both transmission and reception stages
- Array dimension must be generally limited, symmetry and far field integral simplification are to be employed, in order to avoid huge number of nodes/calculation
- Pulse-echo needs two consecutive simulations to limit the model dimensions
- IFFT algorithm must be performed separately on FEM output data if simulations run in the frequency domain

In the present work a fast and efficient 'duplex-FEM system' was developed, where the ultrasound transmission and reception stages are separated.

The main idea is shown in next figure:

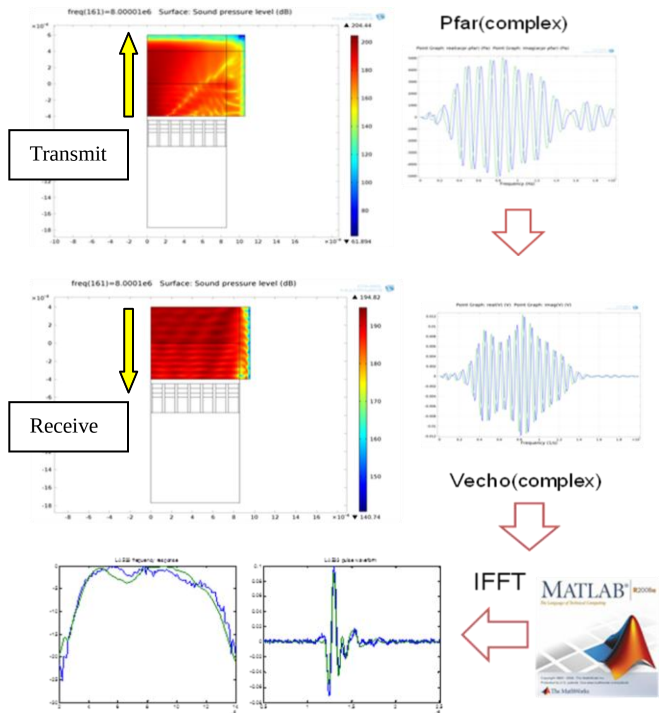


**Figure 3:** diagram of 'duplex-FEM system'

The flow of data and simulations can be described as follows :

1) Comsol FEM transmit : probe is modeled and pressure wave transmission into a reduced size symmetrical acoustic domain leads to the calculation of the far field pressure frequency response.
2) Comsol FEM receive : Complex far field pressure data from transmission are imported and set as incoming pressure wave in the reduced size symmetrical acoustic domain, so that

the pulse-echo voltage can be recorded on the piezoelectric array element

3) Matlab analysis : Complex pulse-echo voltage data are imported into a Matlab dedicated script, in order to calculate the pulse waveform from the frequency response data, through IFFT algorithm
4) Comparison with measurement data is easily performed in Matlab

## 3. Comsol model

### 3.1. Piezoelectricity equations in Comsol

The constitutive equations for a piezoelectric material are [8], in *stress-charge* form :

$$\begin{cases} \mathbf{T} = \lfloor \mathbf{c}^{\mathbf{E}} \rfloor \, \mathbf{S} - \lfloor \mathbf{e}^{t} \rfloor \, \mathbf{E} \\ \mathbf{D} = \lfloor \mathbf{e} \rfloor \, \mathbf{S} + \lfloor \boldsymbol{\varepsilon}^{\mathbf{S}} \rfloor \, \mathbf{E} \end{cases} \quad (1)$$

where $\mathbf{T}$ is the stress vector, $\mathbf{c}$ is the elasticity matrix, $\mathbf{S}$ is the strain vector, $\mathbf{e}$ is the piezoelectric matrix, $\mathbf{E}$ is the electric field vector, $\mathbf{D}$ is the electric displacement vector, $\boldsymbol{\varepsilon}$ is the dielectric permittivity matrix. The superscripts indicates a zero or constant corresponding field. Equations (1) takes into account both piezoelectricity, both mechanical and electrical anisotropy of the material.

Once these matrices have been specified, COMSOL recognizes which equations domains are to be used inside the FEM elements.

### 3.2. Acoustics equations in Comsol

Pressure waves emitted from the piezoelectric transducer in a biological medium are solution to the wave equation (time domain):

$$\nabla^2 p(r,t) - \frac{1}{c^2}\frac{\partial^2 p(r,t)}{\partial t^2} = 0 \quad (2)$$

where $p(r,t)$ is the pressure and $c$ is the speed of sound in the medium.

It is possible to identify two significant regions where wave propagation characteristics are very different: near field and far field region [2]. As regard our application, the region of interest is generally the far field, where waves are locally planar, velocity and pressure are in phase and the pressure amplitude drops at a rate inversely proportional to the distance from the source.

For homogeneous media, the solution of (2) can be written as a boundary integral (*Helmholtz-Kirchhoff*) anywhere outside a closed surface $S$ containing all sources, in terms of quantities evaluated on the surface. If one takes the limit for distances of observation much greater than the surface extension, then the integral becomes ([5], 2D case):

$$p_{far}(R) = \frac{1-j}{4\sqrt{\pi k}} \int_S e^{ik\frac{r\cdot R}{|R|}} \left( \nabla p(r) - ikp(r)\frac{R}{|R|} \right) \cdot n dS \quad (3)$$

where $k$ is the wave number, $\mathbf{R}$ is the vector position of observation point, $\mathbf{r}$ is the vector position of source point and $\mathbf{n}$ is the normal vector pointing into the domain that $S$ encloses.

Comsol makes the far field pressure calculation available as a post-processing option, making it extremely easy to build a compact and fast model.

## 4. Linear array probe design and manufacturing

In the following paragraphs we briefly describe the manufacturing procedure of the array transducer and its characterization, making use of a dedicated testing equipment.

### 4.1. Transducer assembly

Ultrasound imaging probes typically consist of an array of piezoelements (with sub-mm pitch), surrounded by special material structures with carefully optimized acoustical properties. Following the standard manufacturing procedure, the transducer structure can be described as follows: as first step, the piezoelectric material must be soldered or glued to a conductive fishbone that will provide the electrical connections to the PCBs that send and receive signals from the scanner, through the probe cable. Then, the piezoelectric material is bound on a backing substrate material which acts not only as a support, but also as an efficient damper for the back-traveling pressure wave: we've used an high density rubber, with acoustic impedance of 7 MRayls. On the front, four "matching layers" are glued on top of the piezoelectric material, to allow maximum transfer of power between high impedance piezomaterial (~33 MRayls) and low impedance acoustic medium (i.e. human tissue, ~1.5 MRayls). The matching layers were manufactured from special epoxy resin, charged with different quantities of tungsten fine powder, in order to get the desired acoustic impedance and speed of sound values.

All these materials are modeled in Comsol as isotropic elastic materials, except for the piezomaterial (see §3.1). The assembly is finally diced with special dicing machines, to get the array structure, and the dicing kerfs (25μm large) are filled with polyurethane. The total number of array elements is equal to 192, typical for a high frequency probe and its diagnostic application. In the case of the probe presented in this work, the number of elements is 192. Figures 4 and 5 are pictures of the transducer and probe.


**Figure 4:** Transducer assembly.

The material that covers the transducer piezoelectric array and acts as focusing lens for the ultrasound beam is typically a silicon rubber convex lens, which must be considered as a hyperelastic material in the structural mechanics domain or an acoustical material in the acoustics domain. The latter was choosen in the present work, as density and sound velocity are easily measured.

**Figure 5:** Complete probe head, with silicon lens and plastic covers.

### 4.2. Probe characterization with pulse-echo measurement

The transducer's fundamental performances can be evaluated by the so called pulse-echo measurements, as anticipated in §2.

As regard measurement instrumentation, the following equipment was employed :

- Panametrics 5800 pulser-receiver
- LeCroy LT342 500MHz Oscilloscope
- specialized water tank (see fig.2)
- PC remote controlled probe movement and acquisition software.

## 5. Use of COMSOL Multiphysics

### 5.1. Building the finite element model

The FEM for the transducer array was built using Comsol acoustic-piezoelectric interaction module, in the frequency domain. It was limited in 2D space dimension and symmetry on the transducer axis was employed. Only a set of central elements was modeled, enough to consider the transverse interaction of passive neighbors with the active on-axis element. Mesh on all domains was chosen as free tetrahedral, with adequate minimum element dimensions.

In order to reduce the complete FEM node number, the pulse-echo measurement was modeled through a 'duplex-FEM', separating the transmit and receive operations of the piezoelectric array into two distinct models.

In each model the acoustic domain (water) was reduced to a small region surrounded by Perfectly Matched Layer (PML), which simulate the zero reflection condition. Far field pressure was calculated for the transmit FEM, as previously discussed.

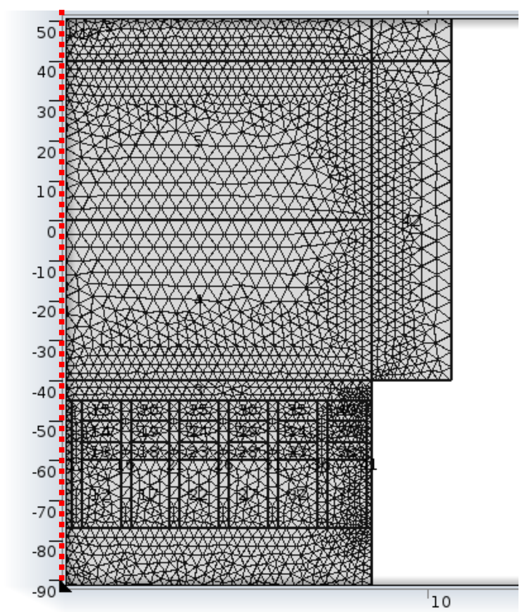


**Figure 6:** COMSOL 2D FEM, with symmetry on y-axis.

Once the far field pressure real and imaginary parts were exported from the transmit FEM, they could be input as incident pressure wave amplitude of a plane wave on the top boundary of the acoustic domain of the receive FEM, to complete the round-trip simulation. The voltage difference across the piezoelectric array element upon pressure wave reception corresponds to the final pulse-echo measurement.

Finally the real and imaginary parts of the pulse-echo voltage can be exported from the receive FEM to the Matlab script, were IFFT calculations and comparison with measurements are performed.

The complete simulation takes less than 20min. to run (on a Dell T3500 workstation, 8GB), which is much lower than what could be obtained with a single FEM model, where the complete acoustics domain (between probe and underwater reflector) should be modeled.

## 6. Results

Here the results obtained from the FEM models are presented, along with the corresponding measurements.

### 6.1. Piezoelectric material

The analysis of the piezoelectric material alone is not reported here, as it's very similar to the ones reported in the previous work [1] and [4]. These are optimization stages where comparison between measurements and simulations allows the complete characterization of the piezomaterial.

### 6.2. Complete probe

After the piezocomposite plate alone was studied, the complete probe was implemented in COMSOL, including the four matching layers designed along with the FEM development. As previously reported, the final pulse-echo performances were available through a 'duplex-FEM' simulation and Matlab data analysis.

Frequency response results are compared in terms of FEM results vs. FFT of measured pulse-echo waveform, while pulse-echo waveform results are compared in terms of measured waveform vs. IFFT of FEM frequency analysis results.

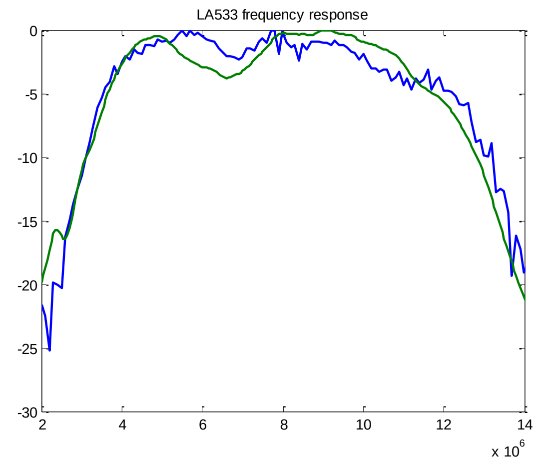


**Figure 7:** pulse-echo frequency response (dB): measured (blue) and simulated (green).

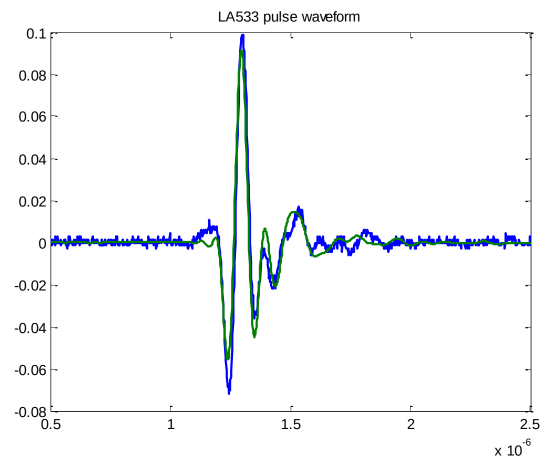


**Figure 8:** pulse-echo waveform (Volts): measured (blue) and simulated (green).

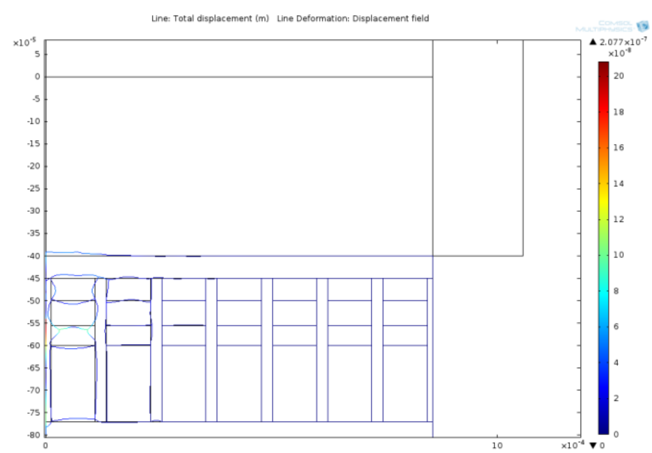


**Figure 9:** Deformed shape at 8MHz, on axis element excited.

The agreement between measurements and simulation results can be considered quite good and the model is validated for further applications and probe performance prediction.
On the other hand, the frequency response shows that the thickness mode energy loss at 6-7MHz is slightly more important for the FEM with respect to the real probe (3dB max.mismatch) , while the sensitivity at 10-12MHz is higher for the FEM (2dB max.mismatch). These minor discrepancies can't be recovered through optimization of material parameters for the matching layers or silicone lens, so they could be results of the approximations that were made to develop a fast and simplified 2D FEM.
What is more important is that 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.
Here some hints are given, in terms of pulse-echo performance variation with respect to modification of some important material properties.
A different design could consist in a 1st Matching Layer with lower density and Young modulus, that results in the following performances :

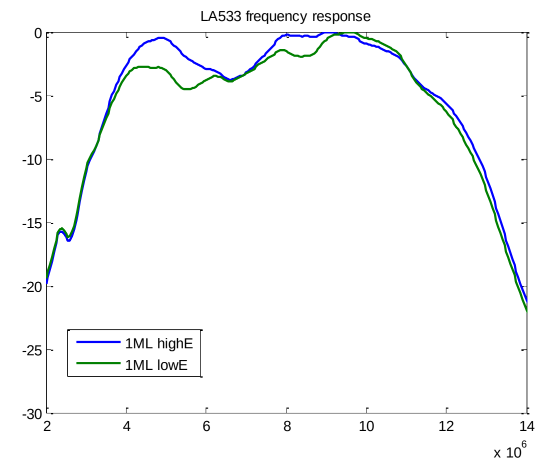


**Figure 10:** more simulations for pulse-echo frequency response (dB): 1st ML high E (blue, density = 8000 $Kg/m^3$ , Young modulus = 10GPa), 1st ML low E (green, density = 6000 $Kg/m^3$ , Young modulus = 7GPa).

The lower density and Young modulus of the 1st matching layer leads to a smoother frequency response, but with lower sensitivity in the low frequency region.

Moreover, another different design could consist in a kerf filler material with higher damping, as follows :

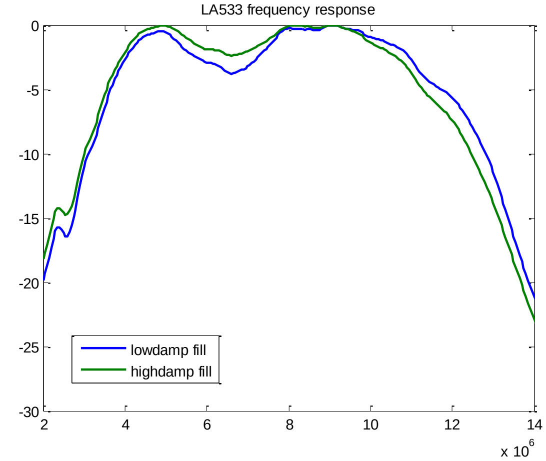


**Figure 11:** more simulations for pulse-echo frequency response (dB): low damping (Rayleigh) filler (blue, alpha = 7 $10^6$ $s^{-1}$ , beta = 1 $10^{-9}$ s), high damping (Rayleigh) filler (green, alpha = 8 $10^6$ $s^{-1}$ , beta = 1.5 $10^{-9}$ s)

Higher damping values for the array kerf filler lead to a smoother frequency response, that would be an upgrade to the current design.

## 7. Conclusions

A fast and efficient 'duplex-FEM' was developed for the simulation of the so called 'pulse-echo' performances of an ultrasound imaging probe. Such type of simulation is seldom found in literature, due to its complexity.

2D approximation and symmetry were employed and the ultrasound transmission and reception stages were separated.

The agreement between measurements and simulation results can be considered quite good and the model is validated for further applications and probe performance prediction.
Indeed, 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.
Finally, the time for complete simulation of probe pulse-echo performance is approximately only 18min (on a Dell T3500 workstation, 8GB).

## 8. References

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