Toward a virtual laboratory for the design of acoustic imaging systems

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ABSTRACT

The need for powerful simulation package devoted to ultrasonic transducers has induced many developments based on finite element techniques. On the other hand, New approaches can be implemented to provide more complete design and analysis tools, including front and back-end electronics. In this paper, examples of computation results are reported concerning 2D acoustic problems (standard probes and 2-2 piezocomposite) and 1-3 connectivity piezocomposites (3D). The use computation results together with a computation simulator is discussed. As a conclusion, The possibility to simulate the construction of an acoustic image using our ultrasonics virtual laboratory is evoked.

INTRODUCTION

Development of modern theoretical tools for the design of ultrasound transducers used for acoustic imaging applications or non-destructive evaluation has received a very large interest during the last decade. Many efforts have been dedicated to the implementation of numerical calculation programs mainly based on finite element analysis (FEA) [1] and boundary element methods (BEM) [2]. The use of such tools allows one to overcome the limitations of classical approaches based on the 1-dimension Mason's model [3] (or its variants like KLM and so on) which poorly simulate devices exhibiting actual 2D or 3D shapes (for which flexural, torsion or shear modes must be accurately taken into account). The corresponding computations give accurately access to the main characteristics of the transducer behaviour either in time or spectral domains (bandwidth, coupling factors, losses, dynamics, etc.). One can then optimise any particular characteristic of a given transducer regarding its geometrical parameters or its constitutive materials.

On the other hand, this optimisation approach does not give any direct information on the actual working of the transducer used in an imaging system. One can easily understand that such information could be of great help in a global design procedure taking into account the whole measurement scheme, from the excitation impulse to the grey scale encoding of the current location of the observed body. In that matter, the possibility to insert numerical computation results in an electronics device simulator offers an attractive approach to try and address this problem. This allows one to simulate a whole imaging system taking into account the way the electric excitation is generated and transmitted to the transducer (using appropriate electrical matching elements) and how the later answers. Treatment of the returned signal can be then simulated, providing the analogic electrical information corresponding to one pixel of the final acoustic image.

This approach is illustrated in the present paper using our home-made finite element/boundary element programs built on the MODULEF package [4] (initially developed by INRIA Rocquencourt) together with a commercial electronics simulator. The specific modules of our computation tool is first described. Computation of ultrasound probes are reported for typical transducers (2D, 3D, non periodic or periodic) assuming different kind of radiation boundary conditions in spectral and time domains. It is then shown how to use the results of these computations to perform the above-described global simulation of a simple acoustic imaging system. Examples of simulation results are reported to illustrate the proposed approach. Finally, future developments are discussed to achieve an integrated set of programs providing one all the tools to design acoustic imaging systems just like one would proceed experimentally, yielding the concept of virtual laboratory for ultrasonics.

BASIC ELEMENTS OF THE VIRTUAL LABORATORY

As a very first and simple approach, the ultrasonics virtual laboratory can be considered conformably to the scheme presented in fig.1. It roughly consists in an open loop modelling system requiring the simulation of the beam forming device providing the excitation of a given probe, a second simulation stage devoted to high voltage electronics, the acoustic package, a low noise detection electronics including signal processing (filtering, averaging, and so on) and finally the virtual image computation tools.

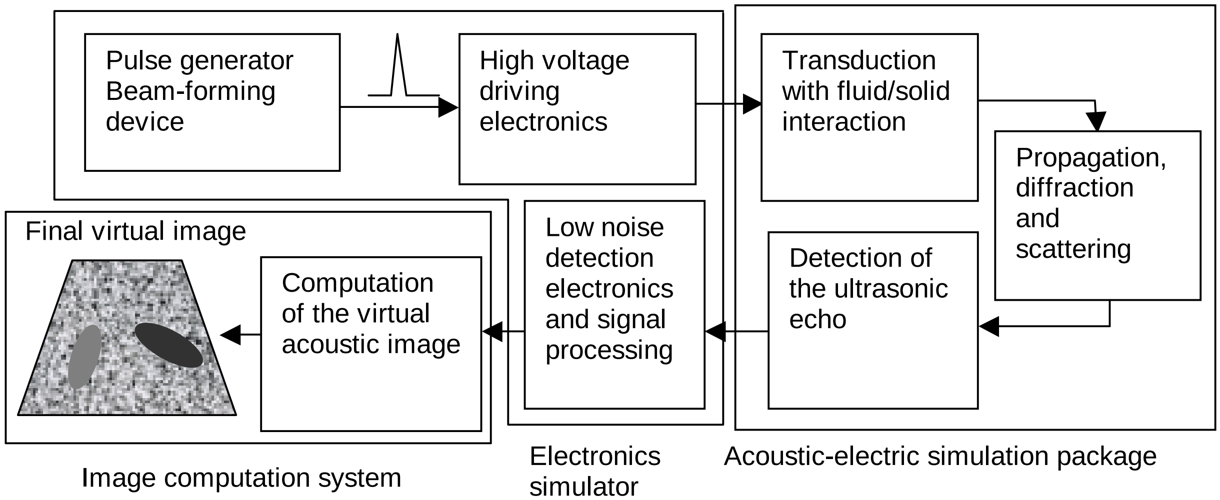


Fig. 1 Scheme of the principle of an ultrasonics virtual laboratory

In the following subsections, we inspect the capabilities of each package required to answer the specific demands for the design and analysis of acoustic imaging systems. One can of course remark that a design tool should provide entries at different level of the simulation procedure and also the possibility to operate in closed loop in order to optimise a given part of the processing chain. This has to be done in future developments but it directly depends on the correct operation of the open loop procedure presented in fig.1.

Acoustic-electric simulation package

This section is devoted to the description of computation tools intended to simulate the excitation of ultrasound pressure waves in the medium to be observed, propagation and diffraction and more generally scattering phenomena arising in that medium and finally the detection of the ultrasonic echo. Many work has been devoted to the implementation of such tools, starting from the well-known Mason model and its numerous improvements to the very last versions of numerical simulation packages like PZFlex [4] or ATILA/SYSNOISE [4] or ANSYS [5].

Common to all these developments is the need to correctly identify the physical properties of the materials used to build the transducers but also of the body in which the waves are launched and scattered. Thus, the acoustic losses are rather difficult to identify for polymers and sometimes for piezoceramics currently used for instance in piezocomposite structures. More specifically, shear elastic constants are poorly accessible for materials used as matching layers or backing or acoustic lenses. Since the accuracy of the resulting simulation will mainly depend on these constants (elastic, piezoelectric, dielectric, etc.), one has to pay a particular attention to the characterisation of the materials of the probe. To avoid any trouble due to uncertainties concerning the materials data sets, it is convenient to benefit by a model updating module as proposed in [7]. According to the corresponding developments, one can accurately correct the data set of a given structure using the same FEA tool as the one used in the virtual laboratory assuming that geometric parameters (thickness of the layers, width and height of the transducer elements) are precisely measured.

Different techniques can be then implemented to represent the operation of the transducer. Most of the groups involved in the developments of such tools prefers the FEA approach for the simulation of the transducer working because it provides enough flexibility to address almost any problem in the field of acoustic imaging probes. However, it is necessary to adapt the computation tools to generic problems (2D, 3D, axial symmetry, periodicity, radiation) to avoid too long computation duration. Moreover, even if most of imaging probe transducers uses piezoelectricity as active principle, it is important to simulate other actuation means capable to provide substantial improvements in the production of acoustic images (for instance cMUTs [8]). Nevertheless, the Lagrangian formulation of the piezoelectric problem is recalled here as an example of fundamental relation used in FEA, assuming an harmonic dependence of all the fields with time :

$$\iiint_{\Omega}\left(\rho\omega^2 u_i \delta u_i^* + \frac{\partial \delta u_i^*}{\partial x_j} C_{ijkl} \frac{\partial u_l}{\partial x_k} + \frac{\partial \delta u_i^*}{\partial x_j} e_{kij} \frac{\partial \phi}{\partial x_k} + \frac{\partial \delta \phi^*}{\partial x_i} e_{ijk} \frac{\partial u_j}{\partial x_k} - \frac{\partial \delta \phi^*}{\partial x_i} \varepsilon_{ik} \frac{\partial \phi}{\partial x_k}\right) dV = \iint_{\Gamma} \delta u_i^* T_{ij} n_j dS + \iint_{\Gamma} \delta \phi^* Q dS \tag{1}$$

In this equation, the equilibrium of piezo-elastic and electrostatic energy is expressed, with kinetics and potential volume energy on the left hand side and the surface forces and electrical charges on the right hand side. This equation serves as the very base of all our developments. It gives access to the simulation of transducers in vacuum (no radiation) including acoustical and electrical losses represented as an imaginary part of the material constants C_{ijkl}, e_{kij} and ε_{ij} (elastic, piezoelectric and elastic constants). The standard FEA interpolation technique is applied to this equation conformably to [1], yielding the final discrete algebraic equation system as follows :

$$\begin{bmatrix} K_{uu} - \omega^2 M_{uu} & K_{u\phi} \\ K_{\phi u} & K_{\phi\phi} \end{bmatrix} \begin{Bmatrix} u \\ \phi \end{Bmatrix} = \begin{Bmatrix} F \\ Q \end{Bmatrix} \tag{2}$$

In this system, the unknowns are the nodal displacements and electrical potential. Different kind of boundary conditions can be applied to solve this problem. For piezoelectric problems, the active electrodes can be considered as grounded or fixed to a given potential or the current can be forced to a given value. In our case, we consider a voltage excitation, imposing a potential difference of 1Volt giving easily access to the electrode charge, hence the admittance, by simply summing the nodal charge on the regarded electrode. More complicated boundary conditions can be applied to address for instance periodic problems. In that case, a pseudo-periodic relation between both sides of the period (see fig.2) is considered as follows :

$$\begin{Bmatrix} u\ \Gamma_B \\ \phi\ \Gamma_B \end{Bmatrix} = \begin{Bmatrix} u\ \Gamma_A \\ \phi\ \Gamma_A \end{Bmatrix} e^{-j2\pi\gamma} \tag{3}$$

where γ represent an excitation parameter defined in fig.2.

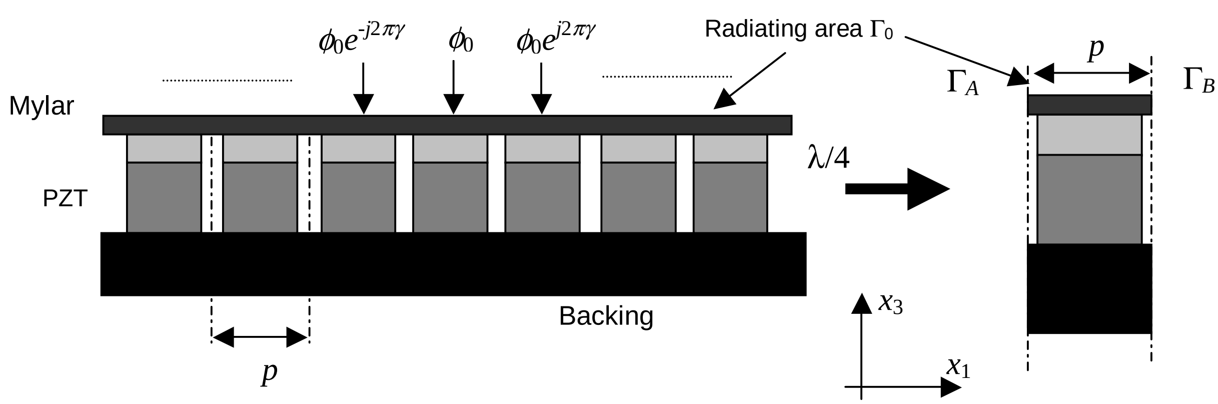


Fig.2 Scheme of a periodic structure represented by only one period

The efficiency of this approach is illustrated by the following comparison between theory and experiments performed on a 2-2 connectivity piezocomposite manufactured by our partners from FRAMATOME-ANP [9].

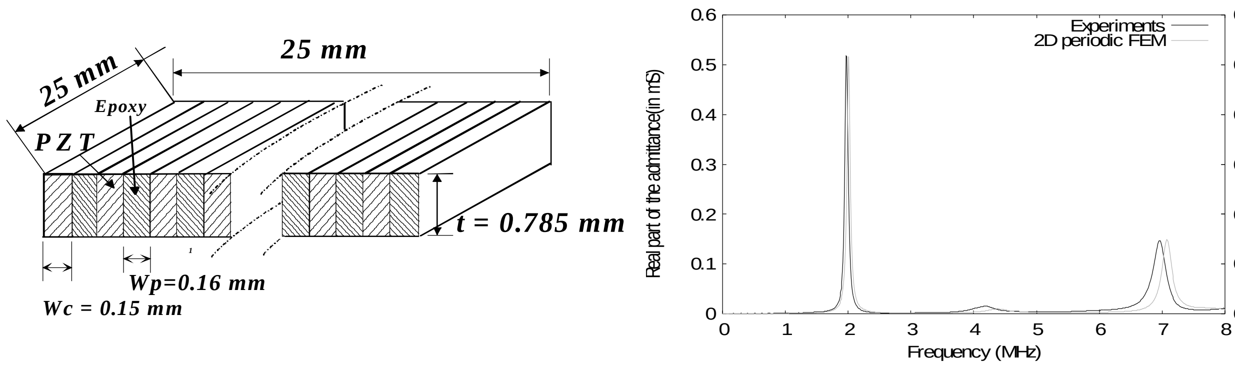
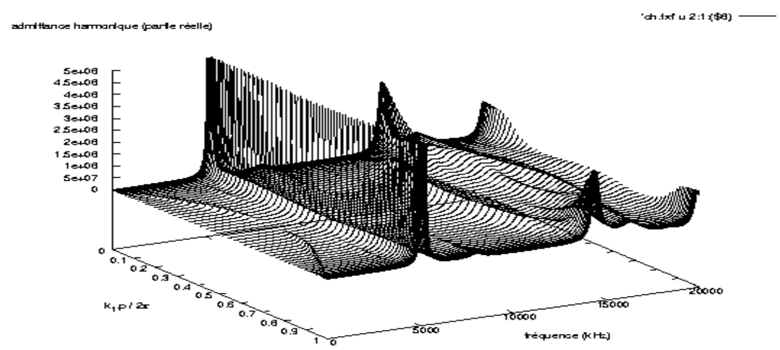
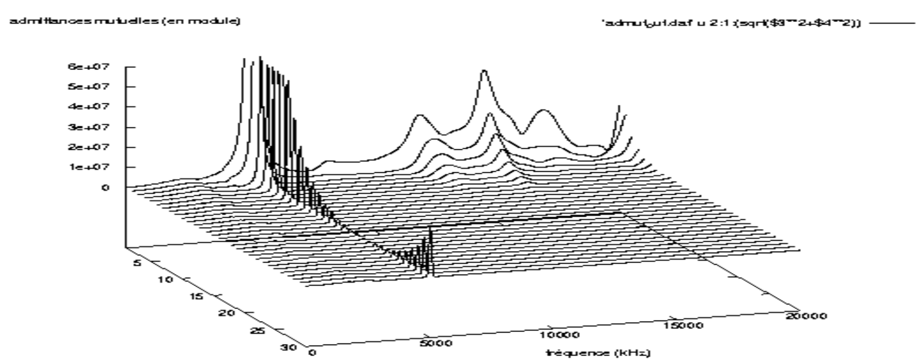


Fig.3 Prediction and measurement of the auto-admittance of the described 2-2 piezocomposite

The approach consisting in taking into account the periodic structure of transducers provides more accurate results and significantly saves computation time. It also gives access to an effective evaluation of cross-talk effects by the use of mutual admittance which is naturally deduced from the harmonic admittance by a simple Fourier transform, as shown in the next figure.



(a)



(b)

Fig.4 Example of mutual admittance (b) computed from the harmonic admittance (a) of a 2-2 piezocomposite

Another fundamental aspect in these developments concerns the radiation boundary conditions. Different approaches can be implemented according to the shape of the radiation boundary, the acoustic aperture but also the medium in which the waves are radiated. The most simple approach consists in assuming a plane wave radiation condition which relates the pressure to the displacements at the radiating boundary as follows :

$$P = j\omega\rho c u_i n_i \tag{4}$$

This expression is then used in the right hand side of eq.(1), substituting $T_{ij}.n_j$ by $-P$ and applying the usual FEA polynomial interpolation. This approach is only valid in the case of large aperture regarding the wavelength, or if a complex value of c is applied to take into account the actual acoustic impedance loading the transducer. In a more general approach, it is preferable to use a boundary formulation based on the Green's function G of the radiation medium. In that case, the pressure is given by a convolution of this Green's function with the normal displacement at the radiating boundary as follows:

$$T_{ij}n_j = -P \quad \text{with} \quad P = \int_{-\infty}^{+\infty} G_{22}(x-x')u_2(x')dx' \tag{5}$$

where the radiation is assumed along the x_2 axis (without any loss of generallity). The following figure shows an example the theoretical admittance of a transducer element of a commercial probe radiating in fluids. It is compared to a simplified computation based on the Mason model which is known in that case to provide accurate predictions (w/t << .5).

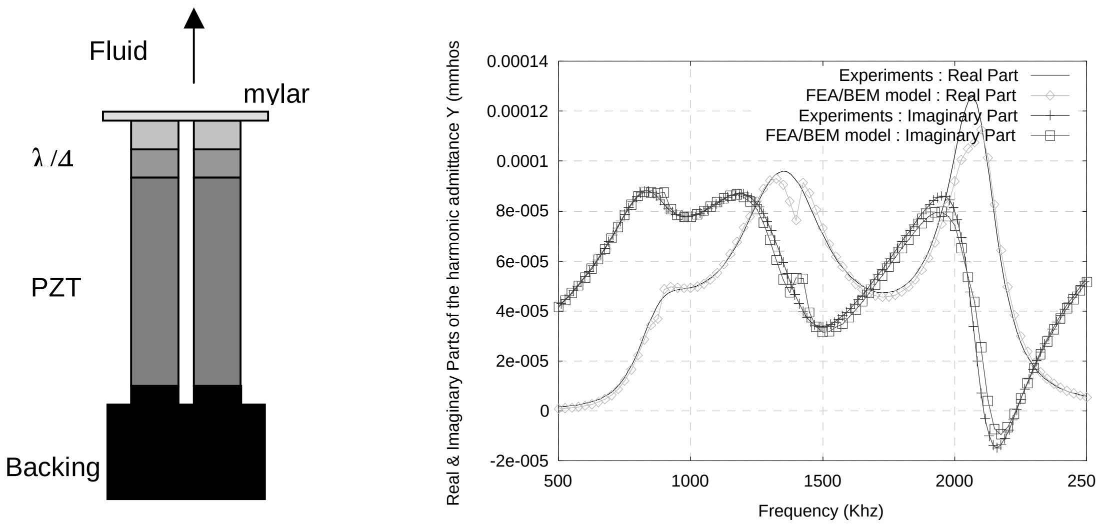


Fig.5 Typical structure of a standard imaging probe, predictions of its response when radiating in water

Another efficient approach can be implemented, consisting in mixing a displacement formulation conformably to equation (1) together with a pressure formulation. In that case, the fluid region close to the transducer is meshed and a simplified radiation condition (based on eq.(4)) is applied on a half circle bounding the near and medium field location. The pressure formulation is reported in eq.(6), showing how it is related to the displacement formulation (via the right hand side):

$$\iiint_{\Omega} \left(\rho\omega^2 P\delta P + \frac{1}{c_F^2}\frac{\partial \delta P}{\partial x_i}\frac{\partial P}{\partial x_i}\right)dV = \iint_{\Gamma} -\rho_F\omega^2 u_i n_i \delta P dS \tag{6}$$

For the implementation of such an approach, we have developed an interfacial element to link the solid and fluid media together. From a numerical point of view, it is necessary to normalise the material data to avoid to large differences of values in the final system to be solved. It is also convenient to divide eq.(6) by $\rho_F\omega^2$ to preserve the symmetric properties of the discrete FEA matrix. The following figure shows a comparison between theoretical admittance of a transducer element radiating in water obtained with the three presented approach. It appears that the Green's function approach and the mixed FEA method provides similar results, whereas the plane-wave (with $c\in\Re$) approach is far from the expected result.

It is also important to note that the three proposed approaches to address fluid/structure interaction can be transposed to periodic problems. In the case of the Green's function approach, one has to develop the boundary condition as a Bloch-Floquet expansion. The corresponding formulation is given as follows:

$$T_{ij}n_j = -P \quad \text{with} \quad P = \frac{1}{p}\int_{-p/2}^{+p/2} G_{22}^p(x-x')u_2(x')dx' \quad \text{and} \quad G_{22}^p(x) = \sum_{l=-\infty}^{\infty}\tilde{G}_{22}(\gamma+l,\omega)e^{-j\frac{2\pi}{p}(\gamma+l)x} \tag{7}$$

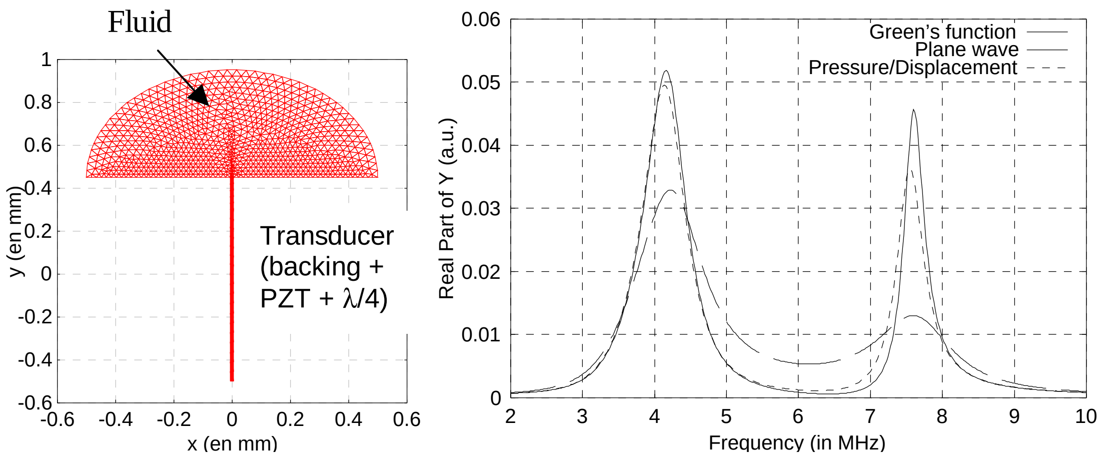


fig.6 Comparison between the three proposed approaches for addressing fluid/solid interaction

Insertion in an electronic simulator

The mixed pressure/displacement approach is the best suited for our purpose. It allows for instance to mesh the non homogeneous part of the problem (i.e. the transducer and a close obstacle to be imaged) to provide an accurate insight of acoustic phenomena arising during the transducer operation. It is also possible to simulate the operation of a given transducer in transmission mode. In that case, one has to mesh a symmetric problem of two transducers in regards, one launching the pressure waves and the second detecting them. It is then possible using proper electrical boundary conditions to extract an admittance or even a scattering matrix describing the behaviour of the system. One can advantageously insert this matrix in an electronic simulator like ADS© providing almost any possibility to model the driving and detection electronics associated to the transducer. This approach is currently under tests.

CONCLUSION

The main developments required for the implementation of our ultrasonics virtual laboratory have been described an illustrated by many examples in 2D. However, one has to note that 3D simulations can be also performed along the proposed approaches and are almost ready to use. The capability to simulate transducers and their driving and detection electronics is currently tested using the reported developments. A major effort is also performed to implement time dependent calculations in order to integrate non linear properties in the fluid FEA to simulate harmonic imaging.

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