Pressure Pulse Fields: Comparison of optical hydrophone measurements with FEM Simulations

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Abstract — Several approaches for simulating ultrasound are available. The main tools are Finite or Boundary element methods and the spatial impulse response methods. Finite and Boundary Element methods are the most flexible but also the most computationally expensive tools available. On the other hand the spatial impulse response is restricted only to linear acoustic problem, but with low computational demands and prime costs. While with diagnostic ultrasound it’s mostly sufficient to confine the equations on linear acoustics, this simplification is not possible with therapeutic ultrasound. High pressure amplitudes of therapeutic ultrasound transducers create strong nonlinear effects in the medium, which cannot be simulated using linear acoustic theory. We compare two types of optical hydrophones developed for pressure pulse measurements, the fiber-optic-hydrophone and the light-spot-hydrophone. Both are based on reflection changes of a laser beam due to the medium density modulation by a sound wave at the sensitive end of the device. The aim of our work is to compare the measurement of a Panametrics NDT Transducer with simulations using ABAQUS FEM Software.

FEM, Abaqus, LSHD, FASO, FOPH, Acoustic Simulation

I. INTRODUCTION

Prediction on the efficacy of an ultrasonic medical treatment device needs measurement of the field parameters. The measurements are carried out by hydrophones in de-gassed water. Two groups of hydrophones are available, the piezoelectric and the piezo-optic hydrophones. The robustness and the ease of use as well as the ability to measure negative pressures make the optical hydrophones the sensor of choice for high pressure pulse fields.

While measurements are needed to characterize the field of an ultrasonic device, simulations are needed in the development period to predict the field of the same. Several approaches for simulating ultrasound are available. As long as the sound propagation occurs in the linear range the emitted and the scattered field can be calculated using spatial impulse response. With diagnostic ultrasound it’s mostly sufficient to confine the equations on linear acoustic, though this simplification is not possible with therapeutic ultrasound. High pressure amplitudes of therapeutic ultrasound transducers create strong nonlinear effects in the medium, which cannot be simulated using linear acoustic theory. The energy from nonlinear waves is deposited in a different way than in the linear case which has strong effect on the bio-effects in human tissue. At the sight of these effects on biological tissue and to ensure patient safety, it is obvious why non-linear wave propagation need to be considered. [1]

In this paper we compare the measurements of two optical hydrophones, the Light Spot Hydrophone and the Fiber Optic Hydrophone, with simulations using ABAQUS®.

II. PHYSICAL PRINCIPLES

A. Hydrophones

Measurements of ultrasonic fields are often performed using PVDF membrane hydrophones. PVDF is a piezoelectric material and is preferably used for hydrophones due to its high sensibility and high bandwidth. The disadvantage of PVDF hydrophones are the hydrophobic properties of the membrane surface and hence a poor ability to measure negative pressures. [2] The hydrophobic properties of the membrane abet the occurrence of cavitation in the fluid and consequently destroying the hydrophone. To avoid averaging effects the sensor element diameter should be in the sub-millimeter range. Due to fringe effects, PVDF sensor element diameters below 0.5 mm are difficult to realize. [3].

The first approach for robust optical hydrophones arrived with the fiber optic hydrophone (FOPH). The principle of FOPH is based on the change of light reflectivity at the end-face of a fiber, when the incident wave passes the fiber tip. The pressure wave changes the mass density of the fluid and the fiber, which in turn modulate the refractive index. Laser light is coupled into the fiber and the reflected part is measured by a photodiode. The electrical signal of the photo-detector represents the pressure-time-development at the location of the fiber tip. [3] The FOPH shows good results for pressure and energy estimation. [2] [6] Advantages of the FOPH are the high adhesion between the sensor and water, the small diameter of the fiber tip and the high bandwidth of the sensor which is mainly limited by the photodiode. Unfortunately, with fiber-diameters less than 100 μm the fiber tends to break during measurements in presence of high peak pressures, which leads to complicated recalibration of the sensor. [2] The LSHD is based on the same principle as the FOPH with some enhancements regarding the stability and the ease of
recalibration of the sensor. The sensitive area of the hydrophone is a laser light spot at a water-glass interface. At the glass-water interface of a solid glass block the pressure variation changes the density of the medium and hence the refractive index, which modulates the intensity of the reflected light at the interface. The transformation of the reflected light into an electrical signal by a photodiode reproduces the pressure history at the spot position.[2]

In both cases the hydrophone output voltage depends only on the reflectivity parameters at the interface and on the electronic properties of the system. Due to the low compressibility of the solid material, in contrast to the high compressibility of water, the change of refractive in the solid material can be neglected.[3] The calibration of optical hydrophones is completely defined by the material properties, and there is no need of frequent calibration with reference hydrophones. [6]

B. Finite element techniques applied on acoustic nonlinearity

Linear acoustic theory is based on small acoustic pressure waves and linear propagation of the sound waves. While these assumptions are sufficient for most diagnostic sound fields with low pressure levels, they are invalid in sound fields with high pressure values, e.g. therapeutic ultrasound fields. If the wave amplitude reaches a certain threshold nonlinear effects predominates the wave propagation and the linear wave equation becomes inadequate.[3] Nonlinearity implies that the sound speed depends on the acoustic pressure in the fluid. As the sound wave prop-ages it distorts and energy is transferred from lower harmonics to higher harmonics leading to a steepening of the wave.[4]

The application of Finite Element (FEM) and boundary element techniques (BEM) on acoustic problems can be divided into two steps. First: the creation of the mesh and discretization of the model in triangular, quadratic, tetrahedral and several other finite elements. The second step is the solution of the problem by solving differential equations describing the physical model and post-processing of the results. Both techniques serve to approximate the acoustic solution. The main difference between the FEM and BEM is the discretization approach. While for FEM the whole domain of interest need to be modeled, for BEM only the boundary is discretized. Another distinction is that BEM applications are mostly limited on linear problems.[7]

The FEM – using Abaqus® FEM Software – models the acoustic equilibrium equation with nodal pressures on an acoustic mesh. All the effects included in the underlying equations are included in the solutions of the finite element model. The acoustic properties in the model are defined by adding the fluid bulk modulus, density and a volumetric drag. In Abaqus® acoustic analysis are assumed to be linear perturbations of the base state. Particle of a medium displace from an original, stress free condition only through dilatation or compression. [8] Despite of the ease of use of acoustic elements in Abaqus®, non-linear effects cannot be modeled with acoustic element with the same simplicity. For certain non-linear effects equation-of-state (EOS) material model can be used. EOS materials are non-acoustic solid-continuum elements, where all the properties of the material are given in terms of pressure, volume and temperature. Equation of state material definition in Abaqus® is available as Mie-Grüneisen equation of state, providing the linear \( u_s = \frac{C_0 + s}{u_p} \) Hugoniot form. \( u_s \) – Up Hugoniot model is based on many experiments conducted to determine the EOS of materials. The experiments show that the shock wave velocity \( u_s \) and particle velocity \( u_p \) are linearly related in most materials by the equation

\[
U_s = C_0 + s \cdot U_p
\]

The parameter \( C_0 \) is equal to the zero-pressurebulk sound speed. The second parameter \( s \) is related to the isentropic pressure derivative of the bulk modulus, and describes the nonlinear properties of the material.[9]

III. EXPERIMENTAL SETUP

The measurements are done in degased and deionized water with constant temperature of 25°C. The Panametrics 5 MHz NDT Transducer is placed in a water tank. A GE Panametrics Square-wave pulser (GE Panametrics Wal-them, MA) is used to drive the transducer. Measurements are done with the Light Spot Hydrophone LSHD-2 (Siemens Erlangen and University of Erlangen) and a fiber op-tic hydrophone FASO-01 (Siemens Erlangen) and recorded with an HAMEG 1508-2 oscilloscope. The same transducer was measured at PTB in Braunschweig using a Laser-Interferometer-Hydrophone. This calibrated hydro-phone is used for comparison. All the measurements are done at a distance of 10 mm.

IV. RESULTS

The measurements with the LSHD and FASO – after deconvolution of the FASO signal to remove the transfer properties of the hydrophone due to the rigid reflections at the fiber tip– show good agreement with calibrated interferometer measurements (Figure 1 and 2).

![Figure 1](image-url)  

Figure 1. The LSHD in comparison to the interferometer measurements at 300 V excitation of the Panametrics NDT Transducer. Measurement at 10 mm distance to the transducer on the acoustic axis.

The LSHD overestimates the negative part of the pulse which has a significant effect on the Energy of the pulse. This has also been noticed by N. Smith et al. [10], though there is not yet an explanation for this phenomenon.
Figure 2. The FASO measurements after de-convolving of the signal at 300 V excitation. Despite averaging of 64 measurements a significant noise level remains. Measurement at 10 mm distance to the transducer on the acoustical axis.

Despite long signal averaging the FASO still suffer from low signal-to-noise-ratio (SNR), which is a drawback of refractive type hydrophones when used for low pressure field measurements (Figure 2).

As obvious in Figure 1 and 2 the Panametrics NDT transducer shows nonlinear steepening effects of the pressure wave. In our first approach we simulate the steepening effect using EOS material model (Figure 3). For this propose we assume an ideal model to simulate the nonlinear propagation of waves in water without damping effects.

Figure 3. Illustration of the model. The environment is modeled using EOS material. The boundaries are specified by natural boundary condition (rigid surface). The sound source is specified as pressure values (1 MPa).

We simulate an acoustic source with 2 MPa acoustic pressure for two different EOS materials, the first with a nonlinearity value of zero and the second with a non-linearity value of 1.75 (Figure 4). Our results were comparable to those provided by Simulia.

In a second step we simulate the field of the Panametrics NDT transducer using the same EOS Model. The source was modeled by providing a pressure load at the end-face of the model. To resolve the frequency components of the load sufficiently the mesh has to be seeded with an element size of 3 \( \mu m \). The analysis is performed using dynamic explicit procedure.

Figure 4. Simulation of signal distortion and shockwave formation due to nonlinear wave propagation in water at a distance of 43 mm of the source. The blue chart is modeled with an EOS non-linearity value of 0 and the red chart with an value of 1.75. No numerical dissipation used.

For the first attempt we do not include damping effects in the material definition, though some amount of numerical dissipation need to be included to avoid high frequency oscillations and stability problems while solving the differential equations. The other end-face of the acoustic system is modeled with infinite structure elements to ensure propagating waves without reflections at the end face. Since the model is based on finite elements appropriate boundary conditions are applied to fix the displacement degree of freedom of the mesh orthogonal to the wave propagation. The pressure can be extracted at the element facets as output value.

Even though the result of the simulations show good agreement with the measurement (Figure 5), it wasn’t possible to find the same good agreement for other setups. Furthermore we need to run the simulation several times and change the focusing and excitation of the transducer as well as the material properties (EOS Parameter) until we obtain an acceptable agreement.

Figure 5. Simulation of the Panametrics NDT transducer with Abaqus using EOS Material at a distance of 10 mm (blue chart). Interferometer measurement at the same distance with 300 V excitation of the transducer.

At that moment we haven’t an explanation for this, especially why the excitation in the simulation had to be changed to from a square wave to a sinusoidal signal to achieve a signal comparable to the measurements. Reasons for that could be the lack of information about the pressure distribution on the...
transducer surface. We extrapolate the pressure distribution on the surface of the transducer by pressure measurements in vicinity of the transducer using a 1/r fit. Other influence could be the simplicity of our model.

V. DISCUSSION

The measurements show that high fidelity measurements of lesser focused pressure pulse sources could be made. Processed pressure-time signals of both hydrophones at the same position in the pressure pulse fields are in very good agreement. The advantages of the piezooptic hydrophones are the ease of use and the lapse of an acoustic calibration. Disadvantage of both hydrophones is the low sensibility and the poor SNR of the sensor making long averaging of the signal for low amplitude pressures needed.

With simulations we could approximate the pressure distribution but couldn’t find a model to predict the field on an arbitrary setup. Further work on this issue are needed.

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