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NON-LINEAR PROPAGATION AND BROADBAND SCATTERING SIMULATIONS USING THE K-SPACE METHOD

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ABSTRACT

Underwater acoustics represents vast area of knowledge with huge number of applications, some of hottest topics in this field are studied using numerical methods that integrates partial differential equations (e.g FDTD, FEM..). These kind of techniques are actually applied in fish target strength calculations giving a promising results in terms of biomass estimation or even identifying species using the backscattering generated by target. But these numeric techniques of integration require an intensive use of CPU time, turning difficult the problem of calculate the backscattering of big size target (e.g simulation of tuna species). In this communication is presented work related with the use of k-Space-pseudo-spectral. Advantage of use pseudo-spectral method is based on the fact that uses less points to recover the temporary perturbation, propagating through the spatial mesh due to the use of Fourier collocation method. During this communication will be shown two studies, one in relation with simulation of acoustic field pattern for linear and non-linear regime with the aim to check the capabilities of k-wave [1] toolbox in relation with parametric acoustic generation. The other one is related with the calculation of target strength (TS) of tungsten carbide sphere of 3.8mm of radius. The interest of this study is mainly related with the possibility of use kwave toolbox to simulate the TS of underwater targets with complicated symmetry (e.g fish taxa with swim bladder). The use of a classical calibration ball as a target can bring the possibility to test the feasibility of use k-space method to calculate TS parameter using the backscattering produced by target.

1. Introduction

Underwater acoustics is a vast field of knowledge that covers multiple kind of problems from propagation of sound under variable conditions (e.g soundscape predictions), to studies related with development of techniques to predict the acoustic signature of ships or target strength related to specific fish taxa (e.g species with swim bladder). The major part of topics related with underwater acoustics have a common characteristic that is dimensions of acoustic field to solve are large. By this reason some problems like simulation of target strength of fish are difficult to sort out applying methods of simulation like FDTD or FEM, especially if the species considered presents large dimensions. Focusing on target strength topic, some authors are applying simulation techniques that achieve the knowledge of the acoustic field in an efficient way trying to reduce the CPU time needed, turning approachable the integration of governing acoustic equations [1]. The aim of this communication is test the feasibility of use the kspace pseudo-spectral method in relation to underwater acoustic problems, specifically related with linear and non-linear field pattern prediction and calculation of backscattering produced by target. What makes interesting kspace pseudo spectral method is the fact that allows solve partial differential equations system for broadband acoustic waves in heterogeneous media, applying even absorption in the selected medium and thanks to combine the spectral calculation of spatial derivative with the use of temporary propagator expressed in the spatial frequency domain or k-space, need less CPU time. In fact, classical methods like FDTD or FEM need at least typically 10 points of grid per acoustic wavelength to achieve a certain level of accuracy in results, but considering the discretization of equations using Fourier series and keeping in mind that the basis of these functions are sinusoidal seems that less points per grid are needed, theoretically only two grid points are needed to solve the problem. These aspects are clearly explained in [2]. Kwave is an acoustic toolbox able to be used in Matlab software that implements the Kspace pseudo spectral method. This code has been developed since 2009 by Bradley Treeby and Ben Cox (University College of London) and has been widely used in the field of medical ultrasound and specifically in photoacoustic tomography. Kwave solves time domain simulation of acoustic wave fields in 1D, 2D or 3D. It works for both linear and nonlinear regimes. There is a C++ version driven by Jiri Jaros (Brno University of Technology), Cox and Treeby released in 2016. The equations governing the K-wave code are first-order differential equations based on the conservation equations of mass, momentum and pressure density.

$$\frac{\partial \mathbf{u}}{\partial t} = -\frac{1}{\rho_0}\nabla p \ , \qquad \text{(momentum conservation)}$$

$$\frac{\partial \rho}{\partial t} = -\left(2\rho + \rho_0\right)\nabla\cdot\mathbf{u} - \mathbf{u}\cdot\nabla\rho_0 \ , \qquad \text{(mass conservation)}$$

$$p = c_0^2\left(\rho + \mathbf{d}\cdot\nabla\rho_0 + \frac{B}{2A}\frac{\rho^2}{\rho_0} - \mathrm{L}\rho\right) \ . \qquad \text{(pressure-density relation)}$$

The operator L present in pressure- density equation shown above, takes in to account the attenuation of media and dispersion of acoustic field.

$$\mathrm{L} = \tau\frac{\partial}{\partial t}\left(-\nabla^2\right)^{\frac{y}{2}-1} + \eta\left(-\nabla^2\right)^{\frac{y+1}{2}-1}$$

$$\tau = -2\alpha_0 c_0^{y-1}, \qquad \eta = 2\alpha_0 c_0^{y}\tan\left(\pi y/2\right)$$

In the following sections are covered two problems related with underwater acoustics as was introduced before, with the aim to test Kwave tool applied on underwater acoustic area.

2. Linear and non-linear propagation

Study was performed in the framework of the research and development of parametric echosounder, able to work in a single frequency range or using a properly modulated signal. Parametric generation theory [3] predicts that signal modulated by two frequency primary components, assume f_1 and f_2, can generate a parametric signal of harmonics (f_1 + f_2,) 2·f_1, 2·f_2, and (f_2 – f_1). In our study difference parametric beam was selected as the most interesting one, because it offers the possibility to have a high frequency and low frequency emission using the same transducer. Parameterize the threshold in terms of pressure level needed to generate parametric beam or prediction of directivity of linear and non-linear harmonics in function of radius of transducer designed, were crucial. With this aim were developed several kind of measurements at laboratory facilities located at Gandia's harbor (Unidad Mixta IEO-UPV) and simulations were carried out using Kwave acoustic toolbox. Experimental measurements were performed using two prototypes of planar transducer (fig.1) that implements different type of piezo-ceramic as an active element. Concerning about the experimental setup the directivity measurements and pressure level recorded, including for parametric beam difference, were performed using a tank of dimensions (10 x 5 x 1.5) m^3 with a full tridimensional positioning system installed (fig.2).

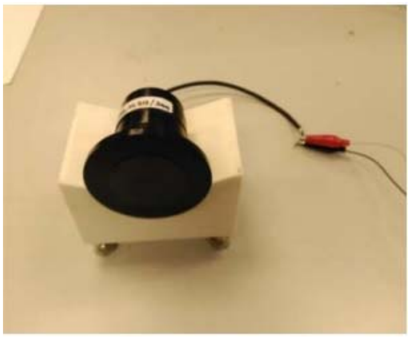


Fig.1. Detail of planar transducer prototype used as a parametric non-linear difference beam generator.

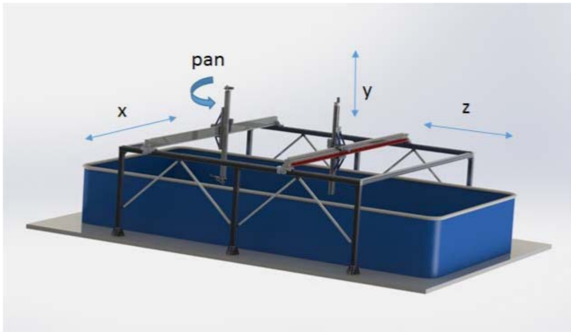
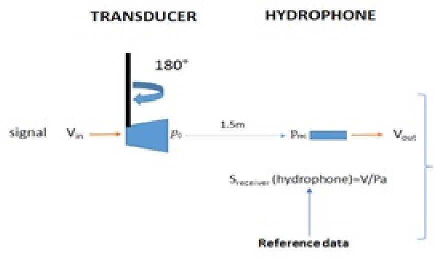


Fig.2. Cad design of calibration tank installed at laboratory facilities of Unidad Mixta IEO-UPV located in Gandia´s harbour.

2.1. Results achieved, linear and non-linear propagation

Summarizing some results obtained correlating experimental and simulated data, seems that predictions obtained using kwave toolbox are in good agreement with experimental data. In figure 4 & 5 are shown results for directivity of two prototypes of transducer considered in this study. Were simulated and measured the two main important aspects related with the expected use of the designed devices that are, considering a tone at its resonance frequency, 120kHz for both transducers, and using a modulated two frequency signal (90kHz & 150kHz) trying to generate parametric frequency beam at the medium.



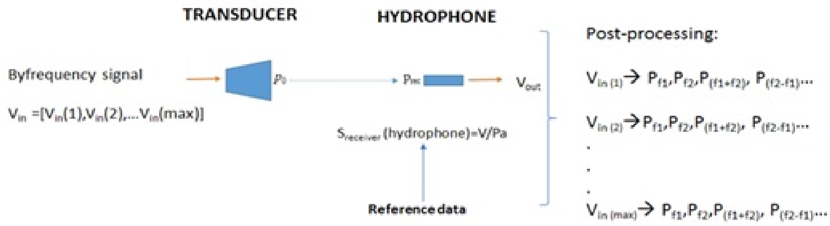


Fig.3. Detail of type of measurements performed depending on signal used to feed the prototype transducers. Directivity of beams were measured using the pan axis rotation applied on the emitter. Distance among emitter and receiver was 1.5m.

Figures 4 and 5 shows results obtained for linear and parametric beams generated, both simulations were performed assuming non axisymmetric 2D model. In spite of this type of model is not the most realistic (because consider an infinite radiating plane) results are in quite good agreement due to the good experimental alignment between emitter and receiver (by proper directivity characterization). Angle of aperture at -3dB (is a commonly accepted parameter to define the directivity of underwater acoustic emitters) correctly matches for experimental and simulated data.

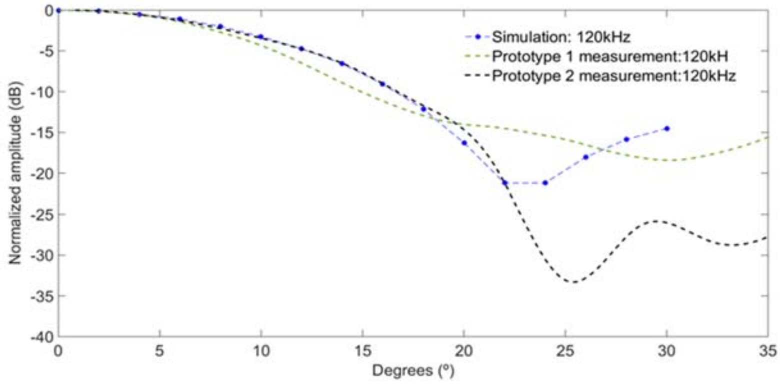


Fig.4. Experimental and simulated directivity considering transducer prototype 1 and prototype 2, for linear case signal of 120kHz.

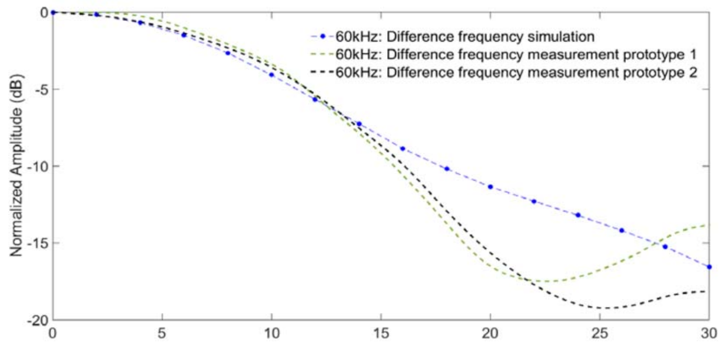


Fig.5. Experimental and simulated directivity considering transducer prototype 1 and prototype 2, for non linear case, parametric beam of 60kHz.

With respect to the sound pressure levels results at non-linear regime, is important to remark that figure 6 shows the simulated sound pressure level considering different amplitude of pressure radiated to the medium by the vibrating surface. This was used to feed in a correct way the transducers with the optimum level of voltage to achieve the threshold level in terms of amplitude of pressure at which starts to form the parametric difference beam. In figure 7 are collected results for sound pressure level predicted in function of transducer radius. This kind of simulation was helpful in the process of improvement the transducer prototype, being possible increase the level of pressure for difference non-linear beam.

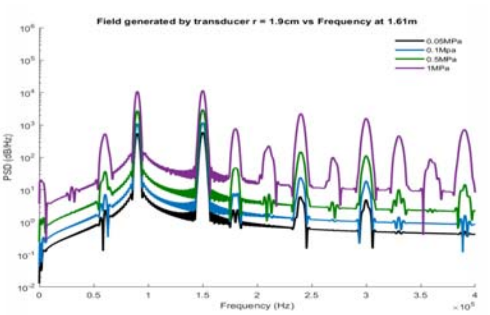


Fig.6. Detail of sound pressure level calculated using kwave, considering different pressure level at vibrating surface.

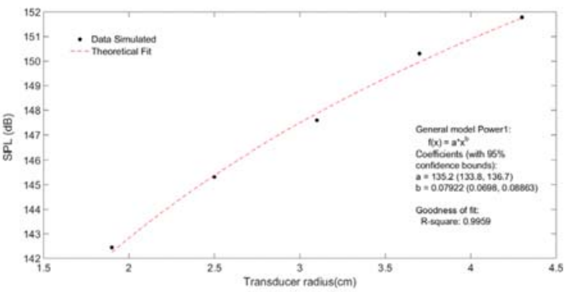


Fig.7. Expected relation of sound pressure level amplitude for difference frequency parametric beam with radius of transducer.

3. Target strength simulation of calibration tungsten carbide sphere using broadband signal

Calculation of target strength of taxa fish is a hot spot in underwater acoustic field. The possibility of use the backscattered acoustic signal of a specific target and the possibility of use it to perform biomass estimations [4,5]. Is known that target strength depends of size of fish but also the type and physiological characteristics of considered specie [6]. Considering that some species that are under study (e.g tuna species), due to present large dimensions, some authors are exploring methods that allows simulate the backscattering of fish but trying to reduce the CPU time requirement. By reasons exposed above, kwave could be a useful tool to perform simulations of acoustic complicated targets trying to reduce the number of spatial mesh points. With the aim to test the feasibility of this technique in backscattering problem, has been performed simulations to calculate the TS considering a calibration sphere of tungsten carbide with 38.1 mm of radius. Traditionally, spheres of different materials and radius has been widely used to perform calibrations of scientific echo-sounders systems. Simulations carried out can be divided in two types considering fluid-fluid interaction that means, are not considered shear waves at solid target so can be defined 'as a fluid' and fluid-solid interaction. Kwave has implemented a solver that considers elastic wave propagation through solid allowing to compute also shear waves and not only compressional [7]. With the aim to study the possible influence of consider fluid fluid or fluid solid interaction both kind of simulations has been developed. In addition, signal used has been a broadband signal with the aim to study the TS of three commonly used frequencies related with calibration sphere considered (90kHz, 120kHz & 200kHz). To conclude if results coming from simulations have been achieved accuracy needed, simulated data has been compared with results obtained using TS-Package developed by Dezhang Chu that implements an analytical model solution of solid sphere backscattering. This solution is commonly accepted as a correct value of TS for calibration spheres of different materials and sizes. The detail of geometry developed at kwave can be observed at figure 8. In this case a 3 dimensional simulation has been performed considering the radiating plane vibrating with 10 cm of diameter followed by calibration sphere located in the far field of the acoustic radiator surface. The sensor point represents the spatial point where pressure is recorded at the simulation and is located at 1m of calibration sphere.

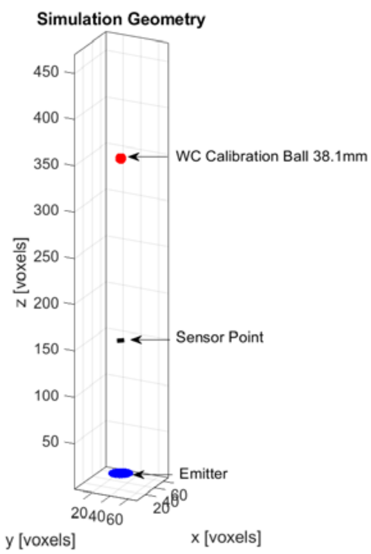


Fig.8. Detail of simulation scheme developed in kwave toolbox

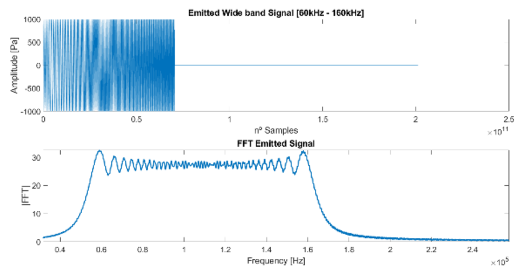


Fig.9. Broadband signal used to calculate de target strength of calibration sphere (Chirp with frequency range from 60kHz to 160kHz)

3.1. Results of fluid-fluid and fluid-solid interaction for tungsten carbide calibration sphere

As can be observed at figure 8, the sensor point collect the pressure of signal emitted by the vibrating circular plane when the disturbance introduced travels from the emitter to the calibration sphere and when sound is backscattered and comes from tungsten ball to emitter. Considering the pressure recorded during the whole time of simulation is possible to calculate the TS as 20log10(P_{back}/P_{inc}). Figures 10 and 11 shows the results obtained assuming fluid-fluid and fluid-solid interaction. Calculations of TS for each frequency has been computed using the analytical model developed by Chu, TS using wide band signal needed the application of filtering process to recover the frequency of interest, tone pure signals has been also considered to compare with wide band signal results (see legend of figures). The aim of use tone signals from wideband signal was test the feasibility of use wide band signal to recover different TS for each frequency using a single excitation signal.

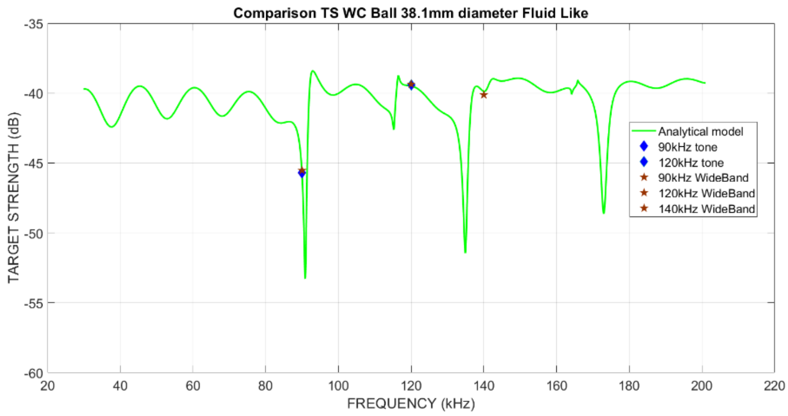


Fig.10. Comparison among TS calculation results considering wideband signal, tone signals at required frequencies and analytical model assumed as a accepted as an accurate result. Results obtained corresponds to fluid like interaction, this means that computation does not consider shear waves propagation and calibration sphere presents only compressional waves.

Results obtained pointed that for case of calibration sphere considered, the implementation of elastic solver do not affect clearly to results of TS obtained.

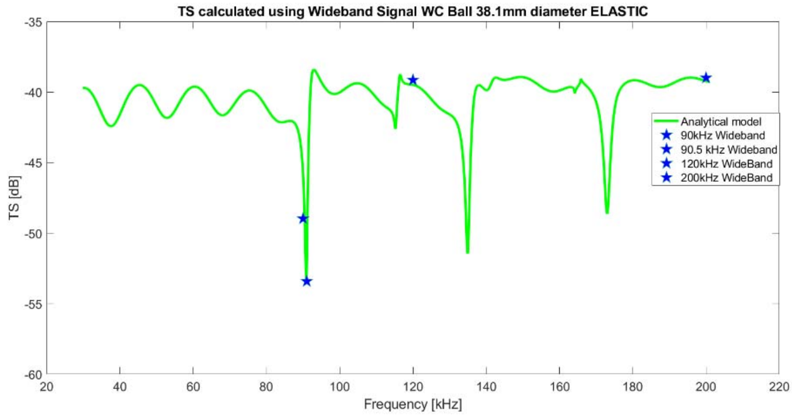


Fig.11. This figure contains results obtained considering fluid-solid interaction. In this case only wide band signals has been used to calculate TS.

Table 1 collects results of kwave simulations for both type of interactions considered in comparison with analytical model.

Table 1	TS [dB] Analytical	TS [dB] Fluid Fluid	TS [dB] Fluid Solid
90kHz	- 49.0	-45.5	-48,9
120kHz	-39.5	-39.4	-39.2
200kHz	-39.2	-	-38.9

Attending to all kind of simulations carried out with respect to TS calculation seems that all results are in quite good agreement with analytical model. The approximate CPU time required to simulate the wideband signal case with fluid-solid interaction (was the most intensive one in terms of computational resources used) was 36 hours. Is remarkable that volume considered was (0.25 x 0.25 x 1.5) m^3.

4. Conclussions

Summarizing the results collected in this communication, seems that Kwave can be used successfully in underwater acoustic simulations. Both type of simulations carried out (non-linear generation beam and backscattering calculations) offer good agreement if are compared with experimental data measured in case of non-linear parametric beam generation, or with analytical model for backscattering generated by calibration sphere target. Among other type of capabilities kwave works with images, allowing define masks with different type of material properties even allowing compute the backscattering from CT scan for example. This opens an opportunity for target strength calculations related to specific taxa fish if is available data in terms of image in 2D or 3D of physiognomy.

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