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Efficiency of parametric ultrasound generation in relaxing media for very shallow-water echo sounders

Patricia Ordóñez Cebrián[1*], Noé Jiménez González[1], Víctor Espinosa Roselló[1], Vicente Puig-Pons[1], Ester Soliveres González[1]

1Instituto de Investigación para la Gestión integrada de zonas Costeras (IGIC) Universitat Politècnica de València-Campus de Gandia, C/. Paranimf nº1, 46730 Grao de Gandía, Valencia, España ;

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Abstract

Parametric acoustic generation provides the possibility to obtain narrow and nearly side-lobe free acoustic beams for low frequencies [1]. In this way, the nonlinear interaction of two intense beams with close frequencies generates combinations of the spectral components: high frequency harmonics, difference-frequency harmonics and sum harmonics [2]. The most used in underwater acoustics to obtain the advantages above mentioned is the difference-frequency harmonic for its lower attenuation [3]. Moreover, sea water ultrasound absorption presents not only thermo viscous, but also ionic relaxation losses, both at the primary beam (due to magnesium sulfate presence), and at lower frequencies (boric acid ions). In this work, a computational finite differences method for nonlinear acoustical propagation with relaxation losses is employed to study the efficiency of the parametric sound generation in sea water [4]. Thereby, we present the design and development of parametric echo sounders for very shallow water (<20m), with typical wider beam apertures than commercially available scientific or parametrical echo sounders. This kind of devices, with low frequency narrow beams, provides the possibility to go through a fish school without screening effects due to the proximity between the targets. Beam spatial properties has been studied both numerically and experimentally.
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Keywords: underwater acoustics, parametric generation, nonlinear acoustics, echosounders, relaxation losses.

1. Introduction

The parametric sound generation is a well-known non-linear effect introduced by Peter Westervelt in the 60's [1]. This effect is based in the generation of spectral components: high frequency harmonics, difference-frequency harmonics and sum harmonics [2]. This is due to the non-linear interaction in the medium of two high intensity beams with close frequencies. In underwater acoustics, echo integration techniques have been developed over 30 years giving us a good estimation of fish abundance and size, performed by target strength measurements [6]. Nowadays these techniques have been carry out in open sea as in shallow water. The last one, have to present certain special characteristics in terms of biomass estimation and species characterization. These qualities are the utilization of wider

* Patricia Ordóñez. Tel.: +96 -3877000-ext.43681.
E-mail address: patorceb@epsg.upv.es.

beams to insonify the full fish school and generating collimated beams with free side-lobe in order to avoid as much as possible reflective interfaces. Apart from that, other important features in order to achieve good results are the possibility to realize multifrequency measures with the same insonify area as well as to go through the entire fish school without screening effects. Therefore the parametric echo sounders for very shallow water are chosen as a good work tool. Although there are parametric commercial echo sounders, they are few experiments done in this field [3] being its principal purpose the sub-bottom profile characterization. Moreover sea water ultrasonic absorption presents not only thermo-viscous losses, but also ionic relaxation losses due to magnesium sulfate presence and boric acid ions [4]. These losses could have an influence in the parametric beam and it is important to have into account in the predictions.

The aim of this work is establish the principal steps in the design of a parametric echosounder for shallow water with a wide aperture (~ 20º to 30º), and study the efficiency of the parametric sound generation by a computational finite differences method and experimental results. In addition it will be introduced the relaxation losses to analyze the results for the model in the sea water.

2. Materials and methods

2.1. Model equations

The main constitutive relations for nonlinear acoustic waves, which for a viscous fluid can be expressed as [5]

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) \ , \tag{1}$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \eta\nabla^2\mathbf{v} + \left(\zeta + \frac{\eta}{3}\right)\nabla(\nabla\cdot\mathbf{v}), \tag{2}$$

where ρ is the total density field, $\mathbf{v}$ is the particle velocity vector, p is the pressure, η and ζ are the coefficients of shear and the bulk viscosity respectively. The acoustic waves described by this model exhibit viscous losses with squared power law dependence on frequency. In order to include a power law frequency dependence on the attenuation, a multiple relaxation model will be added into the time domain equations.

The basic mechanism for energy loss in a relaxing media is the appearance of a phase shift between the pressure and density fields. This behavior is commonly modeled as a time dependent connection at the fluid state equation, that for a fluid retaining the nonlinear effects up to second order an be expressed as [5]

$$p = c_0^2\rho' + \frac{c_0^2}{\rho_0}\frac{B}{2A}\rho'^2 + \int_{-\infty}^{t} G(t-t')\frac{\partial \rho'}{\partial t}dt, \tag{3}$$

where $\rho' = \rho - \rho_0$ is the density perturbation over the stationary density ρ_0, B/A is the nonlinear parameter, c_0 is the small amplitude sound speed, and $G(t)$ is the kernel associated with the relaxation mechanism. The first two terms describe the instantaneous response of the medium and the convolutional third term accounts for the "memory time" of the relaxing media. Thus, by choosing an adequate time function for the kernel $G(t)$ the model can present an attenuation and dispersion response that fits the experimental data of the heterogeneous media. If a sum of N exponential forms of the kernel $G(t)$ is taken into account, the integral form of the state eq. (3) leads to

$$p = c_\infty^2\rho' + \frac{c_0^2}{\rho_0}\frac{B}{2A}\rho'^2 - \sum_{n=1}^{N} S_n. \tag{4}$$

Here the "frozen" sound speed for N mechanisms is defined as

$$c_\infty^2 = c_0^2\left(1+\sum_{n=1}^{N}\eta_n\right) \tag{5}$$

and each state variable S_n obeys

$$\frac{\partial S_n}{\partial t} = -\frac{1}{\tau_n}S_n + \frac{\eta_n c_0^2}{\tau_n}\rho' \tag{6}$$

for each relaxation process. Model equations (1-2, 4, 6) are solved by finite differences in time domain method (FDTD). Thus, a space-time staggered discretization is employed and central finite differences operators are applied for solving both spatial and time differential operators. Due to the generalization formulation of the relaxation in the present model, frequency dependent attenuation can be obtained for the classical relaxation processes of boric acid and magnesium sulfate in seawater as shown in Fig. 1.

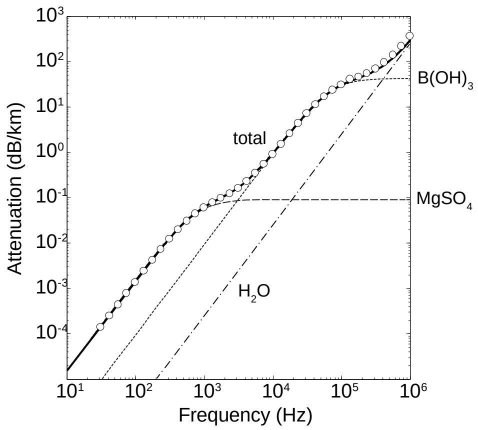

Fig. 1. Attenuation retrieved by the numerical method for the relaxation processes of oxygen and nitrogen in air (left), and magnesium sulphate and boric acid in seawater (right)

2.2. Analytical description

In parametric generation there are three important distances which control its behavior: the absorption distance, R_A, the Rayleigh distance, R_F, and the shock distance, R_S. Depending on the relation between them, different mathematical models can predict the sources levels for primary and secondary beam as well as the beamwidth. In our experimental case, transducers are governed by Berktay and Leahy model [2], where $R_S > R_A > R_F$ (under saturation level). Thus, the primary source level, SL_p can be expressed as:

$$SL_p = 10\log W_0 + 171 + 10\log\frac{4\pi S}{\lambda_p^2}(\text{ref.dB}/\mu\text{Pa@1m}) \tag{7}$$

where W_0 is the acoustic power, S is the transducer surface, and λ_p is the primary wavelength, the secondary source level , SL_S is expressed as:

$$SL_s = 2SL_p + 20\log(f_s)_{kHz} + 20\log\Delta - 287 \tag{8}$$

where f_s is the secondary frequency and Δ is the "effective length" of the parametric array. Finally, the beamwidth of the parametric array can be obtained as:

$$2\theta_{3dB} = \max\left\{4\sqrt{\frac{\alpha_T\lambda_s}{4\pi}}, 1.03\frac{\lambda_p}{d}\right\} \tag{9}$$

where d is the diameter of the transducer and λ_s is the secondary wavelength.

2.3. Experimental set-up

The acoustic field produce in parametric generation is experimental measured with two transducers with a resonance frequency around 200 kHz and with different diameter sizes (40 mm and 75 mm). Five parametric signals are chosen with frequencies oscillating between 15 kHz to 75 kHz. A standard configuration transmitter-receptor is established being the receptor the omnidirectional spherical hydrophone RESON TC4034. The measure procedure is realized in a water tank with dimensions $1.10\ \text{m} \times 0.80\ \text{m} \times 0.47\ \text{m}$. For directivity characterization acoustics waves are evaluated along the axis transducer axis in three different axial lines (-200 to 200 mm) with a spatial resolution of 25 mm. In the case of spreading and attenuation measurements acoustics waves are evaluated along the transducer axis, from 100 to 500 mm with a resolution of 50 mm.

3. Results

3.1. Efficiency parametric array

In order to validate computational model with experimental results and check the efficiency of our parametric array, comparisons in the beam pattern have been done. As shown in Fig. 2, numerical and experimental results presents similar pattern with small variations. On the other hand another important characteristic to pointed out is both primary and secondary beam are showing similar beamwidth, which is one of our principal features in the design of our parametric shallow water echosounder.

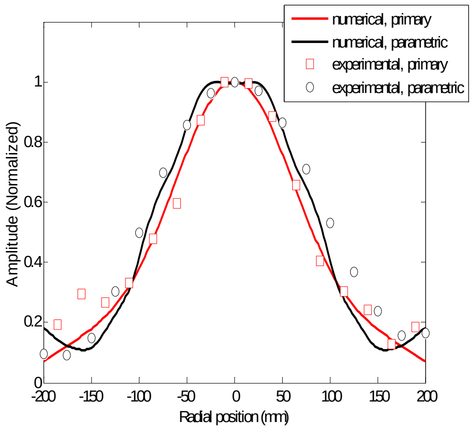

Fig. 2. Primary and secondary beamwidth comparison for numerical and experimental result for a parametric frequency of 45 kHz.

Figure 3 shows secondary beams for different parametric frequencies for the AIRMAR P19 transducer (Fig.3, left) and Sensortech SX20 (Fig. 3, right), where the beamwidth is maintained constant in all the frequency range. In terms of aperture angle, both transducers present smaller beamwidth than we are looking for our echosounder design $(\sim 20^{\circ}, 30^{\circ})$.

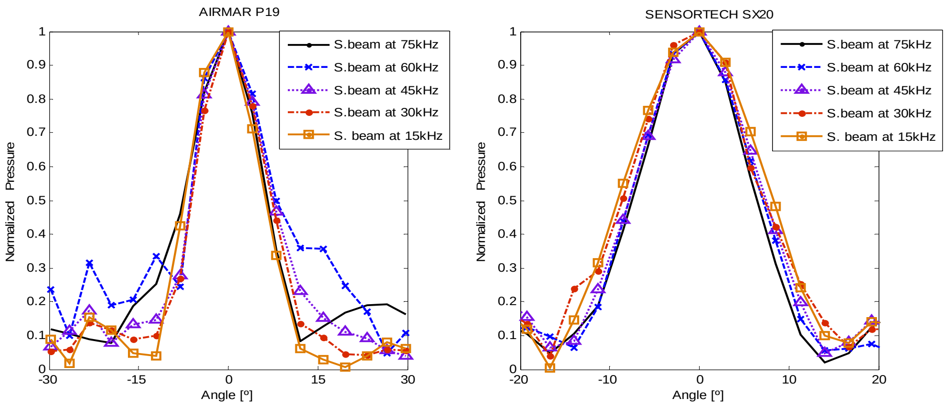

Fig. 3. Beamwidth measured at different parametric frequencies for AIRMAR P19 transducer (left), and Sensortech SX20 (right).

3.2. Analytical approach vs. experimental results

The prediction model based in Bektay & Leahy theory presents close results to the experimental measurements. The differences in the pressure level in the primary beam as well as in the secondary beam values are due to a certain level of reverberation in the measurements water tank. However the beamwidth is really close in both cases.

Table 1. Analytical approach vs. experiment results

	Measure			Analytical result		
	SL_P (dB)	SL_S (dB)	$2\theta_{3dB}$ (°)	SL_P (dB)	SL_S (dB)	$2\theta_{3dB}$ (°)
AIRMAR P19	197	163	6	202	148	5,88
SENSORTECH SX20	196	164	10	194	134	11

3.3. Sea water model

Introduction of relaxation losses does not offer significant changes in parametric sound generation in shallow water, as shown in Fig. 4. Although this losses can be neglected in the present configuration, the introduction of relaxation that provides the frequency attenuation dependence showed in Fig. 1 leads to the inclusion of weak dispersion. In this way, the progressive energy transfer from one spectral component to another is modified due weak phase mismatching [5], and consequently the nonlinear cascade interactions that lead to the formation of the parametric difference frequency are modified. Thus, for high acoustic powers, close to the saturation level, the secondary beam amplitude is expected to be modified.

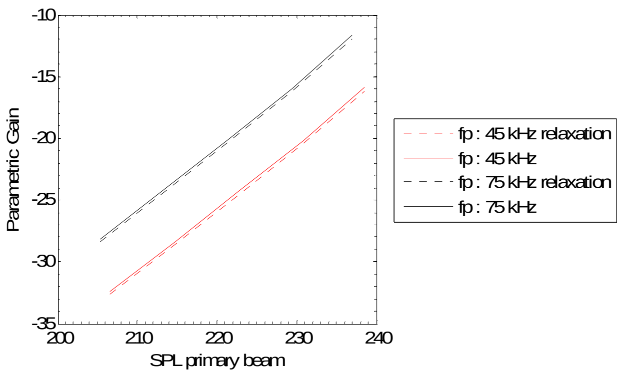

Fig. 4. Parametric gain for two frequencies (45 kHz and 75 kHz). Comparison between the numerical model without relaxation losses and with them.

3.4. Aperture transducer

Previous results show than the beamwidth obtain with transducers under test is not wide enough to achieve the aperture size setup in the parametric echosounder design. An extra numerical simulation has been done in order to orientate our design in the right aperture. A comparison between two different diameter sizes (35 mm and 75 mm) is shown in the Fig. 5. Beamwidth increase from 10^{o}_{3dB} (75mm aperture) to ~ 20^{o}_{3dB} (35mm aperture) getting closer to the required features.

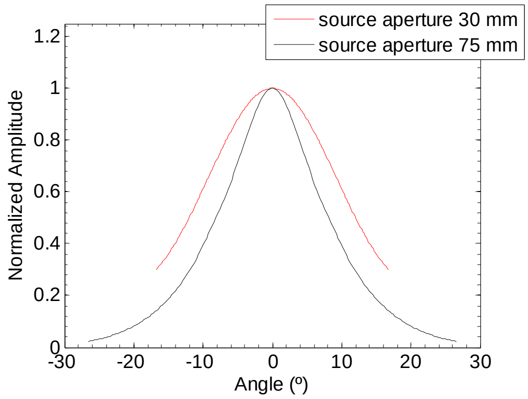

Fig. 5. Parametric beamwidth comparison between a source aperture of 30mm of diameter against 75mm one

4. Conclusions

A preliminary design for shallow water echosounder has been setup studying the efficiency of parametric sound generation and testing important beam features like beamwidth, attenuation and frequency range. Comparison between numerical and experimental results reveals that the computational method is a valid tool for future studies and designs. It has also been shown and discussed that relaxation losses not offer significant changes in the nonlinear parametric beam generation for shallow water in the present configuration.

Acknowledgements

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