A NEW METHOD FOR DETERMINATION OF THE ACOUSTIC NONLINEARITY PARAMETER *B/A* IN MULTILAYER BIOLOGICAL MEDIA

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Abstract

A new numerical method for determination of the acoustic nonlinearity parameter in liquids and biological structures on the basis of the applied numerical solver, allowing to predict the behavior of the axially symmetrical nonlinear acoustic beam propagating in multi-layer media, has been established. The mentioned solver made it possible to realize fast simulations of the spatial pulse pressure and harmonic distributions for various boundary conditions. A variety of simulations for the two-layer standard media with known linear acoustic parameters and variable nonlinearity parameters have been done. The obtained results were compared with the measurement results to find the best correlation between the calculated and the experimental curves.

Introduction

Recently a technique of the Tissue Harmonic Imaging (THI), utilizing acoustic nonlinear propagation effects, has become of a major interest in biomedical ultrasound. During propagation of the pulses of sufficient intensities at biomedical frequencies in liquids and biological tissues, harmonic components of the ultrasound beam are natively generated. The Tissue Harmonic Imaging demonstrates much better spatial resolution and, as a result, allows significantly to improve the quality of diagnostic images. Therefore, wider and wider applications of THI technique in medical diagnosis have increased the importance of the tissues nonlinear properties investigation. The nonlinearity parameter *B/A* in an attenuating medium is a basic parameter to determine the degree of acoustic waveform distortions. Several methods of the nonlinearity parameter measurements in liquids and in biological media are used [1, 4, 5] in the practice. Each of them has its own limitations and accuracy.

The purpose of this work was to establish the versatile method of determination of the liquids and biological tissues nonlinearity parameter *B/A,* using the numerical code proposed by J. Wojcik [6, 7]. It describes the finite amplitude, axially symmetrical acoustic wave distortions in space and time due to the native harmonics generation during its propagation in the multi-layer attenuating media.

Method of calculation

The theoretical analysis of nonlinear effects of the finite amplitude two-dimensional (with axial symmetry) acoustic wave propagation in the lossy medium was presented in our previous works [2, 3] and based on the exact solution of the nonlinear acoustic wave equation in the continuous lossy medium for a scalar acoustic potential.

On the basis of the mathematical model, the numerical code as well as the applied numerical solver for the exact determination of pressure waveforms, amplitude and harmonic distributions in space and time (at the very near, near and far field) in the nonlinear axially symmetrical acoustic beam, propagating in a layer structure, has been produced. The numerical solver made it possible to realize fast simulations of the pulse pressure and harmonic distributions in the finite amplitude ultrasonic beam propagating in the attenuating multilayer media, when linear acoustic parameters and nonlinearity parameters of every layer are known. As the reference medium, the degassed distilled water with the known nonlinearity parameter $(B/A)_w = 5.2$ has been chosen. The simulations could be performed in selected planes, points or in the space (x, y, z) of the investigated multilayer liquid or biological structure for various boundary conditions. The boundary conditions were determined by: 1) parameters of the transmitting and receiving transducers (the diameter, focal distance and the resonance frequency); 2) the acoustic pressure amplitude p_0 at the transmitting transducer surface; 3) the waveform, the carrier frequency and repetition frequency of the radiated acoustic pulse; 4) the apodisation function of the source radiating aperture; 5) the number of penetrated layers and linear acoustic parameters of every layer (density, acoustic velocity, attenuation coefficient); 6) the index of the frequency- dependence of the attenuation coefficient; 7) the nonlineariry parameters of the layers.

Using the solver, a variety of pressure and harmonic distribution simulations in liquid two-layer structures (containing layers of various thickness of water and corn oil, water and ethylene glycol, water and linseed oil, water and glycerine) as well as in biological two-layer structures (containing layers of various thickness of water and homogenized porcine liver, water and porcine blood) for various boundary conditions has been carried out. The obtained numerical results have been compared with the measurement results for the same boundary conditions.

Method of measurement

The method for measuring the tested liquid or biological tissue *B/A* value was adapted from the FAIS method introduced by Gong et al. [1989], however modified in few aspects. The experimental block-diagram for the *B/A* value measurement is shown in Fig. 1.
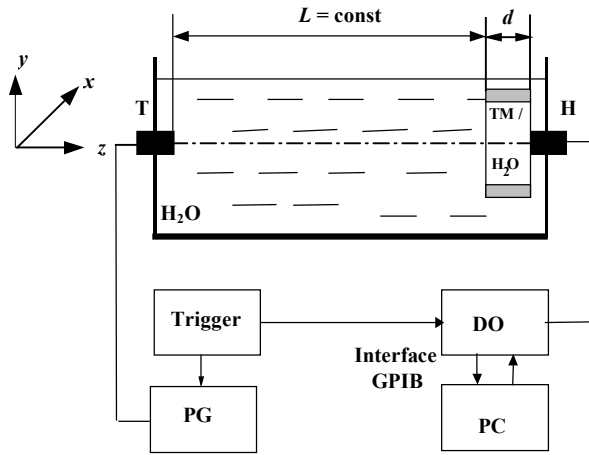

Fig. 1. Block diagram and experimental setup for the *B/A* measurement.

The transmitting transducer T, a ceramic plane disc with a fundamental frequency of 3 MHz and a diameter of 15 mm, was driven by a 8-cycle sinusoidal pulse with the carrier frequency of 3 MHz and a peak-to-peak amplitude of 100 V, produced by the pulse generator PG (RITEC Model 1000). The waveform of the acoustic pressure pulse on the radiating transducer aperture used in numerical calculations as a boundary condition, as well as measured in a very close vicinity to it, are presented in Fig. 2.
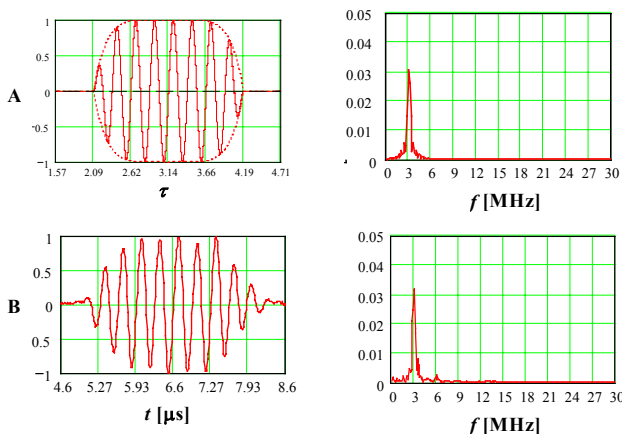

Fig. 2. The pulse pressure waveform (left) and its spectrum (right) (normalized in respect to the initial amplitude $p_0 = 0.4$ MPa) measured on the beam axis at the distance of $z = 5$ mm from the radiating surface (B) and assumed for numerical calculations (A).

The transmitter had the possibility to move along and across the acoustic beam axis z with a variable step starting from 0.1 mm. The receiver H was a wideband (1-40 MHz) membrane PVDF hydrophone (Sonora 4, S4-153) with an active electrode diameter of 0.4 mm. The hydrophone was located on the acoustic beam axis and measurements have been realized in a tank filled with degassed distilled water at the temperature of 26 $^{\circ}$C. The radial pressure distribution on the transmitting transducer surface is shown in the Fig. 3.
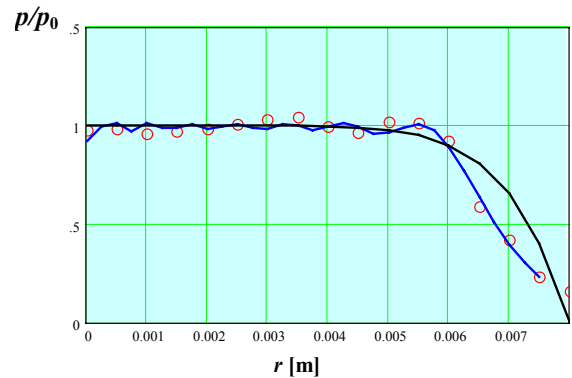

Fig. 3. The normalized radial pressure amplitude distribution of the 7.5 mm in a radius transmitter measured at the distance of $z = 2$ mm from the radiating surface (points) and analytical apodisation function $f(r) = 1 - (r/a_t)^{10}$ for $z = 0$ mm (black) and for $z = 2$ mm (blue) assumed in the numerical solver.

The tested material samples were inserted in test cylinders with a sound-permeable, 7 μm thick, polyethylene foil on each end. The test cylinders had a diameter of 6 cm and thickness d, varying from 1 cm to 4 cm along the direction of the pulse wave propagation. Each sample was inserted at the distance L from the source radiating surface where the initial acoustic pulse pressure of amplitude p_0 was produced. The distance L was the same for the same applied voltage of the source transducer and depended on the value of p_0. It was the distance where at least 3 harmonics have been already generated during the acoustic pulse propagation in water. For example, in the case of $p_0 = 0.4$ MPa the distance $L = 7$ cm has been chosen (see Fig. 4). Each sample was inserted between the hydrophone and the transmitter, keeping it as close to the hydrophone as possible and making sure that no evidence of reverberations between the sample and the hydrophone was present in the received signal waveform. An identical test cylinder containing degassed distilled water was used for obtaining the reference pulse. Thus, the transmission loss due to the polyethylene foil was the same in both cases.
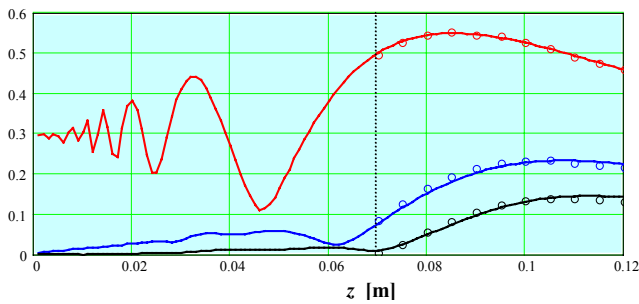
Fig. 4. The 1-st (red), the 2-nd (blue) and the 3-rd (black) harmonic axial distribution in water, calculated by the numerical solver for the propagating acoustic pulse with the initial pressure amplitude $p_0 = 0.4$ MPa (lines) and measured by the PVDF hydrophone (points).

The received signal was digitised with a 50 MHz digital oscilloscope DO (Hewlett Packard Model HP54503A). Then 50 consecutive waveforms were averaged in the memory of the scope and sent to a PC *via* a GPIB interface for analysis. The amplitudes of the 2-nd and higher harmonics were found by computing the FFT of the received pulse after selection of the pressure amplitude maximum value in the radial distribution at the distance $L + d$. The ratio of the amplitudes of the second or the higher harmonics for the case, when the test cylinder of the fixed thickness d was filled with the test liquid or biological tissue and when it was filled with degassed distilled water, has been used to determine the tested material B/A value.
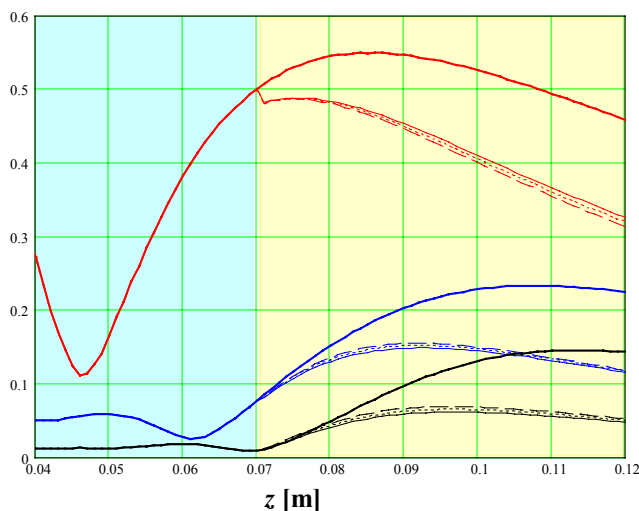

Fig. 5. The 1-st (red), the 2-nd (blue) and the 3-rd (black) harmonic axial distribution in water (solid lines) and in two-layer structure containing 7 cm of water and 5 cm of corn oil (only the range for $z = 4$ - 12 cm is shown) calculated for the propagating acoustic pulse with p_0= 0.4 MPa, assuming corn oil nonlinearity parameter value equal to 9.5 (thin solid lines), 10.5 (dotted lines) and 11.5 (dashed lines).

The measured ratio as a function of sample thickness was compared with the calculated ratio (using the above mentioned numerical solver) as a function of the tested material thickness, assuming the identical boundary conditions but various B/A values. The calculated curve, best fitted to the experimental curve, allowed to determine precisely the B/A value of the tested material. The proposed method has no theoretical approximations and limitations, contrary to the FAIS method. The determined B/A results for some representative liquids and biological tissues, using the proposed method, were compared with the published B/A values. The obtained results were in excellent agreement with the previously published B/A values. As an example, Fig. 5 shows the 1-st, the 2-nd and the 3-rd harmonic axial distributions in two-layer structure: 7 cm water + 5 cm corn oil calculated for the initial acoustic pulse of the waveform shown in Fig. 2A, amplitude $p_0 = 0.4$ MPa and the apodisation function shown in Fig. 3, when the nonlinearity parameters of corn oil were assumed to be equal to 9.5, 10.5, 11.5.
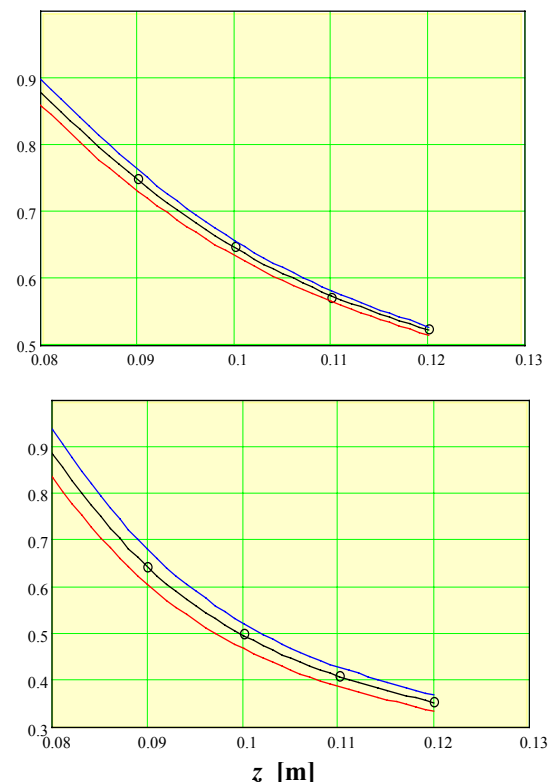

Fig. 6. The ratio of the amplitudes of the 2-nd (top) and 3-rd (bottom) harmonics in corn oil with respect to water as a function of the corn oil thickness calculated for the initial acoustic pulse shown in Fig. 2A when $p_0 = 0.4$ MPa, the apodisation function $f(r) = 1 - (r/a_t)^{10}$, and the B/A values equal to 9.5 (red lines), 10.5 (black lines) or 11.5 (blue lines).

Fig. 7 shows the axial harmonic distributions in two-layer structure: 7 cm water + 5 cm ethylene glycol for the same boundary conditions as in Fig. 6.
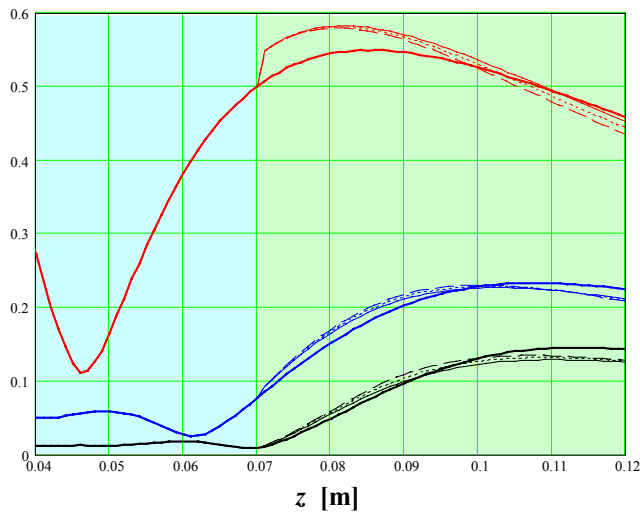
Fig. 7. The 1-st (red), the 2-nd (blue) and the 3-rd (black) harmonic axial distribution in water (solid lines) and in two-layer structure containing 7 cm of water + 5 cm of ethylene glycol calculated for the propagating acoustic pulse with p_0=0.4 MPa, assuming the ethylene glycol B/A value equal to 9 (thin solid lines), 10 (dotted lines) and 11 (dashed lines).
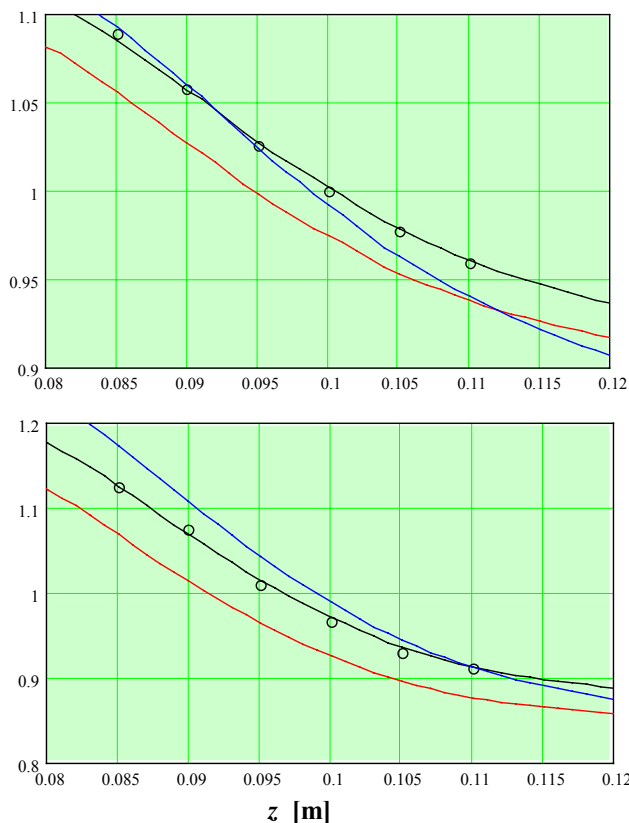

Fig. 6. The ratio of the amplitudes of the 2-nd (top) and 3-rd (bottom) harmonic in ethylene glycol with respect to water as a function of the ethylene glycol thickness calculated for B/A values equal to 9 (red lines), 10 (black lines), 11 (blue lines) and measured values (points).

Results

Table 1 contains the B/A values determined at 26 °C by the proposed method for some representative materials, in comparison with the values published by other authors. The accuracy of the proposed method was estimated to be better than 5%.

Table 1: Comparison of B/A values determined by the proposed method and mentioned in references below.

Material	B/A (the proposed method)	B/A (the mentioned in references)	
Water	5.2	5.5 ± 0.3	[5]
Corn oil	10.5	10.6 ± 0.2	[1]
Ethylene glycol	10	9.8 ± 0.2	[4]
Linseed oil	9		
Homogenized pig liver	6.5	6.6	[4]
Pig blood	6	6 ± 0.2	[4]

Conclusions

The main advantages of the proposed method, that makes it more credible, are: 1) the exemption from the theoretical approximations (the plane wave condition), 2) the decreasing of the error in the B/A value determination by varying of the thickness of tested samples.

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