ISSN 1392-2114 ULTRAGARSAS, Nr.4(53). 2004.

Dependence of non-linear ultrasound beam propagation on boundary conditions

T. Kujawska, J. Wójcik

Ultrasonic Department, Institute of Fundamental Technological Research,
Polish Academy of Sciences, Warsaw, POLAND
tkujaw@ippt.gov.pl

Introduction

The significance of non-linear propagation in medical diagnostic ultrasound is unquestionable. The Tissue Harmonic Imaging (THI) technique, which utilize the non-linear propagation to improve image quality of tested structures, is of great importance in clinical practice and it still has considerable potential for improvement due to a number of factors. Firstly, the availability of wide-band (up to 100 MHz) hydrophones and high speed digital oscilloscopes has facilitated the accurate acquisition of the waveforms distorted during non-linear propagation. Secondly, the increase in computing power made it possible to model non-linear fields fairly fast on the PC platform. To investigate the complex dynamic characteristics of fields produced by harmonic imaging it is necessary to have a time-efficient computational tool. Numerical calculations were possible due to the powerful software applied (2D numerical solver), developed by the second author and implemented in the PC operating system environment, which made it possible to realize fast simulations (for various boundary conditions) of the spatial harmonic field distributions for axially symmetrical ultrasound beams propagating in the multi-layer attenuating media. The boundary condition parameters were the input data of this solver. The mathematical model and the frequency-domain numerical approach to this problem, using the truncated Fourier series (TFS) method, were presented in previous publications [1, 3]. The frequency range up to 40 MHz (conditioned by the possessed PVDF hydrophone frequency range) have been considered in the numerical calculations.

Boundary conditions

The boundary conditions were determined by: 1) parameters of the transmitting and receiving transducers (diameter, focal distance and resonance frequency); 2) initial acoustic pressure amplitude p_0 at the transmitter surface; 3) waveform, carrier and repetition frequencies of radiated acoustic pulses; 4) radial pressure distribution (apodisation function) on the radiating aperture; 5) number of penetrated layers and linear acoustic parameters of every layer (density, acoustic velocity, weak-signal attenuation coefficient); 6) index of frequency-dependence of attenuation coefficient; 7) non-linearity parameter of every layer. The investigated boundary conditions have been chosen to be relevant to those used in medical ultrasonic imaging systems.

The numerical simulations of spatial field harmonic distributions in water and in two-layer structures: water–liquid and water–soft tissue were performed for the beams radiated by plane sources with a diameter of ∅ = 10, 15, 20, 30 mm and by focused sources with the same diameter and focal distance of F = 80 mm. Water has been chosen as a reference medium. Numerical computations were realized for acoustic pulses with carrier frequencies of f_0 = 1, 2, 3, 4 MHz and initial acoustic pressure amplitudes of p_0 = 0.1, 0.2, 0.3, 0.4 MPa, radiated in water. The cases of long (8-cycle) and short (4-cycle) pulses were simulated assuming a constant ratio (equal to 0.4) of the pulse duration to its repetition period for all the resonant frequencies. The pressure envelope of the initial acoustic pulse was chosen in the form of a polynomial function, the best matched to the pressure pulse envelope measured very close to the radiating source surface. The initial apodisation function was selected analytically by searching the initial radial distribution that settles the simulated radial pressure distribution in the nearest vicinity of the radiating aperture as close as possible to the measured one at the same distance. The linear and non-linear acoustic parameters of tested liquids and soft tissues in two-layer structure are presented in Table 1.

Table 1. **Ultrasonic properties at 25°C of the tested materials**

Material	Density (kg/m^3)	**Acoustic velocity** (m/s)	Attenuation coefficient (Np/m · Hz^b)	B/A (literature)	b
Distilled degassed water	997	1497	$2.8 \cdot 10^{-14}$	5.2	2
Ethylene glycol	1110	1660	$18 \cdot 10^{-14}$	9.9	2
Corn oil	920	1470	$70 \cdot 10^{-14}$	10.5	2
Glycerol	1260	1890	$570 \cdot 10^{-14}$	9.4	2
Porcine blood	1080	1600	$16 \cdot 10^{-7}$	6.2	1.1
Homogenized porcine liver	1060	1550	$78 \cdot 10^{-7}$	6.6	1

b – attenuation coefficient frequency-dependence index

The thickness of water layer in two-layer structure has been chosen to be equal to the distance (on the beam axis z) from the source immersed in water at which the higher harmonics start to grow rapidly (Fig. 1). Three values of the tested medium non-linearity parameter B/A have been considered: known from publications (Table 1), 10% lower and 10% higher. Degassed distilled water with the known non-linearity parameter $(B/A)_w$ = 5.2 has been chosen as a reference medium.

Numerical simulation results

The numerical simulations of the peak-compression, peak-rarefaction and peak-to-peak pressure amplitude distributions as well as the harmonic pressure amplitude distributions in space and time were performed for various combinations of the mentioned above boundary conditions. The analysis of the obtained results allowed to notice that for the plane sources the larger is the source size or the source resonance frequency the greater is the distance from the radiating surface at which the maxim harmonic pressures are occurred. The 1-st harmonic reaches its maximum earlier compared with the higher harmonics. Its maximum depends on the source size, resonance frequency and initial pressure amplitude inconsiderably, whereas the 2-nd and higher harmonic maxim increase significantly with the increase of mentioned parameters (Fig. 1). The 2-nd and the higher harmonics start to grow rapidly at a certain distance from the source which depends on the source size and resonance frequency but doesn't depend on the initial acoustic pressure amplitude (Fig. 2). For the focused sources the mentioned dependences are similar, however non-linear effects are much more significant. In strongly attenuating medium the weak-signal attenuation coefficient and its frequency-dependence index have the dominant influence on the field harmonic distributions with respect to the non-linearity parameter. For example, in the two-layer structure water-glycerol the attenuation coefficient of glycerol is about 200 times higher than in water. In this case the differences of harmonic amplitude distributions in glycerol for 3 assumed values of its non-linearity parameter $(B/A)_{GC}$= 9.5, 10% higher and 10% lower) are unnoticeable (Fig. 3a).

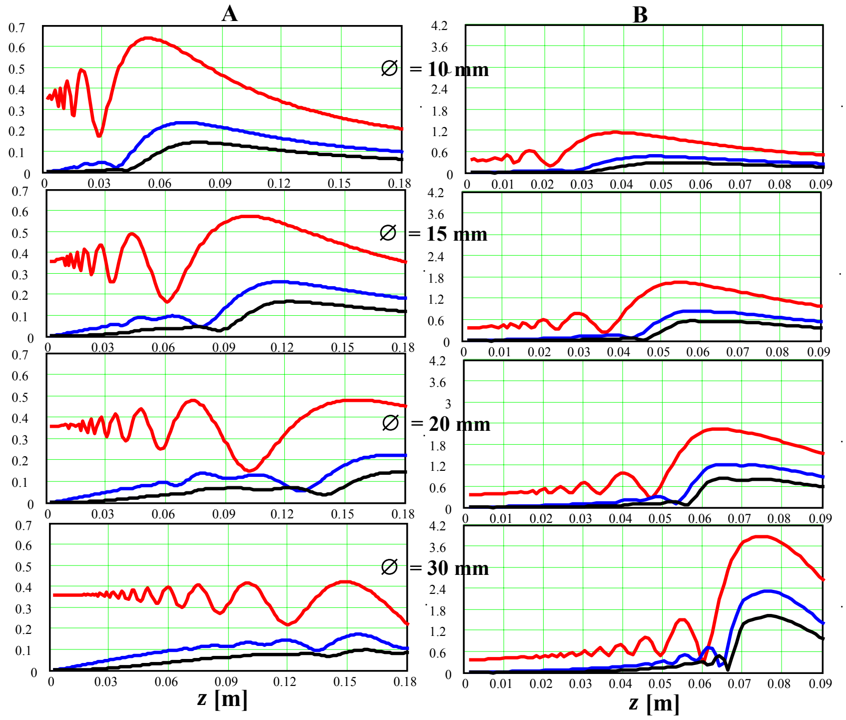

Fig. 1. **Simulated the 1-st (top curves), the 2-nd (middle curves) and the 3-rd (bottom curves) harmonic axial distributions of the acoustic beam radiated in water by circular plane (A) and focused (B) sources (F = 8 cm) of various diameters, driven by the 8-cycle sinusoidal pulse of 4 MHz and initial pressure amplitude p_0 = 0.4 MPa.**

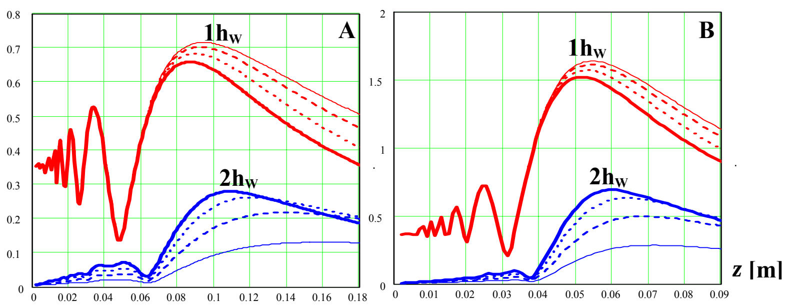

Fig. 2. **The 1-st (top 4 lines) and the 2-nd (bottom 4 lines) harmonic axial distributions for the case of 8-cycle pulse with the carrier frequency of 2 MHz, radiated by the plane (left) and focused (right) source of 10 mm radius, when the initial acoustic pressure amplitude p_0 is equal to 0.1 (thin solid lines); 0.2 (dashed lines); 0.3 (dotted lines); 0.4 (thick solid lines) MPa**

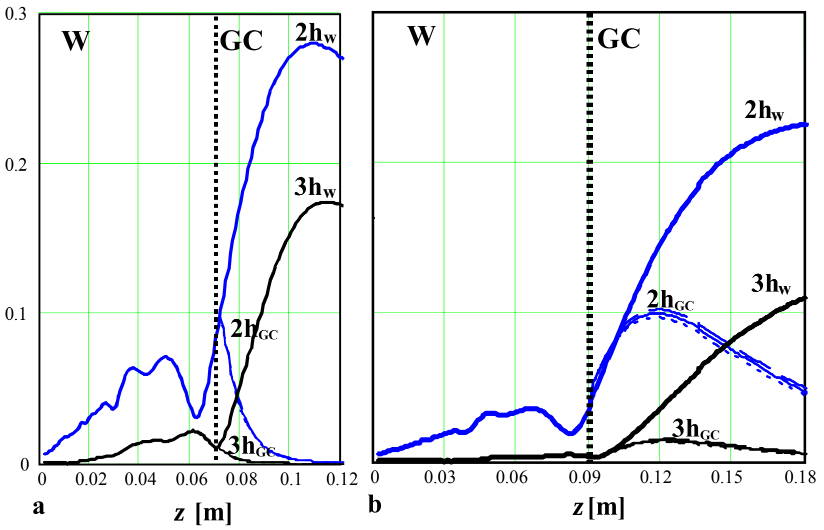

Fig. 3. **Simulated the 2-nd ($2h_w$) and the 3-rd ($3h_w$) harmonic axial distributions in water and in two-layer structure: water-glycerol. A) - for the plane circular source with diameter of 15 mm and 3 MHz resonance frequency; B) – for the plane source of 30 mm in diameter and resonance frequency of 1 MHz when initial pressure amplitude was equal to p_0 = 0.4 MPa. The values of the glycerol non-linearity parameter equal to 8.5; 9.5; 10.5 have been assumed**

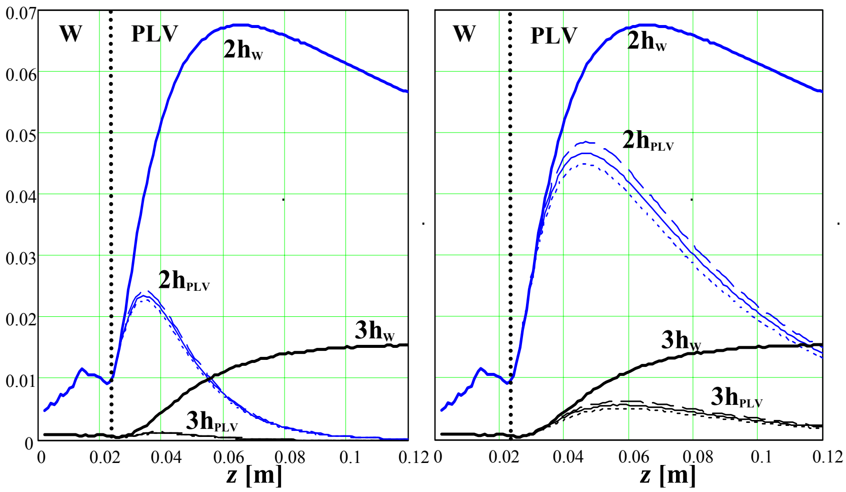

Fig. 4. **Simulated the 2-nd (2h) and the 3-rd (3h) harmonic axial distributions in water (subscript W) and in two-layer structure: 2.5cm of water + 9.5 cm of homogenized porcine liver (subscript PLV) when the plane circular source of 15 mm in diameter is radiated ultrasonic pulse with carrier frequency of 1 MHz and initial pressure amplitude of p_0 = 0.4 MPa. The 3 values of the porcine liver non-linearity parameter are assumed to be equal to 5.9 (dotted lines); 6.6 (thin solid lines); 7.3 (dashed lines) while the attenuation coefficient's frequency-dependence index b = 1.1 (left) and b = 1 (right).**

Therefore to distinguish the 3 overlapping curves (for determination of the non-linearity parameter value of tested medium by comparing it with the measurement results) it is necessary to change boundary conditions: to decrease the radiated frequency or to increase the source diameter or to apply the higher voltage to the source. Fig. 3a demonstrates the simulated harmonic distributions in two-layers: 7 cm of water + 5 cm of glycerol for the circular plane source of 15 mm in diameter radiated acoustic pulse with carrier frequency of 3 MHz and the initial pressure amplitude of p_0 = 0.4 MPa, when the non-linearity parameter $(B/A)_{gc}$ of glycerol was assumed to be equal 8.5; 9.5; 10.5. Fig. 3b shows the same harmonic distributions when the source diameter equal to 30 mm and resonance frequency equal to 1 MHz.

For soft tissues a great influence on the harmonic field distributions has also the attenuation coefficient's frequency-dependence index *b* which usually oscillates in a range of 1÷1.4. Fig. 4 demonstrates the dependence of the harmonic beam propagation in homogenized pig liver on the index *b*. The higher is the index *b* value the lower is the influence of the medium non-linearity parameter value (with respect to the attenuation coefficient value) on the amplitude of harmonic distributions. So, the accuracy of determination of the non-linearity parameter value of strong attenuating liquids or soft tissues by the new comparative method [2], described in our previous publications, depends on the proper selection of boundary conditions.

Conclusions

The numerical solver, which allows prediction of behavior of 2D nonlinear acoustic beams propagating in layered attenuating media for various boundary conditions has been developed and implemented on the PC platform. The dependence of the spatial harmonic beam distributions on such boundary condition parameters as the geometry of the system, the nature of the waveform and the medium non-linear properties has been analyzed. On the basis of the analysis of numerical simulation results and of the comparison of them with measurement results a new comparative method for determination of the non-linearity parameter in liquids and biological tissues [2] has been established. The accuracy of determination of the non-linearity parameter value *B/A* of tested liquids or soft tissues by the new method depends on the proper selection of the boundary conditions.

Acknowledgments

This work has been supported by the Grant Nr 5T07B00924 of the National Committee of Scientific Research.

References

1. **Kujawska T., Wójcik J.** Harmonic ultrasound beam forming by means of radiating source parameters. Hydroacoustics. 2004. Vol.7. P.135-143.
2. **Kujawska T**. A new method for determination of the acoustic non-linearity parameter *B/A* in multi-layer biological media. Proc. of the World Congress on Ultrasound. 2003. P.81-84.
3. **Wójcik J**. A new theoretical basis for numerical simulations of nonlinear acoustic fields. Proceedings of the 15th ISNA. Ed. Am. Soc. of Physics. 2000. Vol.52(4). P. 141-144.

T. Kujawska, J. Wójcik

Ultragarsinio spindulio netiesinio sklidimo priklausomybė nuo pradinių sąlygų

Reziumė

Pristatomi netiesinio, simetriško ašiai (2D) ultragarso spindulio sklidimo tyrimai. Nustatytos tokio sklidimo charakteristikų priklausomybės nuo pradinių sąlygų: akustinio šaltinio geometrijos, pradinio impulso charakteristikų, taip pat nuo tiesinių ir netiesinių sklidimo terpės savybių. Tyrimuose buvo naudojami apskriti plokšti akustiniai 2D šaltiniai, kurių skersmenys 10, 15, 20 ir 30 mm, taip pat šių skersmenų fokusuoti šaltiniai (fokuso atstumas – 80 mm). Pradiniai žadinimo impulsai turėjo 8 arba 4 periodų trukmę, nešančiuosius dažnius f_0 = 1, 2, 3, 4 MHz bei akustinio slėgio amplitudes p_0 = 0.1, 0.2, 0.3, 0.4 MPa. Tiriant akustinio lauko harmonikų pasiskirstymą erdvėje ir laike įvertintas aplinkos tankis, ultragarso sklidimo greitis, silpno signalo slopinimo koeficientas ir jo dažninės priklausomybės indeksas, taip pat aplinkos netiesiškumo parametras. Analizei atlikti naudotas skaitmeninis erdvinio harmonikų pasiskirstymo modeliavimas ultragarsiniam spinduliui, sklindančiam vandeniu (atraminė aplinka) ir dvisluoksnėmis struktūromis: vanduo–standartinis skystis bei vanduo–minkštas biologinis audinys. Skaičiavimams naudota antrojo autoriaus pasiūlyta greita skaitmeninio modeliavimo programa, įvertinanti visas minėtas pradines sąlygas. Programa dažnių srityje sprendžia netiesinę banginę lygtį baigtinės amplitudės ultragarsiniams spinduliams ir įvertina difrakcijos efektus, aplinkos netiesiškumą, termoklampią absorbciją bei nuo dažnio priklausantį slopinimą sklidimo terpėje. Modeliavimo rezultatai, gauti pritaikius įvairias pradines sąlygas, rodo, kad stipriai slopinančiuose skysčiuose arba biologiniuose audiniuose vidutinis silpno signalo slopinimo koeficientas bei jo nuo dažnio priklausantis indeksas turi vyraujančią įtaką lauko harmonikų pasiskirstymui, palyginti su terpės netiesiškumo parametro įtaka.

Pateikta spaudai 204 11 03