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Fast prediction of pulsed nonlinear acoustic fields from clinically relevant sources using Time-Averaged Wave Envelope approach: comparison of numerical simulations and experimental results

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Abstract

The primary goal of this work was to verify experimentally the applicability of the recently introduced Time-Averaged Wave Envelope (Tawe) method [1] as a tool for fast prediction of four dimensional (4D) pulsed nonlinear pressure fields from arbitrarily shaped acoustic sources in attenuating media. The experiments were performed in water at the fundamental frequency of 2.8 MHz for spherically focused (focal length $F = 80$ mm) square (20×20 mm) and rectangular (10×25 mm) sources similar to those used in the design of 1D linear arrays operating with ultrasonic imaging systems. The experimental results obtained with 10-cycle tone bursts at three different excitation levels corresponding to linear, moderately nonlinear and highly nonlinear propagation conditions (0.045, 0.225 and 0.45 MPa on-source pressure amplitude, respectively) were compared with those yielded using the Tawe approach [1]. The comparison of the experimental results and numerical simulations has shown that the Tawe approach is well suited to predict (to within ± 1 dB) both the spatial-temporal and spatial-spectral pressure variations in the pulsed nonlinear acoustic beams. The obtained results indicated that implementation of the Tawe approach enabled shortening of computation time in comparison with the time needed for prediction of the full 4D pulsed nonlinear acoustic fields using a conventional (Fourier-series) approach [2]. The reduction in computation time depends on several parameters, including the source geometry, dimensions, fundamental resonance frequency, excitation level as well as the strength of the medium nonlinearity. For the non-axisymmetric focused transducers mentioned above and excited by a tone burst corresponding to moderately nonlinear and highly nonlinear conditions the execution time of computations was 3 and 12 hours, respectively, when using a 1.5 GHz clock frequency, 32-bit processor PC laptop with 2 GB RAM memory, only. Such prediction of the full 4D pulsed field is not possible when using conventional, Fourier-series scheme as it would require increasing the RAM memory by at least 2 orders of magnitude.

Keywords

rectangular focused apertures; pulsed acoustic fields; nonlinear distortion; numerical modelling and experiments

I. INTRODUCTION

A majority of currently used ultrasound imaging systems employs linear arrays, which launch an interrogating wave into tissue by sequential activation of a square or rectangular subsection of the array.

However, there are relatively few papers published [3-8], which consider nonlinear sound beams in attenuating media emitted from sources with the non-axisymmetric aperture. Also, they provide field modelling based on the continuous wave excitation. For example, Kamakura *et al.* [3] performed theoretical analysis and examined harmonic generation in finite amplitude sound beams in air using planar rectangular aperture source excited by a CW wave. Baker *et al.* [4] and Nachev *et al.* [5] investigated both theoretically and experimentally nonlinear sound pressure fields in water produced by plane rectangular apertures, again, using continuous wave excitation. Similarly, Cahill *et al.* [6,7] compared the acoustic field emitted by a 3.5 MHz phased-array scanner in water with numerical simulations performed as well for the case of CW excitation. More recently, Zemp *et al.* [8] developed the numerical model capable of predicting the finite-amplitude sound beam propagation in water and in tissue from linear phased arrays and other (arbitrarily shaped quasi-planar) transducers, however, the source excitation was also applied as CW wave. In contrast, the model discussed here and used to obtain the results presented is capable of predicting faithfully pulsed nonlinear acoustic fields in biological media and concurrently, as described in the following, reducing the computer calculation time. A comprehensive description of the development of the novel algorithm based on the Time Averaged Wave Envelope (TAW) approach to the numerical solution of the second order nonlinear differential wave equation was presented in [1]. However, in [1] only axisymmetrical acoustic source was used to verify the validity of the TAW approach. This work presents a verification of the TAW algorithm by comparing the experimental data obtained for focused square and rectangular sources generating clinically relevant linear and nonlinear fields with the results of computer simulations. The reduction in computational time was determined by using both the TAW and conventional Fourier series approaches, and comparing the time needed to obtain the complete 4D presentation of both the spatial-temporal and spatial-spectral pressure variations in the pulsed nonlinear acoustic beams.

The paper is organised as follows. First, for the convenience of the reader, the very basic principles of the numerical model used here are succinctly summarised. Next, the experimental setup, materials and methodology of measurements are described along with the comparison of numerical simulations and experimental results. The results confirm that the TAW method is capable of predicting clinically relevant fields at computational times that are significantly shorter. The discussion of the possible sources of errors experienced at the axial distances at which the pulsed nonlinear wave was not fully developed is also given.

II. NUMERICAL MODEL

As noted above, the numerical model used for describing the nonlinear waveform distortion of the pulsed finite-amplitude sound pressure wave propagating in a thermoviscous medium was comprehensively described in [1]. Briefly, the model was made computationally efficient by replacing the conventional Fourier-series solution approach by Time-Averaged Wave Envelope algorithm. The TAW approach is based on decomposition of the propagating, nonlinearly distorted acoustic pulse or tone burst into a series of sinusoidal pulses with carrier frequencies being the harmonics of the initial (undistorted) acoustic pulse and with envelopes being the product of two specific functions. The first function represents the solution to the nonlinear wave equation under linear propagation conditions whereas the second function accounts for nonlinear interactions of harmonic components under given boundary conditions.

The model is semi-empirical. In order to optimize the model's ability to predict fields generated by "real-life" transducers an apodisation function is applied. The function reflects the intrinsic imperfections in the transducer design, which often manifest themselves as nonuniform distribution of the surface displacement amplitude. As described in the next section, this distribution is measured in terms of the pressure amplitude in the immediate vicinity of the transducer surface and used to determine the apodisation function. In this work, the function was introduced in analytical form as $f(x, y) = P_0 |1 - (x/a)^m| \cdot |1 - (y/b)^m|$, which produced the transverse pressure distributions in both the x and y directions close to the radiating aperture (5-15 mm) that best reproduced the distributions measured.

III. MATERIALS AND METHODS

A. Experimental set-up

The experimental set-up used for the measurements is shown in Fig. 1.

All measurements were performed at 25 °C in temperature-controlled degassed distilled water using two spherically focused piezoelectric transducers made of PZ27 ceramic (Ferroperm, Denmark) having geometrical focal length F of 80 mm and operating at the fundamental frequency of 2.8 MHz. This frequency is frequently used in clinical imaging as it allows both cardiac (fundamental) and abdomen (2nd harmonic) imaging. In addition, it was selected to maximize the number of experimentally generated harmonics that could be quantified using 40 MHz calibrated membrane hydrophone (model 805, Sonora Medical Systems, Inc. Longmont, CO, USA). The amplitude of the measured harmonics was determined at a given frequency using hydrophone sensitivity (V/Pa) and compared with the corresponding, TAFE algorithm simulated one. The design of the transducers mimicked that of ultrasound imaging array sub-sections. One of the transducers was square ($a_g = b_g = 20$ mm) and the other one rectangular ($a_g = 10$ mm, $b_g = 25$ mm). Both transducers were backed and had a quarter-wavelength matching layer to optimise transmitting efficiency. As already mentioned, the pressure field generated by the transducers was measured using a broadband bilaminar polyvinylidene difluoride (PVDF) membrane hydrophone (Sonora Medical Systems Inc. SN S5-153, preamplifier P-159, Longmont, CO, USA) with an effective diameter of the sensor element of 0.414 mm and calibrated up to 40 MHz. The transmitting transducer was mounted in the mechanical positioning system driven by three stepper motors allowing its motion in the x , y , z directions with steps adjustable from 0.1 to 5 mm. The xyz micromanipulator allowed also its rotation in azimuth. The measuring hydrophone was fixed. To maximize the signal to noise ratio at the measurement of the 14th harmonic the tested transducers were driven by 10-cycle tone bursts via RF Power Amplifier (ENI 3100LA, Rochester, NY, USA), see Fig. 1. The amplitude of the tone burst excitation voltage was controlled by the Step Attenuator (Tektronix 2701, Beaverton, OR, USA), to enable linear, moderately nonlinear and highly nonlinear wave distortion. The frequency and duration of the tone bursts were adjustable using Arbitrary Function Generator (LeCroy 9109, Chestnut Ridge, NY, USA). As described below at the low excitation level the sources produced surface pressure of 0.045 MPa. Moderately and highly nonlinear fields were produced by enhancing voltage at the output of the RF amplifier by a factor of 5 (producing surface pressure of 0.225 MPa) and 10 times (producing surface pressure of 0.45 MPa), respectively. The hydrophone output was additionally amplified by 20 dB using the linear broadband amplifier (Ritec BR-640, Warwick, RI, USA) and then fed to the input of an 8-bit digital oscilloscope (HP54503A, Hewlett Packard, Colorado Springs, CO, USA) with a 200 MHz sampling frequency. The received signals were digitised and averaged over 16 consecutive waveforms in the oscilloscope memory and then transferred for spectral analysis to 1.5 GHz clock frequency, 32-bit processor PC laptop with 2 GB RAM. The amplitude of the measured harmonic components was corrected for the hydrophone sensitivity dependence on frequency.

B. Methodology of measurements

As noted above three excitation levels were used. Initially, the measurements were carried out at low excitation level (linear propagation mode). This was done for each of the tested sources in order to determine the input parameters to the numerical model based on the Tawe approach [1].

These parameters included the speed of sound in water, actual focal length F , pressure amplitude P_0 at the transducer surface (source pressure), initial pressure-time waveform and apodisation function.

The apodisation function and pressure amplitude P_0 at the transducer surface were determined at low (45 kPa) excitation level by measuring the transverse pressure distributions and their maxima in both the x and y directions close to the radiating surface (5-15 mm axial distance). Specifically, the measured axial and lateral pressure distributions were compared with those theoretically predicted using the linear propagation theory and accounting for attenuation while keeping the source pressure P_0 constant and varying the radiating aperture dimensions a , b and exponent m of the apodisation function (see section II). At higher excitation levels (here, 250 and 450 kPa), the value of P_0 was scaled up directly proportional to the increase in the applied excitation voltage (5 and 10 times, see below).

Fig. 2 shows the apodisation function for the square aperture at low excitation level in the x direction, described by the polynomial $f(x, 0) = P_0 |1 - (x/a)^8|$, which produced the transverse pressure distribution calculated at the axial distance 15 mm that best fitted to the measured one at the same distance. Here a and b are the transducer dimensions in both the x and y directions, m is positive integer number that was determined by iteration process. Water density and sound speed input to the Tawe model corresponded to those at 25 °C, i.e. 1000 kg/m³ and 1497 m/s, respectively. In addition, the frequency-dependent attenuation was introduced into the numerical model as $\alpha(f) = \alpha_0 f^2$, where weak-signal or linear attenuation coefficient $\alpha_0 = 2.5 \cdot 10^{-14}$ Np/(m·Hz²) was used. The nonlinearity parameter B/A of water at 25 °C, i.e. $B/A = 5.3$ was used.

Fig. 2 shows apodisation function $f(x, 0)$ corresponding to the maximum source pressure amplitude P_0 of 0.045 MPa (low excitation level). The transverse pressure distributions calculated at the axial distance of 15 mm for the apodisation function selected as eighth order polynomial (see Fig.2) are also depicted and compared with those measured experimentally.

The effective aperture dimensions were found to be 19 × 19 mm for the square and 24 × 9 mm for the rectangular transducer, respectively. As already noted, in order to generate nonlinear acoustic fields the voltage applied to each transducer was increased 5 and 10 times (14 dB and 20 dB, respectively). Similarly to the case of low excitation level the value of the source pressure amplitude for the higher excitation levels was found from the transverse pressure distributions in both the x and y directions measured at the same axial distance as in the case of low excitation level.

The acoustic axis was determined from symmetry of the beam cross-sections measured and visualised in a form of isobar contour lines. To obtain the data needed to plot the isobars, the measurements were made along the acoustic beam (in both the xz and yz planes) and across the beam (in the xy planes) at various distances from the source.

The measurements along the beam axis, at the axial range from 10 to 140 mm were done in 1 mm steps using 10-cycle bursts. The measurements across the acoustic axis at the axial distance 5 mm were carried out with 4-cycle tone bursts to avoid reflections. Beyond the axial distance

of 10 mm 10-cycle tone bursts waveforms were recorded in 0.5 mm steps in both the x and y directions at the range $\pm (a/2 + 0.5)$ mm and $\pm (b/2 + 0.5)$ mm, respectively.

The initial pressure-time waveform was also determined analytically by adjusting the analytical function to the waveform measured on the beam axis close to the transducer surface. The initial acoustic pulse waveform was described by its fundamental frequency, envelope function, pulse duration and repetition period (PRP). The PRP determined the time-window for spectral analysis. The window was chosen to ensure the highest possible sampling density in the frequency domain and hence to maximise simulation accuracy.

The results of the experiments along with a succinct discussion are presented in the next section.

IV. RESULTS AND DISCUSSION

Figures 3 ÷ 8 show the comparison between the measured pulsed acoustic fields (dots) and their theoretical predictions (solid lines) obtained using the Tawe approach for both transducers tested.

Fig. 3 shows both the axial and lateral pressure distribution for the peak-compression, peak-rarefaction and peak-to-peak amplitudes in the pulsed nonlinear beam produced by the square aperture at the moderate excitation level (transducer surface pressure of 0.225 MPa). The axial pressure variation of fundamental, 2nd and 3rd harmonics for the same square aperture at the moderate and high (transducer surface pressure of 0.45 MPa) excitation levels are shown in Fig. 4 and Fig. 5, respectively.

The results presented in these figures demonstrate that close to the transducer surface pressure amplitudes of 2nd and 3rd harmonics are at least 20 dB lower in comparison with the pressure amplitude of the fundamental one. These results confirm that the waveform distortion is not produced by the source transducer but is induced by the medium (water) nonlinearity. The agreement between the simulations and the measurements is good, with the discrepancies being negligible at the axial distances larger than 5 cm, however, at the distances shorter than 5 cm the agreement is less favourable. It is likely that the discrepancy is due to the hydrophone's finite aperture, which makes the hydrophone sensitivity angle dependent. Hence, close to the transducer's surface the hydrophone is more sensitive to the impinging direct wave and less sensitive to the edge wave. Consequently, the measured pressure amplitude may be somewhat underestimated due to the missing contribution of the edge wave. The data plotted in Figs. 4 and 5 also show that the nonlinear model is capable of predicting the location of the maxima and minima for 2nd and 3rd harmonics, although their pressure amplitudes are slightly (less than 1 dB) overestimated. It is likely that these discrepancies are caused by the uncertainty of the source boundary condition (apodisation function) assumed for calculations in the plane of the radiating aperture.

Figs. 6 and 7 illustrate pressure variations for the rectangular aperture at high excitation level (transducer surface pressure of 0.45 MPa). Fig. 6 shows the axial distribution of the peak-compressional, peak-rarefactional and peak-to-peak pressure amplitudes. It also shows distributions of these three amplitudes in the geometric focal plane in the y direction (parallel to the short dimension of the aperture). Fig. 7 presents the axial pressure amplitude distribution for fundamental, 2nd and 3rd harmonics. Here the agreement between the distributions predicted by the Tawe approach and the measured pressure amplitudes is less favourable starting at the axial distance that is closer than about 6 cm.

Fig. 8 depicts excellent agreement between the calculated and measured pressure-time waveforms along the beam (z) axis in the geometric (80 mm) focal plane. The corresponding

spectra are also shown and the agreement between the predicted and measured data appears to confirm the validity of the Tawe method.

It is appropriate to note that the experimentally determined focal plane differs from the geometrical one (80 mm). In general, the location of the focal plane is dependent upon the geometry of the source, frequency and the nonlinearity parameter B/A . The results depicted in Figs. 3-8 indicate the focal planes ranged from 60-80 mm. The maximum peak-to-peak pressure amplitude was measured between 70 and 80 mm. For the square aperture producing surface pressure amplitude of 450 kPa the focal plane for the fundamental frequency component was found between 60 and 70 mm but the focal plane of the 2nd harmonic was located at the axial distance of 70 mm. For the rectangular geometry, the maximum peak-to-peak pressure amplitude was measured in the geometrical plane also between 70 and 80 mm, but the focal planes for higher harmonics were shifted away from the source. Overall, based on the simulations and experimental data presented above it would appear that the rectangular and axisymmetric sources show similarity in that the difference in the axial distance between the focal plane for fundamental frequency and the focal planes of higher harmonics decreases with increasing level of excitation (nonlinearity).

The applicability of the Tawe approach for fast prediction of the distribution of the fundamental, 2nd and 3rd harmonics pressure amplitude patterns was also tested. Fig. 9 and 10 illustrate both the longitudinal and lateral cross-sections of the beam patterns produced by the square aperture at high excitation level for the fundamental (2.8 MHz) and the second harmonic (5.6 MHz) fields, respectively. The patterns are presented as isobar contour lines filled with colours (the printed Journal version presents grey-scale photocopies, the colour patterns are available on-line). The highest pressure amplitude is depicted as red and decreases through yellow, green, light blue and finally dark blue. The patterns are presented along the z axis (linear scale, xz and yz planes) and in xy planes at axial distances of 5, 20, 40, 70 and 120 mm to capture the features of the field before and after the focal plane. The xy plane patterns are also shown in logarithmic scale in order to enhance the relatively small amplitude differences within the spectrum and to mimic the logarithmic compression used in clinical ultrasonography.

Similarly, Fig. 11 and 12 illustrate both the longitudinal and lateral two dimensional cross-sections of these patterns for the fundamental (2.8 MHz) and the second harmonic (5.6 MHz) fields, respectively, produced by the rectangular aperture at high (transducer surface pressure of 0.45 MPa) excitation level.

The results shown in Figs 9-12 confirm that, as anticipated, the second harmonic's beam is narrower than that associated with the fundamental frequency.

The execution time of simulation was also estimated. This was done using both the conventional Fourier series approach and the Tawe method. In general, the computer simulation time required for the full 4D pulsed nonlinear pressure field computation depends on the source size and shape, resonance frequency, excitation level, medium density, sound velocity, absorption coefficient with its frequency-dependence law and nonlinearity parameter B/A . It also depends on a number of harmonics taken into account in the spectral analysis. The comparison of the execution time was performed for the square and rectangular sources examined (here, 14). and the axisymmetrical transducer, similar to the one described in [1]. For the axially symmetric transducers the Tawe and conventional method were comparable [1], because in such case the use of Hankel transforms enabled shortening of the computation time. The successful use of Hankel transforms was also reported in [9]. However, a significant shortening of the simulation time was observed for the non-axisymmetric focused transducers tested here and excited by a tone burst corresponding to moderately nonlinear and highly nonlinear conditions. For moderately- and highly nonlinear cases the execution time of

computations was 3 and 12 hours, respectively, when using a 1.5 GHz clock frequency, having 32-bit processor laptop PC and 2 GB RAM memory, only. The execution time increases proportionally to the square power of the source pressure and the results obtained here indicated that without the Tawe approach the prediction of the full 4D pulsed field would not have been possible using a conventional Fourier-series scheme.

Such scheme would require increasing the RAM memory by at least 2 orders of magnitude. Finally, it might be instructional to compare the execution times experienced during the course of this work with those reported in [4] where truncated Fourier-series approach (Bergen Code) was utilized. In [4], the use of a powerful Cray Y-MP4D/464 computer was necessary to predict the CW nonlinear field produced in water from the plane rectangular sources. Depending on the CW excitation level the Cray computer time needed ranged from 400 (7 minutes) to 12300 CPU seconds (205 minutes).

V. CONCLUSIONS

The results of the measurements of pulsed nonlinear acoustic fields in water produced by the 2.8 MHz spherically focused, square and rectangular transducers were compared with the numerical predictions obtained using the Time-Averaged Wave Envelope (Tawe) approach [1]. The comparison of the experimental results and numerical predictions has shown that the Tawe approach is capable of predicting correctly both the spatial-temporal and spatial-spectral pressure distributions. Specifically, closer examination of the results presented in Figs 3 - 7 revealed that the discrepancies between the theoretically predicted axial pressure distributions and those determined experimentally, especially at the axial distances less than 5 cm were within ± 1 dB. As pointed out earlier, it is conceivable that these discrepancies were caused by the finite aperture of the hydrophone sensitive element and the overall uncertainty of the hydrophone calibration (± 1 dB). The data presented verified the applicability of Tawe method as a tool for fast prediction of the full four dimensional (4D) pulsed nonlinear pressure fields from arbitrarily shaped acoustic sources in attenuating media. The implementation of the Tawe approach using widely available laptop PC platform greatly enhanced computational efficiency in comparison with the time needed for prediction of the full 4D pulsed nonlinear acoustic fields using a conventional (Fourier-series) approach.

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Fig. 1. Experimental setup for measuring pressure fields radiated by the square and rectangular transducers immersed in water.

Fig. 2. Square aperture, low excitation level. Half of the apodisation function (solid line) $f(x,0) = P_0 |1 - (x/a)^8|$ at the radiating aperture surface in the x (or y) direction, assumed for numerical calculations. The transverse pressure distribution (dashed line) calculated for the above apodisation function at the axial distance of 15 mm and measured at the same distance (points).

Fig. 3.

Square aperture, moderate excitation level. The peak-compression (P^+), peak-rarefaction (P^-) and peak-to-peak (P) pressure variations measured (points) and calculated (solid lines) along the acoustic axis (left) and across the axis (right) in the plane $z = 7\text{cm}$.

Fig. 4. Square aperture, moderate excitation level. Axial pressure variation of the fundamental (1), second (2) and third (3) harmonics calculated (solid lines) and measured (points) with correction for variation of the hydrophone sensitivity with frequency.

Fig. 5. Square aperture, high excitation level. Axial pressure variation of the fundamental (1), second (2) and third (3) harmonics calculated (solid lines) and measured (points) with correction for variation of the hydrophone sensitivity with frequency.

Fig. 6.
The same as in Fig. 3, but for the rectangular aperture and high excitation level.

Fig. 7.
The same as in Fig. 5, but for rectangular aperture.

Fig. 8. Rectangular aperture, high excitation level. Pressure-time waveforms and their spectra of the pulsed wave on the acoustic axis at the geometric focus plane ($z = 8$ cm) calculated (solid lines) and measured (points).

Fig. 9.

Square aperture, high excitation level. Pulsed pressure nonlinear beam patterns calculated for the fundamental harmonics ($f_1 = 2.8$ MHz); A) in the xz (yz) plane, B) in xy planes at various axial ranges, C) the same as B) but in logarithmic scale. Spatial scales in mm. Colour scales are normalised to the maximum pressure for the corresponding cross-section.

Fig. 10.

Square aperture, high excitation level. Pulsed pressure nonlinear beam patterns calculated for the second harmonics ($f_2 = 5.6$ MHz); A) in the xz (yz) plane, B) in xy planes at various axial ranges, C) the same as B) but in logarithmic scale. Spatial scales in mm. Colourscales are normalised to the maximum pressure for the corresponding cross-section.

Fig. 11.

Rectangular aperture, high excitation level. Pulsed pressure nonlinear beam patterns calculated for the fundamental harmonics ($f_1 = 2.8$ MHz); A) in the xz plane, B) in the yz plane, C) in xy planes at various axial ranges. Spatial scales in mm. Colour scales are normalised to the maximum pressure for the corresponding cross-section.

Fig. 12.

Rectangular aperture, high excitation level. Pulsed pressure nonlinear beam patterns calculated for the second harmonics ($f_2 = 5.6$ MHz); A) in the xz plane, B) in the yz plane, C) in xy planes at various axial ranges. Spatial scales in mm. Colour scales are normalised to the maximum pressure for the corresponding cross-section.