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AN EXPERIMENTAL INVESTIGATION OF THE FINITE AMPLITUDE WAVE

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An experimental investigation of the pressure field distribution produced by a plane circular piston in water was carried out by means of two receivers of different size. A transducer of 46-mm-diam and 1.0-MHz center frequency was used as a transmitter. The PVdF needle hydrophone of 1 mm diameter was the first receiver, whereas the second one had a diameter equal to that of the source. All experiments were performed using a high precision computer-controlled tank facility. Measurements of harmonic generation are compared with numerical calculations based on the nonlinear parabolic wave equation.

1. Introduction

Recently there has been a steady growth of interest in the nonlinear problem of finite aperture sound beams in number of disciplines such as acoustic microscopy [10], ultrasound therapy and diagnostics [6, 9], parametric acoustic arrays [8], and the measurements of the nonlinear parameter B/A with finite amplitude effects of sound waves [11, 14].

In many applications the most important are phenomena occurring in the nearfield area. It is caused by the fact that due to the applied measurement set up arrangement and the chosen parameters of used transducers the measured or diagnosed object is often situated within the nearfield area.

Many papers have been published devoted to the problem of the nonlinear distortion of the finite amplitude wave in the nearfield of the source. The fine structure of the nearfield presents difficulties to both: the theoretical and the experimental investigations. One of the first papers devoted to the theoretical description of the nearfield of the finite amplitude source was published in 1971 by INGENITO and WILLIAMS JR. [12]. There the second harmonic field of a piston transducer was calculated by means of the perturbation method. A significant step was made by Norwegian scientist, who solved the KZK equation numerically, using the finite difference scheme [1], which is known as the Bergen code. It accounts for the nonlinearity, absorption and diffraction. The solution is widely used in comparing the measurement results [3, 17] and may be modified according to the measurements conditions, for instance for focused circular sources [4] and for rectangular sources [5, 16].

The paper presents the results of the experimental investigations of the finite amplitude wave radiated by the circular piston. The investigations were carried out close to the transmitter in the nearfield and nearfield-farfield transition area using the high precision positioning device which controlled the movement of the receiver. The distance of occurring the last maximum in the pressure distribution on the beam axis is assumed to be the boundary of the nearfield.

2. Experimental methods

A set up shown in Fig. 1 was used for experimental measurements. The transmitter – a piston of 46-mm-diam – was mounted at one end of the water tank 1.4 m long by 1.2 m wide and 1.2 m deep. The transducer was driven at its center frequency of 1.0-MHz corresponding to $ka = 96$ (k is a wave number, a is the transmitter radius). It was driven with a tone pulse, approximately 50 cycles long and the pulse repetition was of about 8 msec. This gave a quasi-continuous wave in the measuring area field without standing waves. Reflections were eliminated by using a time gate on the receiver pulse.

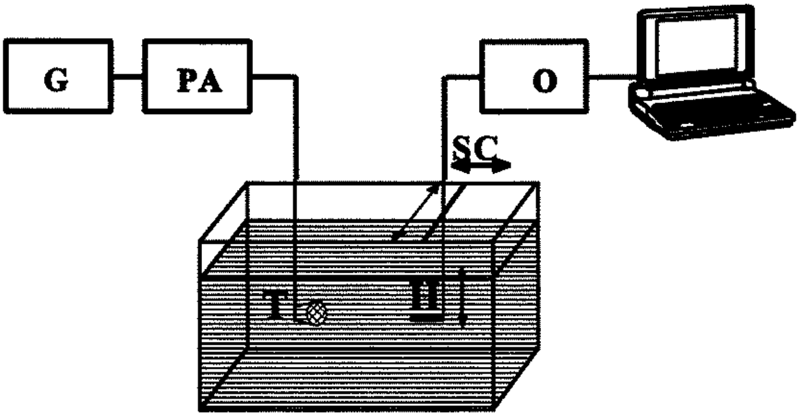

Fig. 1. The measurement set up: G – generator, PA – power amplifier, T – transmitter, H – PVdF needle hydrophone, SC – scanning set up, O - digital storage oscilloscope HP 54503A.

The pressure generated by the transducer was measured using a 1-mm-diam PVdF needle hydrophone. The hydrophone was mounted on a three-dimensional translation stage that allowed to position the hydrophone anywhere in a plane perpendicular to the acoustic axis of the transducer or along this axis. The movement resolution is theoretically equal to 0.0125 mm.

The output from the hydrophone was fed directly into a digital storage oscilloscope (HP 54503A). The oscilloscope was used to capture a middle part of the tone burst. The time waveform was then transferred to the controlling computer and five (or two) cycles underwent the Fourier analysis to extract the harmonic amplitudes. The measured waveforms were averaged before analyzing.

The second receiver used in measurements was of an area equal to that of the transmitter, but it was sufficiently broadband to receive the harmonics appearing as an effect of nonlinear propagation in water. The measuring method of nonlinear distortion in which two coaxial transducers of equal area are used was described by COBB [7].

3. Experimental results

Results of the experiments allow to make a thorough study of the nonlinear distortion growth in the area close to the transmitter. The pressure distribution of the examined plane circular piston transmitter of 46-mm-diam at a distance of 1 mm from the surface is shown in Fig. 2. The amplitude of the pressure p_0 equals to about 157 kPa. In the numerical model that distribution is approximated by the curve shown in Fig. 3.

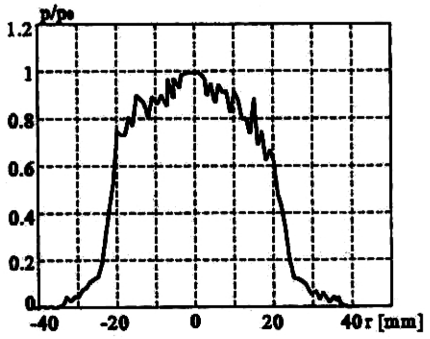

Fig. 2. The pressure distribution measured at a distance of 1 mm from the surface of the examined plane circular piston transmitter.

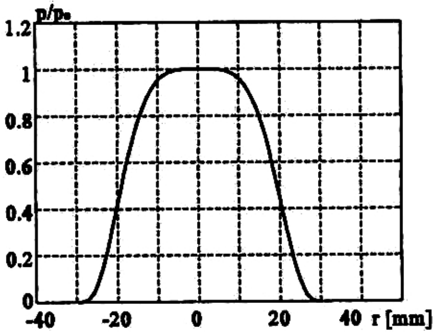

Fig. 3. The curve approximating the measured pressure distribution at the radiating surface.

The growth of the nonlinear distortion can be noticed by observing the changes in the shape of the wave and in the rising of the amplitude of the second harmonic with the increasing distance from the source. Figure 4 shows the shape of the wave measured using 1-mm needle hydrophone at different distances from the source and Fig. 5 shows the shape of the wave measured in the axis of the source at the distance of 70 mm and

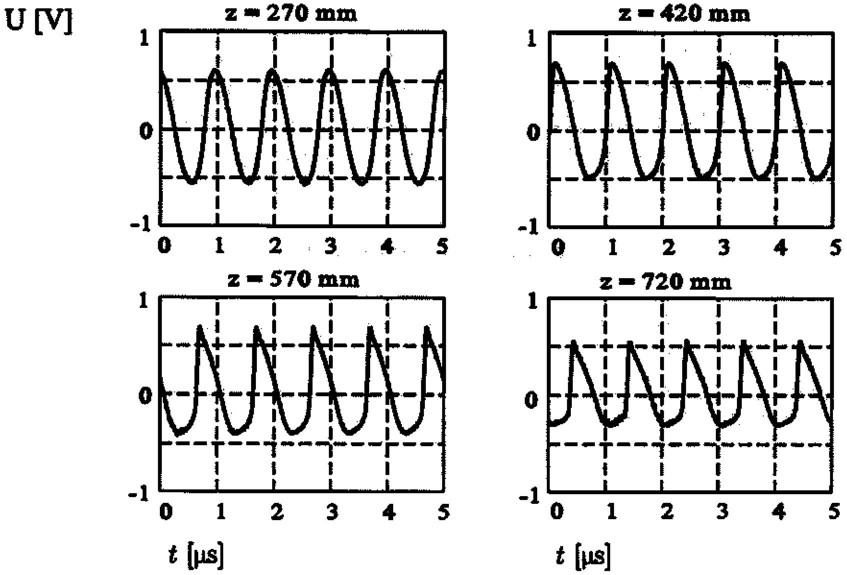

Fig. 4. The changes in the shape of the wave measured on the beam axis with the increasing distance from the source.

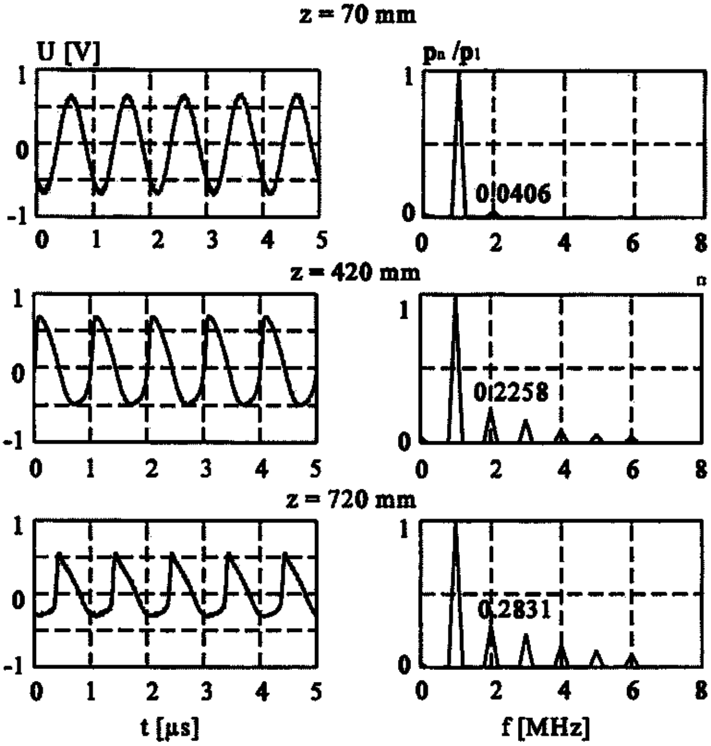

Fig. 5. The shape of the wave measured in the axis of the source at the distance of 70 mm 420 mm and 720 mm and their respective spectra.

720 mm and their respective spectra. In the plane distant 720 mm from the source the distortion is quite great. The amplitude of the second harmonic equals to about 28% of the amplitude of the first harmonic.

The results of measurements allow to obtain the graph (Fig. 6) in which the changes in the amplitude of the pressure harmonics as a function of the distance from the source are presented. The results of experiment (solid line) are shown together with the results of numerical calculation (dashed line). The comparison could be done from the distance come from restriction in validity of the applied numerical model.

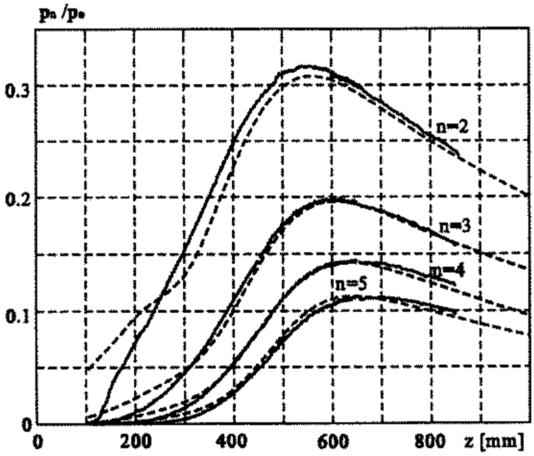

Fig. 6. The changes in the amplitude of the pressure harmonic components on the beam axis as a function of the distance from the plane circular source: (—) obtained experimentally, (- - -) predicted theoretically.

We can also illustrate the nonlinear wave distortion in a form of amplitude pressure distribution in chosen plane. In the next figures are shown distributions of the relative amplitude of the second and higher harmonic components measured in planes placed at the different distance from the source. The growth of the nonlinear distortion can be noticed by observing the rising in the amplitude of the second harmonic component with the distance from the source. It is exemplified in Fig. 7 which shows the growth of the nonlinear distortion expressed in the rising in the relative amplitude of the second harmonic pressure in planes distant 120 mm, 270 mm and 370 mm from the transmitter. In the last of these planes (370 mm from the source) the distortion is so great that higher harmonic components become measurable. In the Fig. 8 are shown the first four pressure harmonics measured in this plane. The distortion rises with the growing of the distance from the source. It is confirmed by the distributions of the relative amplitude of the higher harmonics in the plane distant 720 mm from the source shown in Fig. 9.

Apart from investigations carried out using the needle hydrophone they were made using the receiver of the area as the transmitter. The results of these measurements were compared. The next figures show the results of measurements obtained in the same conditions of the experiment using both of hydrophones at the same distances from the source.

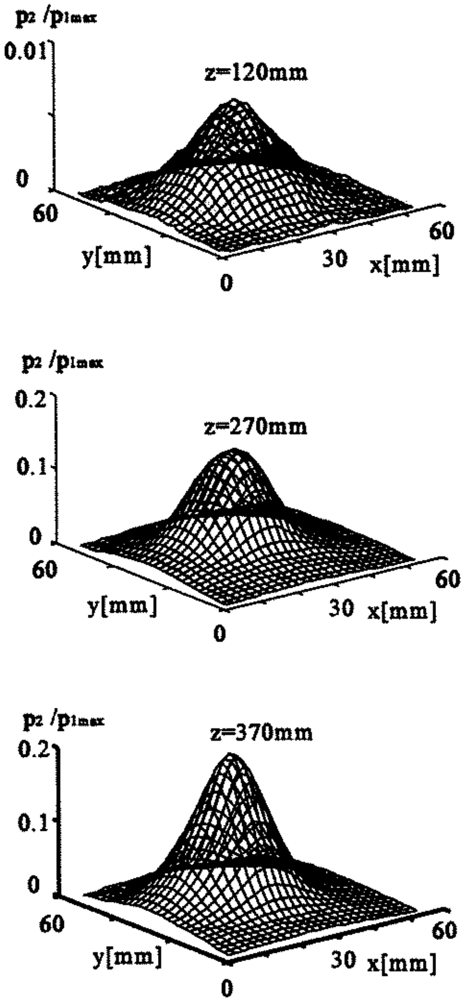

Fig. 7. Relative amplitude of the second pressure harmonic component measured in planes distant 120 mm, 270 mm and 370 mm from the plane circular source.

In Fig. 10 are presented the shape and the spectrum of the wave measured applying the receiver of the same area as the transmitter at two different distances between them. In the successive figure are shown the corresponding shapes and spectra of the wave measured by means of the PVdF hydrophone in the axis of the source (Fig. 11). We can notice that the wave distortion in the axis is more substantial then the one of the wave averaged on the surface of the larger receiver. It is caused by nonuniform distribution of the primary wave pressure across the beam which influences the nonuniform distribution of the higher harmonics. The pressure distribution of the first and second harmonic components at the planes at the same distances as the previous ones can be seen in Fig. 12.

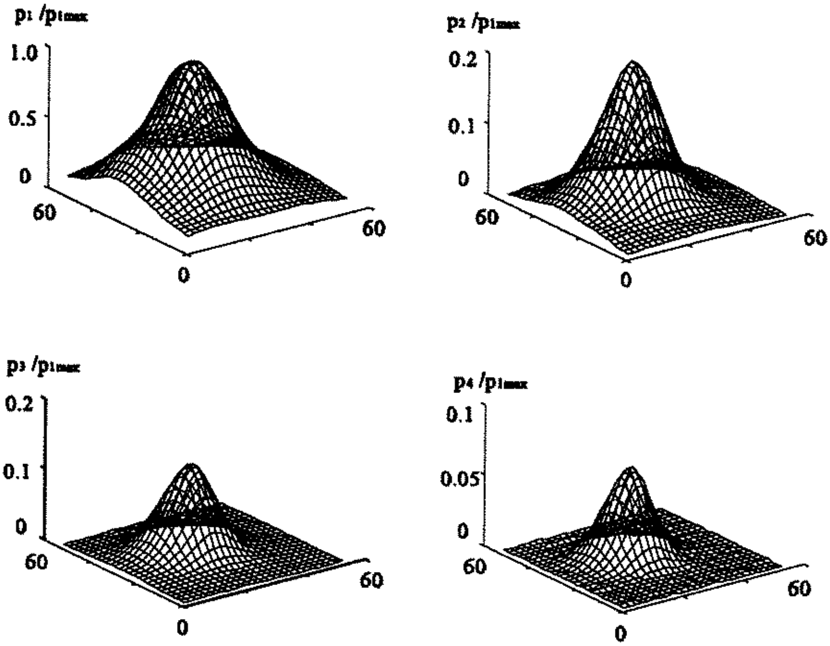

Fig. 8. Relative amplitude of the four first pressure harmonic components measured in the plane placed at the distance of 370 mm from the plane circular source.

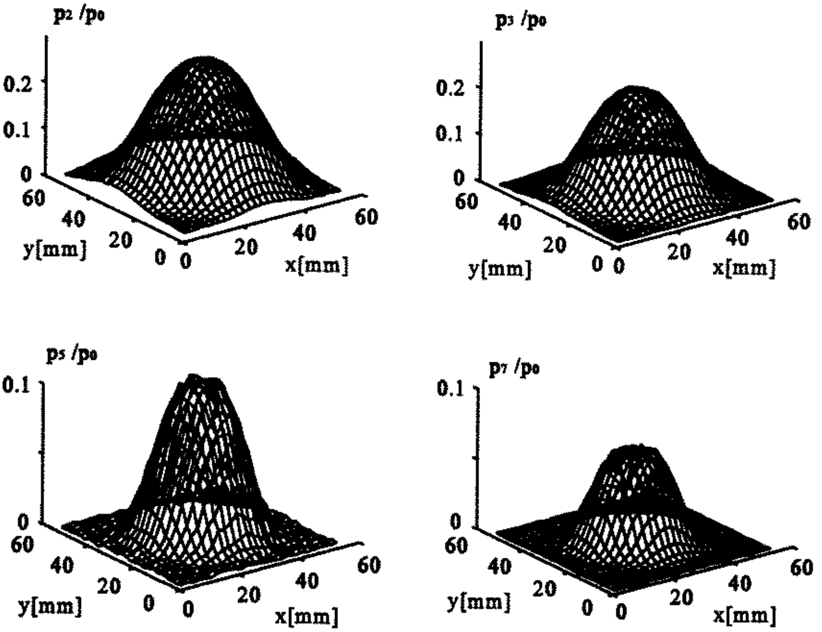

Fig. 9. Relative amplitude of the second, the third, the fifth and the seventh pressure harmonic components measured in the plane distant 720 mm from the source.

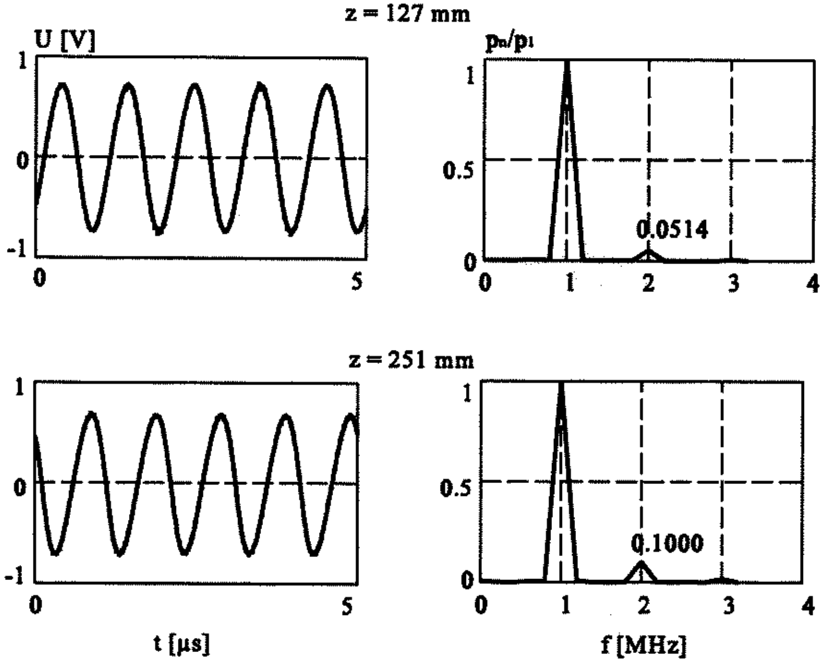

Fig. 10. The shape of the wave measured using the receiver of that area as the transmitter at the different distances and their respective spectra.

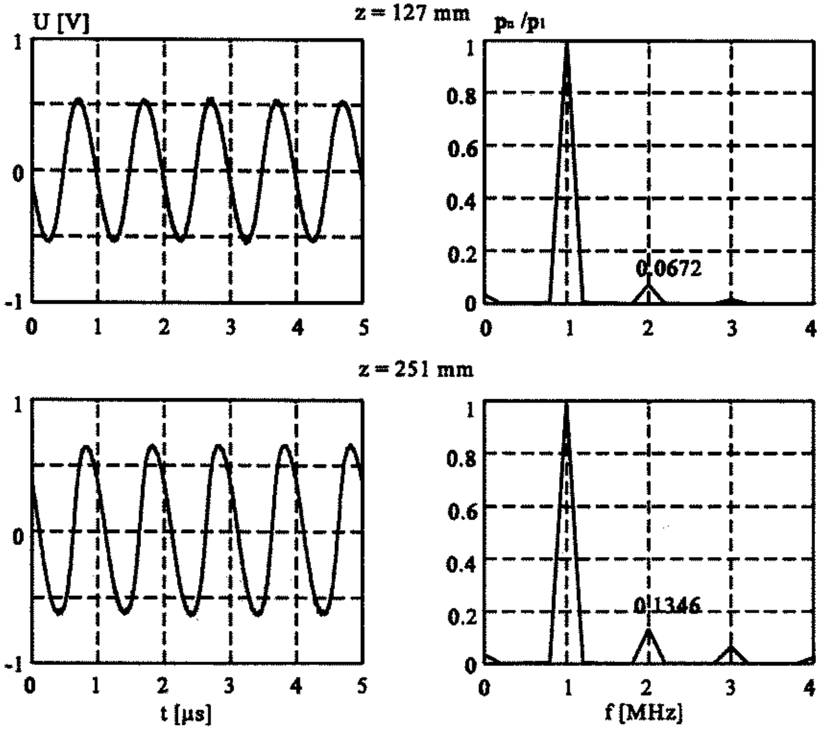

Fig. 11. The shape of the wave in the beam axis measured using the needle hydrophone at the different distances from the source and their respective spectra.

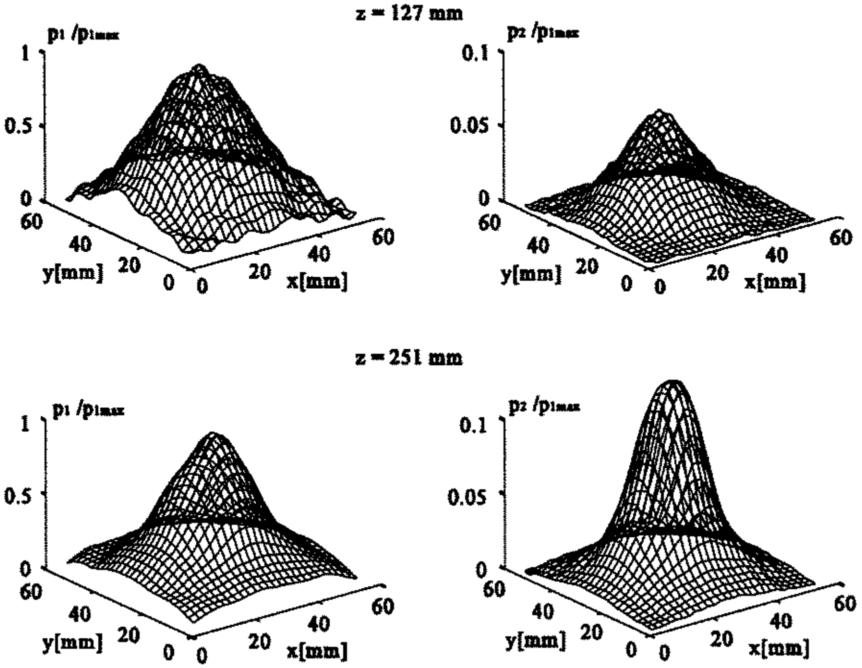

Fig. 12. The pressure distributions of the first and the second harmonics measured in the planes distant 127 mm and 251 mm from the source.

4. Conclusions

The paper presents the results of the experimental investigations of the finite amplitude wave field distribution. The measurement results obtained using the high precision facility which controlled the movement of the receiver were presented as well. The results of measurements together with calculations allow to make a thorough study of the nonlinear distortion growth in the nearfield. They confirm the usefulness of both the elaborated method and the measurement set up for the investigations of the finite amplitude wave source in its nearfield. The use of receivers of an active area dimension greater than a wavelength gives us an averaged value of the measured quantity.

Acknowledgements

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References

[1] I. Aanonsen, T. Barkve, J. Naze Tjøtta, S. Tjøtta, *Distortion and harmonic generation in the nearfield of a finite amplitude sound beam*, J. Acoust. Soc. Am., **75**, 749–768 (1984).

[2] K. Beissner, *Exact integral expression for the diffraction loss of a circular piston source*, Acustica, **49**, 212–217 (1981).

[3] A.C. Baker, K. Anastasiadis, V.F. Humprey, *The nonlinear pressure field of a plane circular piston: Theory and experiment*, J. Acoust. Soc. Am., **84**, 1483–1487 (1998).

[4] A.C. Baker, *Nonlinear pressure fields due to focused circular apertures*, J. Acoust. Soc. Am., **91**, 713–717 (1992).

[5] A.C. Baker, A.M. Berg, A. Sahin, J. Naze Tjøtta, *The nonlinear pressure field of a plane, rectangular apertures: Experimental and theoretical results*, J. Acoust. Soc. Am., **97**, 3510–3517 (1995).

[6] D. Cathignol, J.Y. Chapelon, *High energy ultrasound therapy, Part I and Part II*, Advances in nonlinear acoustics, World Scientific, London, 21–35 (1993).

[7] W.N. Cobb, *Finite amplitude method for the determination of the acoustic nonlinear parameter B/A*, J. Acoust. Soc. Am., **73**, 1525–1531 (1983).

[8] J. Dybedal, *TOPAS: Parametric end-fire array used in offshore applications*, Advances in nonlinear acoustics, World Scientific, London, 264–269 (1983).

[9] L. Filipczyński, J. Etienne, M. Piechocki, *An attempt to reconstruct the lithotripter shock wave pulse in kidney: Possible temperature effects*, Med. Biol., **18**, 569–577 (1992).

[10] L. Germain, J.D.N. Cheeke, *Generation and detection of high order harmonics in liquids using a scanning acoustic microscopy*, J. Acoust. Soc. Am., **83**, 942–949 (1988).

[11] X.F. Gong, X.Z. Liu, *Acoustical nonlinearity parameter and its medical applications*, Advances in nonlinear acoustics, World Scientific, London, 353–357 (1993).

[12] F. Ingenito, A.O. Williams Jr., *Calculation of second harmonic generation in a piston beam*, J. Acoust. Soc. Am., **49**, 319–328 (1971).

[13] E. Kozaczka, G. Grelowska, *Nonlinearity parameter B/A of the low-salinity seawater*, Arch. Acoust., **19**, 259–270 (1994).

[14] E. Kozaczka, G. Grelowska, *Investigation of the nonlinearity parameter B/A in the South Baltic Sea*, Nonlinear acoustics in perspective, Nanjing University Press, 88–93 (1996).

[15] S.-W. Li, Z.-X. Xu, *The harmonic nearfield of a narrow strip transducer*, Nonlinear acoustics in perspective, Nanjing University Press, 200–205 (1996).

[16] J.A. TenCate, *An experimental investigation of the nonlinear pressure field produced by a plane circular piston*, J. Acoust. Soc. Am., **94**, 1084–1089 (1993).