Remote measurements of the ultrasonic pressure distribution using focused transducer

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Abstract

Measurements of the pressure distributions differences of the ultrasonic fields at different zones of the test object can be provided in order to estimate the dimensions of the defects, located in the test object. Such measurements of the field pressure distributions point-by-point can be done using hydrophones, e.g. ultrasonic transducers of a small diameter. The field is measured at the point where the hydrophone is located. The use of hydrophones for the ultrasonic field measurements is complicated due to the field distortions at the measurement points, induced by the hydrophone. In order to avoid for such distortions it is possible to use focused ultrasonic transducer. Presumption is done that the focused transducer measures the field, which is in the focus point of the transducer and the ultrasonic signals are obtained without placing the transducer at the exact point of the ultrasonic field. It is possible to measure remotely the distributions of the ultrasonic field pressure at different distances from the surface of the field radiating source.

There are no transducers, which would radiate the standard or *a priori* ultrasonic field, so the equivalent of the real field was theoretically calculated, which is tagged as a true field. Also the field pressure distribution, measured with the focused transducer, was calculated imitating the real measurement. The modelling results were verified and compared with the results, obtained during experimental measurements of the ultrasonic field distributions. Calculations and measurements were performed at three distances between the surface of the radiating plane transducer and receiving focused transducer.

Keywords: measurement of ultrasonic fields, focused ultrasonic transducers, ultrasonic transducer characterization.

Introduction

The measurements of the ultrasonic fields can be grouped in two main techniques. The first one is point-by-point scanning with a single transducer working as a receiver. The second technique is the whole-at-once field measurement using ultrasound sensitive arrays [1]. Usually for the point-by-point scanning the hydrophones (very small ultrasonic transducers) are used [2]. It is true to say that the ultrasonic field is distorted due to the placing of the hydrophone at the measurement point.

The focused transducer is used for the surface and subsurface scanning in the acoustic microscopy, also for detection of the surface roughness and subsurface defects. It is suggested, that the focused transducer also can be used for measurements of ultrasonic fields propagating in media between the source of the ultrasonic field and the receiver, e.g., focused transducer [3]. Supposedly, the focused ultrasonic transducer is under expose of the ultrasonic field, which is at the transducer's focus point. So, a focused transducer, similarly to the hydrophone, can be used for remote measurements of radiated or backscattered ultrasonic fields, which are located at the focus point of the transducer. This gives the possibility to obtain ultrasonic signals without placing the transducer at the measurement point of the ultrasonic field. The transducer in this case is located at some distance from the measurement point of the field, which is equal to the transducer's focus distance. The bandwidth and spatial resolution or the size of the focus point can be chosen by selecting the transducer with desirable parameters like diameter, focus distance, frequency, also, the scanning path and step can be chosen to increase the accuracy of the field measurements. Such measurements are important for characterization of the

ultrasonic transducers analyzing the measured field, which is radiated by the transducer.

The objective of this article is to verify the proposed remote measurement method of the ultrasonic field pressure distributions using a focused transducer. The results of theoretical calculations and experimental measurements are presented. The theoretical calculations of the field, which can be tagged as a true, or reference field, are performed. Such calculations are necessary because there are no standard radiators, so there are no standard ultrasonic fields, which could be taken as the point of reference comparing the radiated by the transducer true field and the measured field. The calculations, imitating the measurements of the ultrasonic field using focused transducer, are performed. The experimental measurements of the distributed ultrasonic field pressure are provided; also the comparison of practical and theoretical results is done.

Principles of the ultrasonic field measurements

The distributed in space ultrasonic field can be described as the four-dimensional ultrasound pressure function of the temporal and spatial coordinates:

$$p = p(x,y,z,t), \qquad (1)$$

where p is the acoustic pressure; x, y, z are the spatial coordinates, t is the time. The measurements of such fields are complicated because of the field variations in spatial and time domains, e.g. dynamic character of the fields, so the simplification is applied. The ultrasonic field in most occasions vary in time, so the function of the ultrasonic field pressure at the defined spatial coordinates (Fig. 1) depends only on t (Fig. 2):
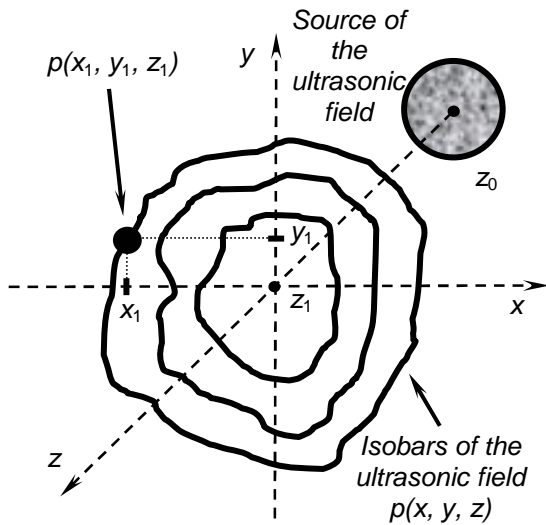
$$p = p(x_1, y_1, z_1, t), \qquad (2)$$

Fig. 1. **The principal scheme of measurement of the distributed in space ultrasonic field:** x, y, z **are the spatial coordinates;** $p(x_1, y_1, z_1)$ – **the ultrasound pressure at the point with the coordinates** x_1, y_1, z_1; z_0 z_1 – **the distance between the measurement point and the ultrasound radiator**
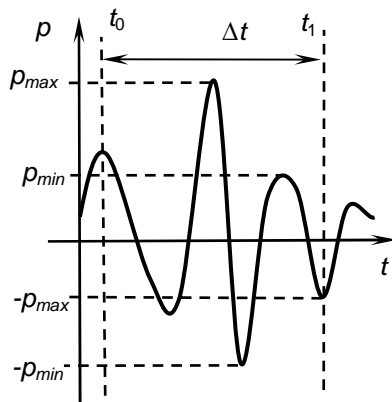

Fig. 2. **The estimation of the ultrasound signal in the time domain:** p – **function of the ultrasound pressure,** Δt – **time interval,** $\pm p_{max}$ – **the maximum positive and negative values of** p **in** Δt, $\pm p_{min}$ – **the minimum positive and negative values of** p **in** Δt

There are various methods to estimate the value of p of the measured varied in time signal of the ultrasonic field at the spatial coordinates x_1, y_1, z_1. The value or modulus of the value of p can be taken at the chosen time instant t_0. In order to determine t for the p estimations, the time interval Δt is defined and various calculations are applied. Several of them are the retrieving the maximum values of p estimating the plus or minus sign of p in Δt, the average value of p in Δt, also the estimation of the polarity is applied. Also t_0 or Δt can be fixed or varying for the particular spatial coordinates x_n, y_n, z_n where n are the integers. The estimation of t is defined in the algorithms of the calculations of p in the particular cases and then p is given by:

$$p = p(x_1, y_1, z_1)\big|_t . \qquad (3)$$

Determination of one of the spatial coordinates helps to replace the measurements of the three-dimensional ultrasonic field into the measurements of the two-dimensional field. Declaring that the ultrasonic field is observed at the fixed and known distance z_1 from the source of the ultrasonic field, the pressure p can be written:

$$p = p(x_1, y_1)\big|_{z_1, t} , \qquad (4)$$

where x_1, y_1 are the coordinates (Fig. 1), z_1 is the distance from the measurement point to the source of the field. Different observation distances z_n in the (x, y) plane can be selected, e.g., cross-sections of the field at one of the axes of the spatial coordinates (x, y or z coordinates) can be performed.

The measurements of the time-varying distributed spatial ultrasonic fields can be performed at the points of the space, where the field is located. The field between the measurement points is obtained using interpolation methods. Performing the measurements of the field $u(x, y)$ in points (Fig.3) the discretization of the field is applied:

$$u(n_1, n_2) = u(n_1 X_1, n_2 X_2), \qquad (5)$$

where n_1, n_2 are integers, X_1, Y_1 are the distances between the measurement points in x, y coordinates, e.g. are the intervals of the discretization.

The discretization of the field can be done at the selected points using different scanning techniques (Fig.3). The chess-type scanning would be more efficient than square-type (Fig. 3), because there is better possibility to cover the gaps between particular measurement points selecting particular X_n and Y_n.
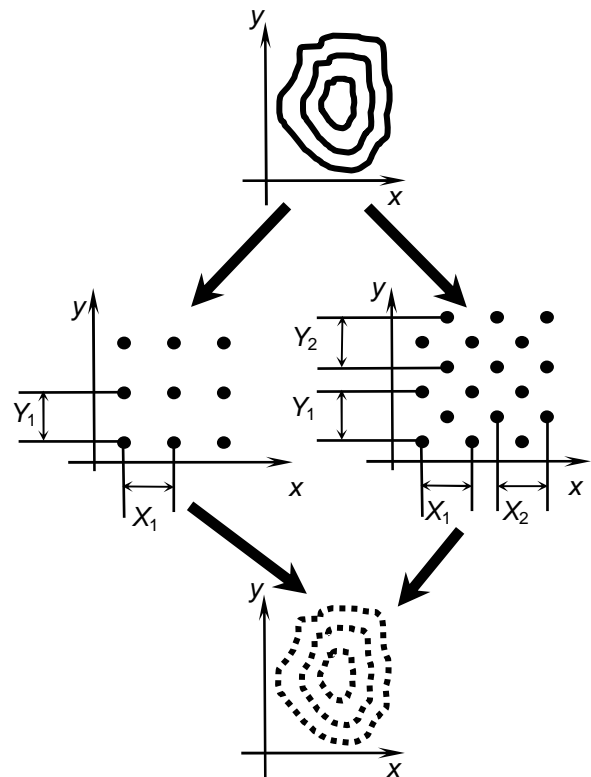

Fig. 3. **The principle of the discretization and reconstruction of the distributed field: on top – the real field, in the middle – two different ways of the selection of the measurement points in the field, at the bottom – the reconstructed field**

In practice it is recommended to choose such a sampling period that the double length of spatial wave would contain five measurement points in order to avoid

the un-retrieve of the field components, which would have shorter spatial period that the distance between the measurement transducers [4].

Theoretical background

There is no *a priori* knowledge about the true field, which has to be measured, so the theoretical modelling is proposed in order to calculate the ultrasonic field, radiated by a planar piston transducer, and it is supposed that the field is radiated and distributed uniformly over the whole surface of the transducer. Such calculated field will be postulated as a true field. The field measured by a focused transducer will be compared to that true field. The field which is measured by a focused remote transducer is also calculated. The comparison of the true field and the measured field must give an answer how precisely the radiated or backscattered ultrasonic field may be measured using the focused transducer.

The ultrasonic field, radiated by a planar transducer, at the exact point which is remote at the known distance from the surface of the transducer, is calculated as a convolution of the excitation signal and the impulse response of the unfocused transducer.

$$u_{PT}(x, y, z, t) = h_{PT}(z, R, t) \otimes u_{EXC}(t), \qquad (6)$$

where the u_{PT} is the signal radiated by the unfocused transducer, h_{PT} is the impulse response of the unfocused transducer, u_{EXC} is the excitation signal, x, y and z are spatial coordinates, t is the time.

The calculation of the impulse response of the unfocused transducer may be found elsewhere [5-7].

The convolution of the impulse response of the focused transducer and the true ultrasonic field, gives the ultrasonic field, which corresponds to the field, measured by the focused transducer:

$$u_{FS}(x, y, z, t) = h_{FT}(x, y, z, t) \otimes u_{PT}(x, y, z, t), \qquad (7)$$

where u_{FS} is the field, measured by the focused transducer; h_{FT} is the impulse response of the focused transducer.

The impulse response of the focused transducer is calculated at a distance F_e, defined by Eq. 8 [8].

$$F_e = \frac{F}{1 + \left(\frac{2}{3}\right) \cdot \left(\frac{F}{L_{nf}}\right)^{4/3}}, \qquad (8)$$

where

$$L_{nf} = \frac{a^2}{\lambda}, \qquad (9)$$

where a is the radius of the transducer, λ is the ultrasonic wavelength, L_{nf} is the near field distance, F is the transducer's geometrical focus distance.

Calculation of F_e is performed because the true focus of the focused transducer, due to wave diffraction effects, occurs closer to the focused transducer's surface than geometrical focus [8-9] and the theoretical calculations of the field which corresponds to the field, measured by the focused transducer, have to be performed at that distance in order to have a better conformity between theoretical modelling and experimental measurements.

Experimental setup

The experiment was performed in order to verify the results of the theoretical modeling. The experimental set-up is presented in Fig. 4. The radiating planar transducer was in a fixed position and the receiving focused transducer was moved parally to the surface of the planar transducer planes at various distances from the planar transducer.

The Measurements were carried out at three different distances $F+L$ from the surface of the planar transducer: 52 mm, 59 m, 69 mm, e.g. the focal distance of the focused transducer was located 2 mm, 7 mm and 17 mm above the surface of the planar transducer. In other words, the calculations and measurements were performed in the near field zone of the planar transducer at $0.003 \cdot N$, $0.013 \cdot N$ and $0.03 \cdot N$, where N is the near field distance. The focused transducer was moved along the x coordinate in order to get the B-scan of the ultrasonic wave, radiated by the planar transducer's surface. The results are presented in Fig. 5 – 10.
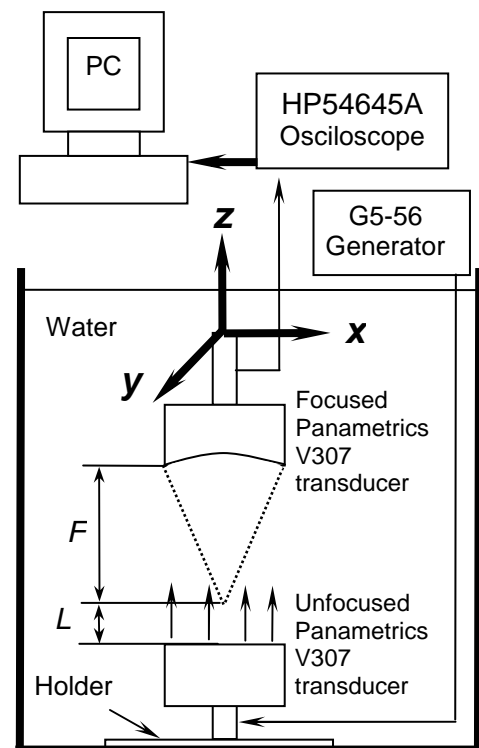

Fig. 4. **The experimental set-up for the ultrasonic field measurements of the planar transducer (*F* – focus length of the focused transducer).**

Results

The theoretical calculations using Eq. 6 and 7 were performed in order to calculate the field, measured by the focused transducer at different distances from the surface of the planar transducer. The calculations were performed using MATLAB. The setups were following: the time step dt for the calculation of the impulse responses - 0.01 μs; the ultrasound velocity c in water - 1.48 km/s; the diameter of the unfocused transducer's surface D - 29 mm; the

frequency of the ultrasonic wave f – 5 MHz. The results are presented in Fig. 7 – 10.

The spatial pressure distributions in Fig. 5 – 10 are normalized. The view of the normalized spatial distribution of the ultrasonic pressure of the true field, radiated by the planar transducer, is presented in Fig. 5. The normalized spatial distribution of the ultrasonic pressure, measurement at which by a focused transducer of the true field distribution was simulated theoretically, is presented in Fig. 6 and the normalized distribution of the experimentally measured field is presented in Fig. 7.
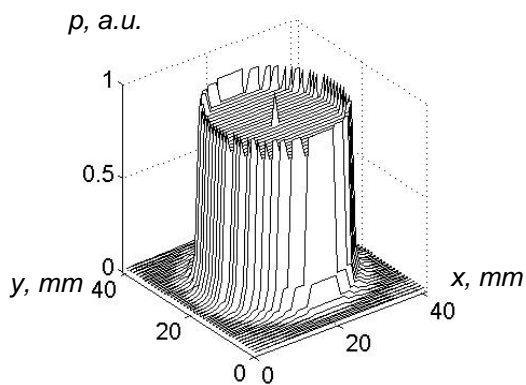
Fig. 5. **The normalized image of the pressure distribution of the true field radiated by the planar transducer at a distance 2 mm from the surface of the transducer**
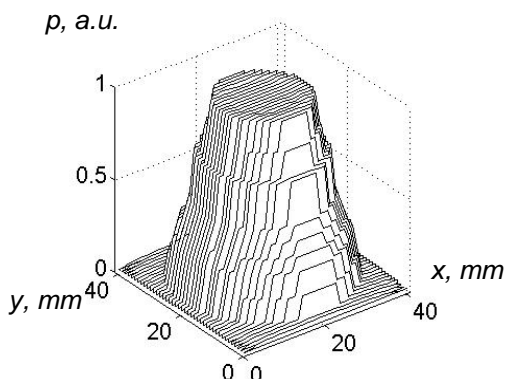

Fig. 6**. The normalized image of the pressure distribution of the simulated measured field obtained by the focused transducer at a distance 2 mm from the surface of the planar transducer**
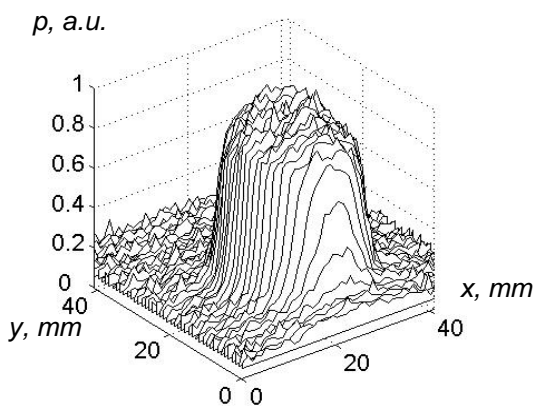

Fig. 7. **The normalized image of the measured pressure distribution of the planar transducer's field obtained by the focused transducer at a distance 2 mm from the surface of the planar transducer**

The spatial cross-sections of the calculated and measured distributions of the ultrasonic field are presented in Fig. 8 – 10. The estimation of the differences between the true fields and the measured fields can be performed calculating the relative error [3]:

$$\Delta p(\%) = \frac{p - p'}{p} \cdot 100\% , \qquad (10)$$

where p is the true simulated field, p' is the measured field. The calculated Δp of the true field pressure and modelled field pressure which corresponds to the field, measured by the focused transducer pressure, is presented in Fig. 11. The calculated Δp of the modelled field which corresponds to the field, measured by the focused transducer pressure, and the experimentally measured ultrasonic pressure field distribution, are presented in Fig. 12. It is true to say that the results, presented in Fig. 12, show the non-ideal operation of the real transducers.
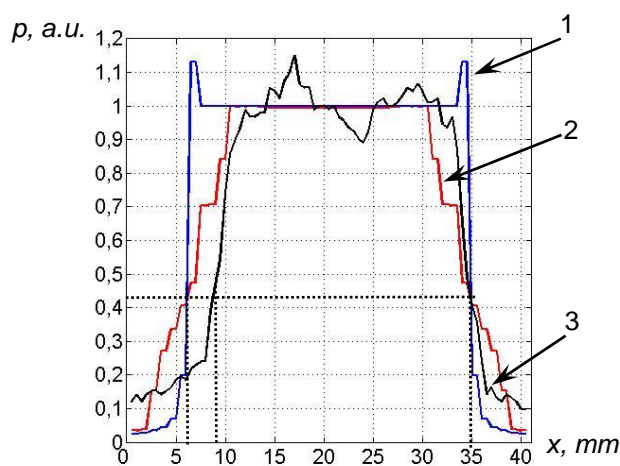

Fig. 8. **The spatial cross-sections of the pressure distributions at 0,003·N distance from the surface of the planar transducer: 1 – true field, 2 – simulated measured field, 3 – measured field**
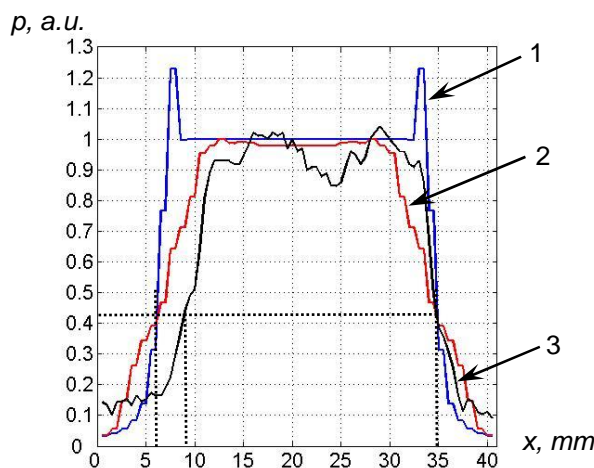

Fig. 9. **The spatial cross-sections of the pressure distributions at 0,013·N distance from the surface of the planar transducer: 1 – true field, 2 – simulated measured field, 3 – measured field**

p, a.u.

Fig. 10. **The spatial cross-sections of the pressure distributions at 0,03·N distance from the surface of the planar transducer: 1 – true field, 2 – simulated measured field, 3 – measured field**
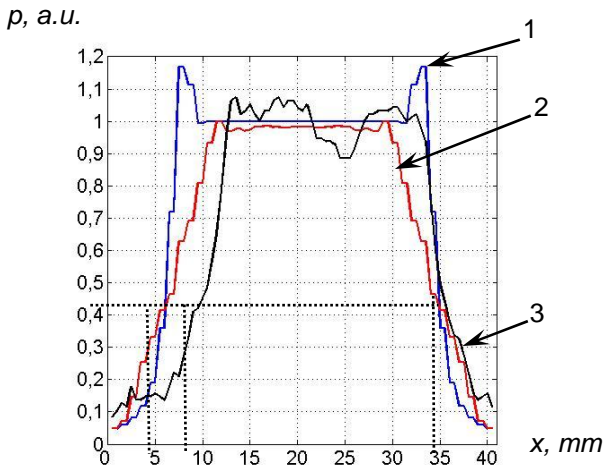
Δp, %

Fig. 11. **The relative errors between the pressure distributions of the true field and modelled field which corresponds to the field, measured by the focused transducer, at: 1 - 0,003·N distance from the surface of the planar transducer; 2 - 0,013·N distance from the surface of the planar transducer; 3 - 0,03·N distance from the surface of the planar transducer**
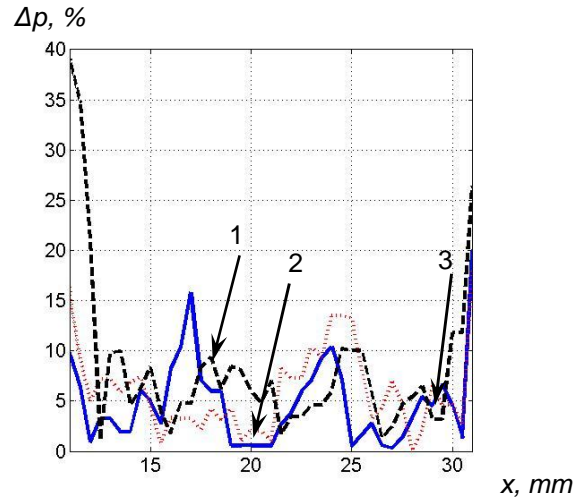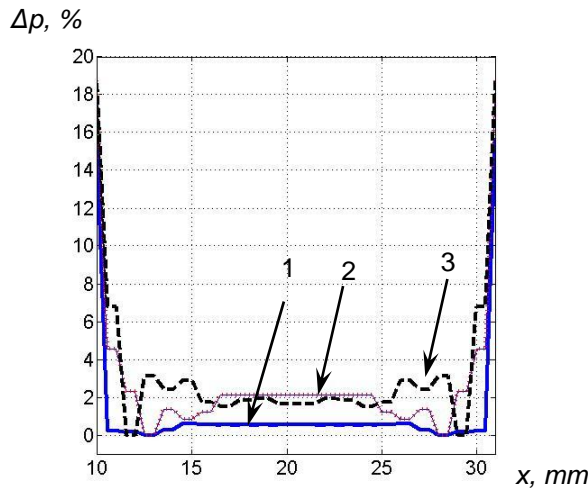
Δp, %

Fig. 12. **The relative errors between the pressure distributions of the modelled field which corresponds to the field, measured by the focused transducer and the experimentally measured field, at: 1 - 0,003·N distance from the surface of the planar transducer; 2 - 0,013·N distance from the surface of the planar transducer; 3 - 0,03·N distance from the surface of the planar transducer**

Table 1. **Obtained diameter D_p of the field pressure distribution**

L, mm	0,003·N	0,013·N	0,03·N
$D_{p1}\|_{p=0.42\,a.u.}$, mm	29	29	29
$D_{p2}\|_{p=0.42\,a.u.}$, mm	29	29	29
$D_{p3}\|_{p=0.42\,a.u}$, mm	26	26	25
$\Delta D_p = D_{p1,2} - D_{p3}$, mm	3	3	4
ΔD_p (%)=$(\Delta D_p/D_{p1,2})\cdot100\%$	10.4	10.4	13.8

the planar transducer. The normalized spatial cross-sections of the calculated and measured distributions of the ultrasonic pressure were compared. The measurement error, obtaining the diameter of the radiating planar transducer was calculated. The results show, that the method for remote ultrasonic field measurements using a focused transducer is acceptable in many practical applications for measurements of the spatial dimensions of the ultrasonic wave sources.

The spatial diameter of the modelled and measured ultrasonic pressure distribution also can be used as an approximate estimation of the modelled and measured ultrasonic field pressure distributions. For estimation of the diameter of the pressure distribution D_p the relative p level was chosen 0.42, the value, where both theoretically calculated distributions concur, e.g. 29 mm.

The measured distribution was compared with theoretically calculated distributions at the same p level. The results are presented in Table 1. The error ΔD_p (%) of the determination of the field pressure distribution diameter D_p also is presented in Table 1.

Conclusions

The true field of the planar transducer was calculated and the measurement of it using focused transducer was simulated in three different distances from the surface of

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Nuotoliniai ultragarsinio slėgio pasiskirstymo matavimai fokusuotuoju keitikliu

Reziumė

Norint nustatyti matuojamo ultragarsinio defekto matmenis, galima matuoti ultragarsinio lauko, išspinduliuoto ar atspindėto nuo tiriamojo objekto, slėgio pasiskirstymą, kuris defektų zonose skirsis nuo aplinkinių zonų. Tam galima naudoti mažų matmenų ultragarsinius keitiklius – hidrofonus. Tačiau dėl buvimo matavimo vietoje tokie keitikliai iškraipo matuojamąjį lauką. Lauko iškraipymams išvengti siūloma ultragarsinių laukų slėgio pasiskirstymą matuoti fokusuotuoju ultragarsiniu keitikliu. Daroma prielaida, kad toks keitiklis priima jo fokuso taške esantį ultragarsinį lauką. Taip galima matuoti ultragarsinių laukų slėgio pasiskirstymus erdvėje norimu atstumu nuo lauko spinduliavimo šaltinio, be to, išvengiama keitiklio įtakos ultragarsiniam laukui matavimo taške, nes keitiklis nuo jo yra nutolęs fokuso atstumu. Kadangi nėra kokių nors etaloninių ar kitokių atraminių ultragarsinių laukų pasiskirstymų, su kuriais būtų galima lyginti kitus laukus, buvo sumodeliuotas ultragarsinio lauko slėgio pasiskirstymas matavimo vietoje esant idealioms sąlygoms ir priimtas kaip atraminis, taip pat sumodeliuotas fokusuotu keitikliu priimto lauko slėgio pasiskirstymas. Modeliavimo rezultatai patikrinti eksperimentiškai. Tiek modeliavimas, tiek matavimai buvo atlikti esant trims skirtingiems atstumams tarp ultragarsinio lauko šaltinio – plokščiojo keitiklio ir fokusuotojo priimančiojo keitiklio. Iš gautų rezultatų nustatytas spinduliuojančiojo keitiklio skersmuo. Panašiai galima nustatyti ir defektų erdvinius matmenis.