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# Application of the focused ultrasonic transducer for remote measurements of ultrasonic fields

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## Introduction

Measurement of ultrasonic fields is an essential part of ultrasonic inspections in various scientific and industrial applications. The measured ultrasonic fields provide information about the properties of their sources, e.g., inner structure, defects, delaminations etc. A number of various ultrasonic systems were realized to make the test objects as the sources of the ultrasonic waves [1]. Such systems can be grouped by operation principle into narrow ultrasonic beam systems and wide ultrasonic beam systems. In the narrow beam systems the properties of the test object are obtained at one point of the object, so electronic or mechanical scanning is necessary for measurement of the ultrasonic field at all required points of the test object [1-3]. Using wide beam systems the test object is irradiated by a wide ultrasonic beam and then the reflected or backscattered ultrasonic field, which carries the information about the properties of the test object, is measured [1]. When the measurements of the whole field in a real-time mode are required, the techniques, which enable measure ultrasonic field at many points simultaneously, are used [1, 4-6].

When there is no need to measure the whole ultrasonic field at the selected spatial zone, the measurement of the field point-by-point can be done using hydrophones, e.g. ultrasonic transducers of a small diameter (Fig. 1). 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 need to place these transducers at the exact points of the field, that distorts the field, and also the limited spatial resolution, which is defined by the size of the transducer. The high costs for the producing of transducers, diameter of which is equal 1-2mm, and the limited bandwidth also make the use of such transducers unacceptable.

For this purpose it is possible to use focused ultrasonic transducers. Such transducers are used in ultrasonic microscopy and subsurface measurements [7-9]. The focused transducer is placed that the focus of the transducer appears at the desirable depth of the object. The pulse is transmitted into that depth and then the reflected signal is observed in the echo mode.

In this paper we analyze the possibility to use the focused transducers for remote measurements of the radiated or backscattered ultrasonic fields (Fig.2, 3). This gives possibility to obtain ultrasonic signals without placing the transducer at the exact point of the ultrasonic field, like in the case of the hydrophones. The bandwidth and spatial resolution or the size of the focal point can be chosen by selecting the transducer with desirable parameters like the diameter, the focal distance and the operation frequency.

One of the problems is the estimation of the accuracy or what is the difference between the true ultrasonic field and the ultrasonic field measured remotely using focused transducers. There are no transducers available, which would radiate the standard ultrasonic field, so there is no possibility to compare the measured ultrasonic field with a true field. For this purpose the theoretical modelling is proposed which enables the calculations of the equivalent of the real field. The calculated field is tagged as a true field. This field is compared with the field measurement results, obtained using the remote focused ultrasonic receiver. The comparison is made in order to estimate the accuracy of the measurements of the ultrasonic fields using focused ultrasonic transducers. Different criterions are proposed for the estimation of the true and measured ultrasonic fields.

## The principle of remote measurement of the ultrasonic field using focused transducer

As it was mentioned above the measurements of the ultrasonic fields using hydrophones are not acceptable.

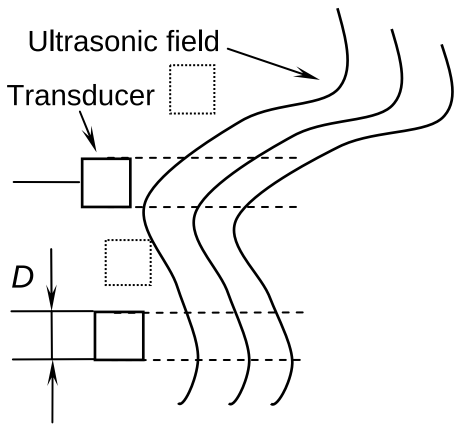


Fig.1. **The scanning of the ultrasonic field with hydrophone. *D* is the diameter of the transducer**

The zone of the ultrasonic field which hits the transducer's surface is integrated by the hydrophone, so the resolution is limited by the lateral dimensions of the hydrophone. Another disadvantage is the distortion of the ultrasonic field due to reflection of the incident wave, caused by the need to place the transducer at the exact point of the field under investigation.

The proposed method for measurements of the ultrasonic fields is based on the use of the focused ultrasonic transducer, which operates as a receiver. The transducer would register the integral value of the pressure of the ultrasonic field, which is in the focal point of the transducer.

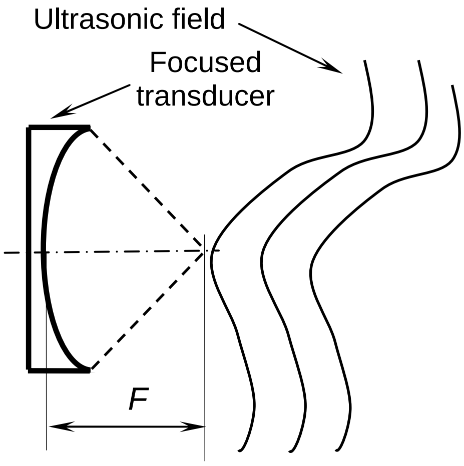


Fig.2. **The ultrasonic field measurement principle with a focused transducer. *F* is the focal distance of the transducer**

It is supposed that the focused transducer registers exactly the ultrasonic field which is at the focus point of the receiver. That should enable realize the remote measurement of the ultrasonic field radiated or backscattered by the object under investigation. The focused receiving transducer is always out of the field which is under investigation. The size of the transducer's focal point, which also defines the resolution of remote imaging, depends on the construction of the transducer. A relationship between the focal spot diameter of an ultrasonic beam at 50% drop in sound pressure (- 6dB point) and the transducer parameters are given by:

$$\phi = 2.44 \cdot \lambda \cdot \frac{F_{TR}}{D_{TR}}, \qquad (1)$$

where $\phi$ is the size of the focus point of the transducer, $\lambda$ is the ultrasonic wavelength, $F_{TR}$ is the transducer focal length, $D_{TR}$ is the transducer element diameter [10]. Ultrasonic wavelength $\lambda$ can be expressed in terms of transducer frequency and ultrasonic velocity in water $c_w$ according to

$$\lambda = \frac{c_w}{f}. \qquad (2)$$

Noting that $c_w$=1.48mm/μs at 20ºC and substituting Eq. 1 into Eq. 2 gives that the 5 MHz center frequency focused transducer with a focal length of 50.8 mm and 29 mm element diameter results a focal spot diameter of approximately 1.27 mm, so the ordinary focused transducer with a suitable parameters can be used instead of the hydrophone.

The proposed method for remote measurement of ultrasonic fields gives the possibility to measure the ultrasonic fields at various distances from the surface of the wave source.

## 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 plane transducer. The field, radiated from the surface of the plane transducer instead of the ultrasonic field, backscattered by any test object, was taken as the simplest case of the problem. This field will be postulated as a true field and the measured field will be compared to that true field. The measurement of the field using focused transducer is also simulated, e.g. the field, which is received by focused transducer, was 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 the unfocused 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 impulse response of the unfocused transducer.

$$u_{PT}(x,y,z,t) = h_{PT}(z,R,t) \otimes u_{EXC}(t), \qquad (3)$$

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 time coordinate. The excitation signal $u_{EXC}$ was simulated using the following expression:

$$u_{EXC}(t) = \exp\left(\left(-\frac{2f\sqrt{-\log 0.1}}{p}\left(t-\frac{2p}{3f}\right)\right)\cdot \left(\frac{2f\sqrt{-\log 0.1}}{p}\left(t-\frac{2p}{3f}\right)\right)\right)\cdot\sin(2\pi f t), \qquad (4)$$

where $f$ is the frequency, $p$ is the number of periods, $t$ is time [11].

The impulse response of the unfocused transducer is given by [12-14]:

$$h_{PT}(z,R,t) = \begin{cases} 0, t < t_0 \\ c, t_0 \le t \le t_1 \\ \frac{c}{\pi}\cos^{-1}\frac{R^2 + c^2t^2 - z^2 - a^2}{2R\left(c^2t^2 - z^2\right)^{1/2}}, t_1 < t \le t_2 \\ 0, t < t_2 \end{cases} \qquad (5)$$

where

$$t_0 = \frac{z}{c}, \qquad (6)$$

$$t_1 = \frac{\sqrt{z^2 + (a-R)^2}}{c}, \qquad (7)$$

$$t_2 = \frac{\sqrt{z^2 + (a+R)^2}}{c}, \qquad (8)$$

$t_0$ is the minimal possible signal travel time from the surface of the plane transducer to the exact calculation point (6), $t_1$ is the signal travel time from the near point of the transducer's edge (7), $t_2$ is the signal propagation time from the far point of the transducer's edge (8), $z$ is the distance between the calculation point and the surface of the transducer, $c$ is ultrasound velocity of the longitudinal wave, $R$ is the radius of the transducer.

The impulse response at the selected of the focused receiving transducer, which is used to measure the ultrasonic field, is calculated in the following way [12-14]:

$$h_{FT}(z,R,t)=\frac{c}{2\pi}\left(\frac{F}{d}\right)\Omega(ct), \tag{9}$$

where

$$d(z,R)=\sqrt{R^2+(F-z)^2}, \tag{10}$$

$$\Omega(ct)=\begin{cases}0, t<t_0\\ 2\pi, t_0<t<t_1, t_2<t<t_0\\ 2\cos^{-1}\dfrac{\eta(t)}{\sigma(t)}, t_1<t<t_2\\ 0, t_2<t_1, t<t_1\end{cases}, \tag{11}$$

$$\eta(t)=F\left\{\frac{1-e/F}{\sin\Theta}+\frac{1}{\tan\Theta}\frac{F^2+d^2-c^2t^2}{2dF}\right\}, \tag{12}$$

$$\sigma(t)=F\left\{1-\left(\frac{F^2+d^2-c^2t^2}{2dF}\right)^2\right\}^{1/2}, \tag{13}$$

$$\Theta=\pi-a/\sqrt{R^2+(F-z)^2}, \tag{14}$$

where $t_0$ in different regions is given by:

$$t_0=(F-d)/c, \tag{15}$$

$$t_0=(F+d)/c, \tag{16}$$

and $t_1$, $t_2$ represents the propagation times from the calculation point to the closest and furthest edges of the transducer:

$$t_1=\left((a-R)^2+(z-e)^2\right)^{1/2}/c, \tag{17}$$

$$t_2=\left((a+R)^2+(z-e)^2\right)^{1/2}/c, \tag{18}$$

where

$$e=F-\sqrt{F^2-a^2}. \tag{19}$$

$F$ is the focal distance of the focused transducer, $a$ is the diameter of transducer.

The one meaning of the impulse response is required to be calculated because the true field is "observed" by the same point of the focused receiving transducer. Theoretically it would be the focal point of the transducer, but in this case the impulse response is equal to zero. So, due to that in reality there is no focal point of the focused transducer, but the focal zone, which is not a singular point, the impulse response of the focused transducer was calculated at the point, 0.01mm further than the theoretically predicted focal point of the transducer.

It is supposed that convolving the impulse response of the focal point of the focused transducer and the ultrasonic signal obtained by simulation of the true ultrasonic field, we obtain the ultrasonic field, which measured by the focused transducer:

$$u_{FS}(x,y,z,t)=h_{FT}(x,y,z,t)\otimes u_{PT}(x,y,z,t). \tag{20}$$

The $u_{FS}$ is the field, measured by the focused transducer, $h_{FT}$ is the impulse response at a focal point of the focused transducer, $u_{PT}$ is the signal of the true field which is radiated by the unfocused transducer.

The focsl point of the focused ultrasonic transducer is not singular. The receiving focused transducer is under the influence not only of the field which is in focus point, but also of the field, distributed in the surrounding space. This adds more problems due to required numerous calculations in order to estimate the important influences to the ultrasonic field measurements with the focused transducer. These influences were not estimated in the presented modelling. The future works are provided for this.

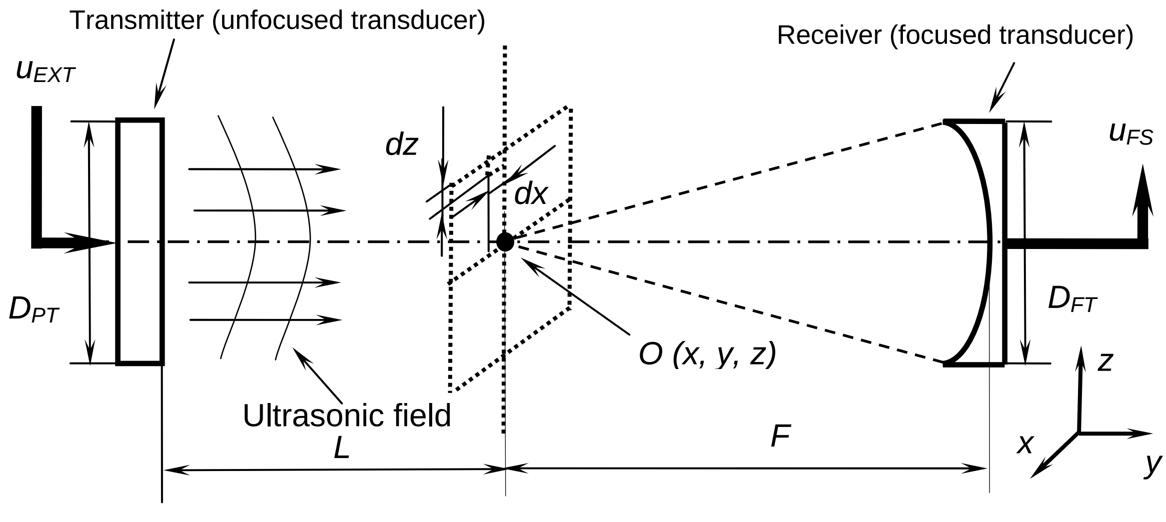


Fig.3. **The detailed principle for remote measurements of ultrasonic field using the focused transducer**

## Criteria of the field estimation

It was mentioned, that there are no standard fields and methodology to estimate the differences between the true ultrasonic field and the measured field. The calculated ultrasonic field can be considered as the true field in the chosen spatial layer. The criteria for estimation of the differences between the true fields and the measured fields are necessary. For this purpose the following estimation criteria are suggested.

It can be considered, that the ultrasonic field pressure $p$ is the 4$^{th}$ dimensional function, which varies in space and time domains:

$$p = p(x, y, z, t), \quad (21)$$

where $x$, $y$, $z$ are the spatial coordinates, $t$ is time. The representation of such a function is problematic due to its 4$^{th}$ dimensionality, so it can be simplified by choosing the $p$ value at one fixed spatial coordinate ($x$, $y$ or $z$) at the fixed time $t$ instant

$$\hat{p} = \hat{p}(x, y), \quad (22)$$

Let us assume that $p$ is the true simulated field, $\hat{p}$ is the measured field at the fixed cut of the space and the time. The first criterion $L_1$ or the difference between true and measured fields at the fixed time instant $t$ and one fixed spatial coordinate, for example $z$, is the difference between Eq.21 and Eq.22:

$$L_1(x, y) = \Delta p = |p - \hat{p}|. \quad (23)$$

The second criterion is given by:

$$L_2(x, y) = \sqrt{\left|p^2 - \hat{p}\right|^2}. \quad (24)$$

The relative error is:

$$\delta(x, y) = \frac{\Delta p}{p}. \quad (25)$$

The presented criterions can be applied both in Decart's or cylindrical coordinate systems; also the required parameter for the estimation can be chosen, e. g. the amplitude or the phase of the signal. The cylindrical coordinate system is suitable when the longitudinal cut of the radiated field is observed. The estimation of the field in this article is done in transversal direction cut (plane $P$ in Fig. 3), so the Decart's coordinate system is chosen.

## Modelling results

The true field of the selected transmitter way calculated at three different distances from the surface of the unfocused transducer in order to obtain how the field changes while it propagates away from the surface of the transducer. Also the impulse response of the focused receiving transducer and the measured field by the focused receiving transducer were calculated at the same distances in order to get the distributions of the ultrasonic field pressure and to compare them in order to estimate of the differences between the true field, the simulated measured field and the experimentally measured field.

The modelling was performed using MATLAB 6.5. The setups were following: the time step $dt$ is 0.01μs; the first distance $L$ from the unfocused transducer's surface is 0.2mm; ultrasound velocity $c$ in water is 1.48 km/s; the diameter of the unfocused transducer's surface $D_{PT}$ is 29 mm; the frequency $f$ is 5 MHz; the focal length of the focused transducer $F$ is 50.8 mm.

The images of the true field pressure $u_{PT}$ at different distances formed by the unfocused transducer are presented in Fig. 4-6. The presented images show the changes of the simulated field pressure at the different distances from the surface of the unfocused transducer. The front wave is clearly seen (Fig. 4), while the distance from the surface of the transducer is small. The edge waves are increasing at further distances from the transducer's surface.

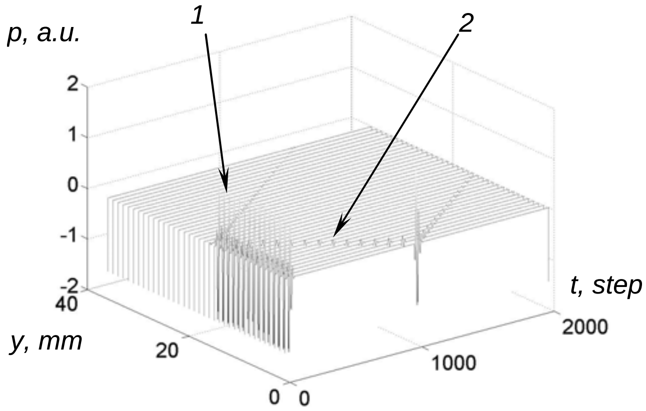


Fig. 4. **The image of the simulated true field radiated by the unfocused transducer at a distance 0.2 mm from the surface of the transducer. 1 is the front wave, 2 is the edge wave**

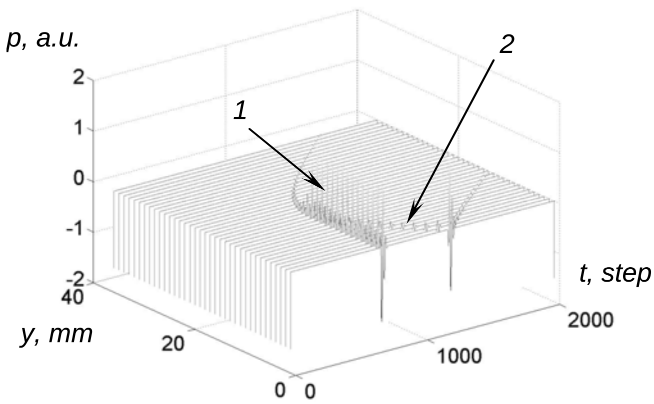


Fig. 5. **The image of the simulated true field radiated by the unfocused transducer at a distance 10 mm from the surface of the transducer. 1 is the front wave, 2 is the edge wave**

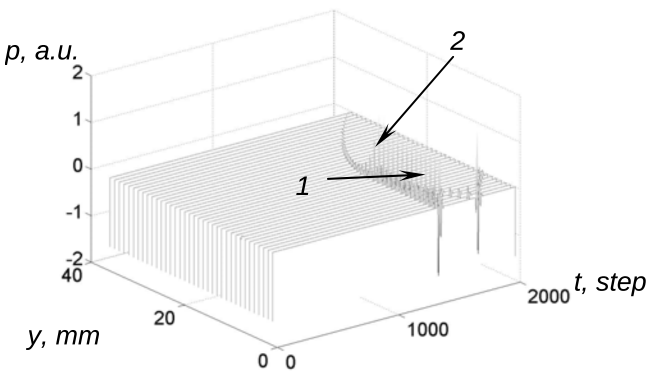


Fig. 6. **The image of the simulated true field radiated by the unfocused transducer at a distance 20 mm from the surface of the transducer. 1 is the front wave, 2 is the edge wave**

The distribution of the normalized pressure of the simulated true field at the different distances from the surface of the transducer is presented in Fig. 7-9. The edge waves are increasing at further distances, so the sharpness of the edges of the pressure distributions is going down (Fig. 10). It follows that the sharpness of the true field is going down while receding from the wave source so the estimation of the test object properties from the measured ultrasonic field is more complex.

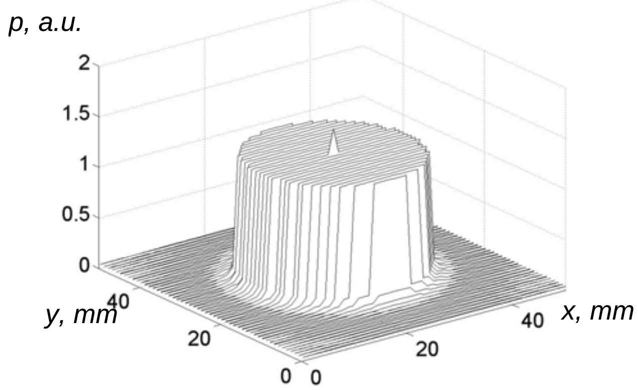


Fig. 7. **The image of the normalized pressure distribution of the true field radiated by the unfocused transducer at a distance 0.2 mm from the surface of the transducer**

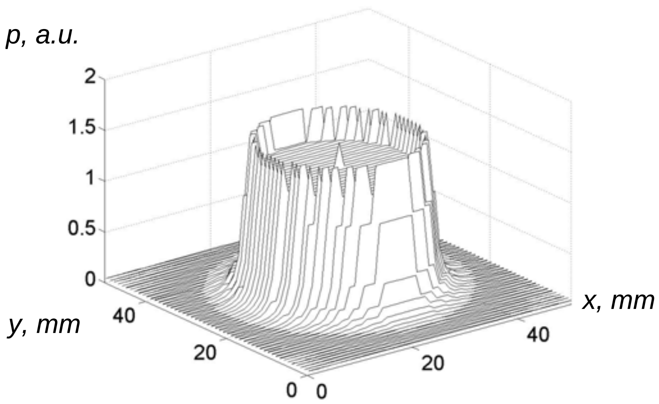


Fig. 8. **The image of the normalized pressure distribution of the true field radiated by the unfocused transducer at a distance 10 mm from the surface of the transducer**

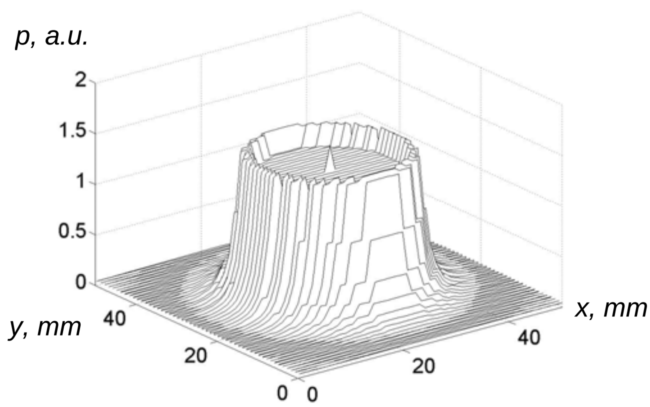


Fig. 9. **The image of the normalized pressure distribution of the true field radiated by the unfocused transducer at a distance 20 mm from the surface of the transducer**

The spatial cuts via *x* coordinate 25mm of the pressure distributions (Fig. 7-9) are presented in Fig. 10.

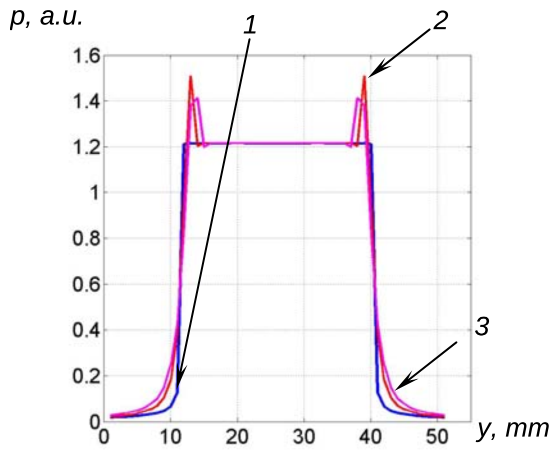


Fig. 10. **The spatial cuts of the pressure distributions at *x*=25mm of the true field radiated by the unfocused transducer at 0.2 (1st curve), 10 (2nd curve) and 20 (3rd curve) mm distances from the surface of the transducer**

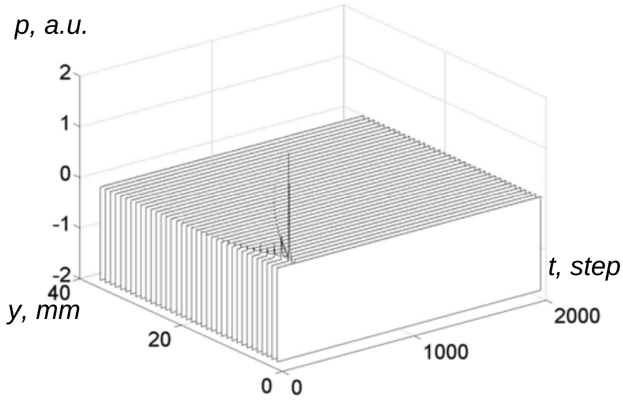


Fig. 11. **The impulse response in the time domain of the focused transducer at a point, 0.01 mm further from the surface of the transducer than the focal point (50.81mm).**

The impulse response of the focused receiving transducer is presented in Fig. 10-11.

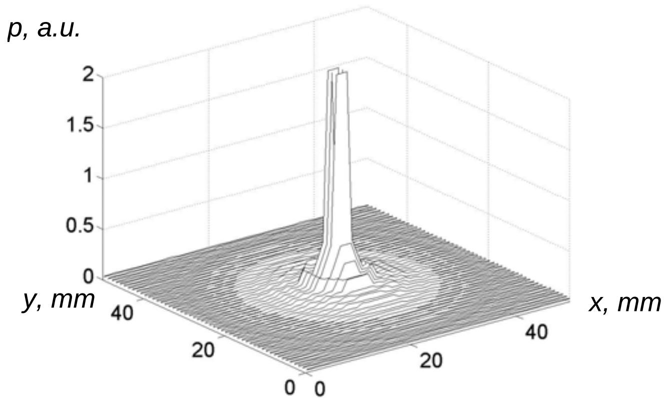


Fig. 12. **The calculated response of the focused transducer to the uniformly radiating surface 50×50 mm, placed. The waveform of the radiated pressure is given by Eq.4 at the 50.81mm distance from the surface of the transducer**

The theoretically measured e.g. calculated field, received at 0.2 mm distance using the focused ultrasonic transducer is presented in Fig. 13-14. The setups were following as mentioned at the beginning of the article.

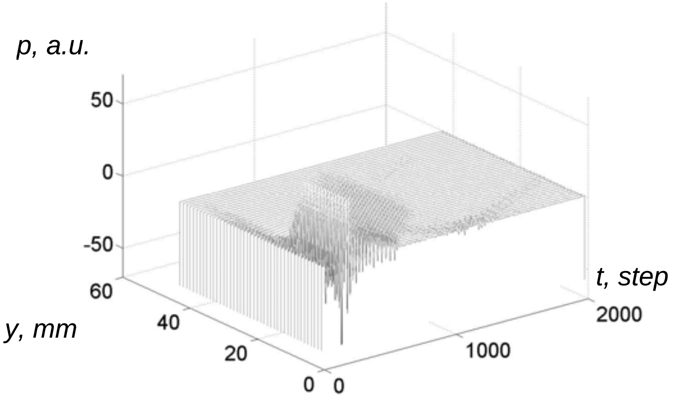


Fig. 13. **The image of the simulate measured field obtained by the focused receiving transducer at the distance 0.2 mm from the surface of the unfocused transducer**

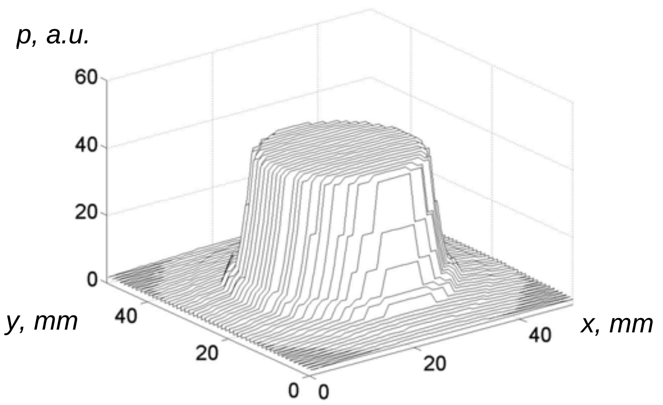


Fig. 14**. The image of the pressure distribution of the simulate measured field obtained by the focused receiving transducer at a distance 0.2 mm from the surface of the unfocused transducer**.

The spatial cuts via *x* coordinate 25mm of the pressure distributions (Fig. 7 and 10) are presented in Fig. 15.

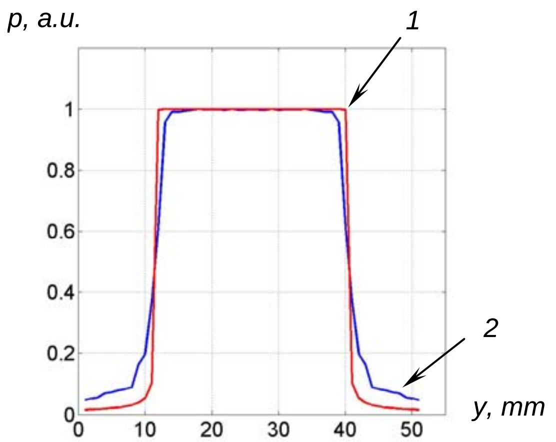


Fig. 15. **The spatial cuts of the pressure distributions at *x*=25mm of the true field (1st curve) and the measured field (2nd curve) at the 0.2 mm distance from the surface of the transducer**

The curves in Fig. 15 are normalized dividing each value by the maximum value of the pressure distribution. A good correspondence between true and theoretically measured fields is observed. The measurement error, obtained by the simulation does not exceed 7% in the zone ±7 mm from the axis of the transmitting transducer at the distance 0.2 mm from the radiating surface.

## The results of the measurements of measurements of the ultrasonic

The following experiment was performed in order to verify the proposed measurement method. The ultrasonic field of the transmitting plane transducer was measured using the focused receiving transducer. The measurements were realized using the measurement system, presented in Fig 16.

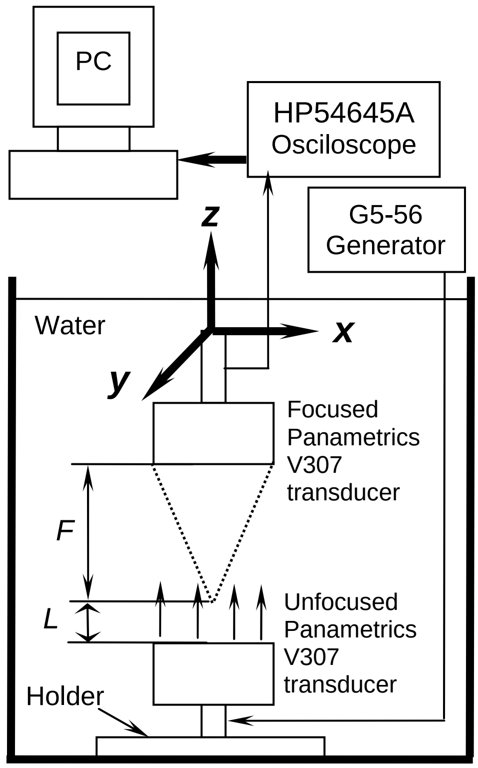


Fig. 16. **The experimental set-up for the ultrasonic field measurements of the plane transducer (*F* – focus length of the focused transducer)**

The 3D positioning system was used to place the focused transducer in various positions to measure the signal over the surface of the plane transducer. The unfocused radiating transducer was in a fixed position. The focused receiving transducer was moved in the x-y plane by 1 mm step, covering 50x50 mm area. The distance (*F*+*L*) was equal to 51 mm. The pulse generator G5-56 generated the excitation square pulse of 5 MHz frequency and 10.9 V amplitude. The radiated by the plane transducer ultrasonic signal is presented in Fig. 17.

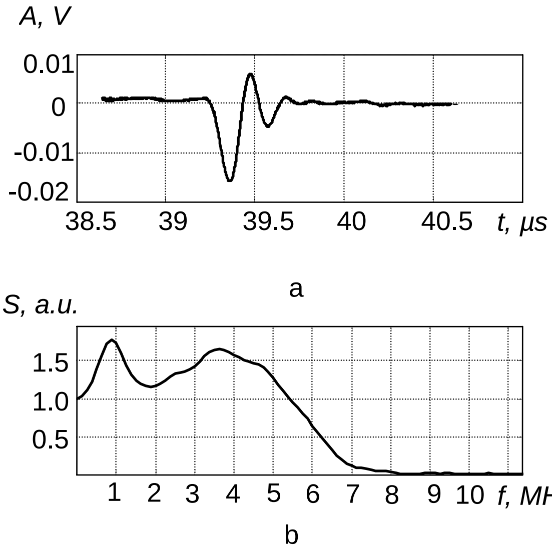


Fig. 17. **The ultrasonic pulse (a), radiated by the unfocused Panametrics V307 transducer and its spectrum (b)**

The distribution of the experimentally measured ultrasonic field pressure is presented in Fig. 18.

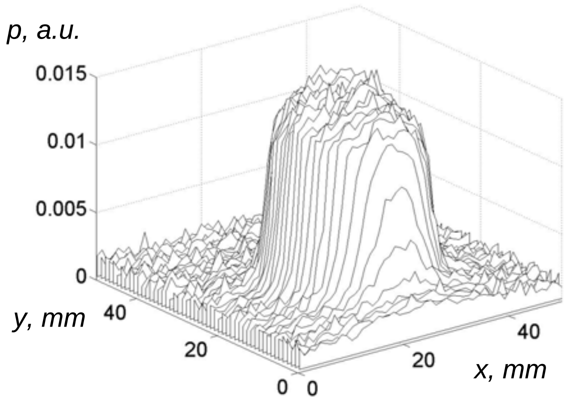


Fig. 18**. The image of the experimentally measured ultrasonic field pressure distribution. The distance between radiating unfocused transducer and focused receiving transducer is 51mm**

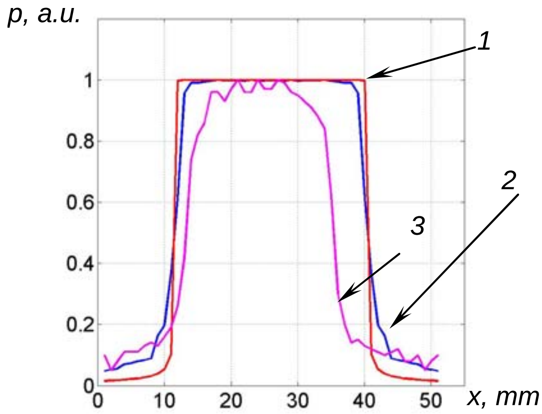


Fig. 19. **The spatial cuts of the pressure distributions at *x*=25mm of the true field (1st curve), theoretically measured field (2nd curve) and experimentally measured field (3rd curve) at the 0.2 mm distance from the surface of the radiating unfocused transducer**

The curves in Fig. 19 are normalized dividing each value by the maximum value of the pressure distribution. The correspondence between true, simulated and experimentally measured fields is worse than between the true and the simulated field, but acceptable.

## Conclusions

The method for remote measurements of the ultrasonic fields was proposed. The true field was calculated and the measurement of it using focused transducer was simulated. The normalized distributions of the true and theoretically measured fields match well. Also the experimental measurements were provided and the obtained field distribution also was compared with the true and simulated fields. The matching is worse, but the sharpness of the filed images is acceptable in all cases. The obtained theoretical and experimental results show suitability of the proposed method for remote ultrasonic field measurements in practical applications.

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**Nuotolinis ultragarsinių laukų matavimas naudojant fokusuotą ultragarsinį keitiklį**

Reziumė

Ultragarsiniuose popaviršinių defektų matavimuose yra aktualu išmatuoti tiriamojo objekto vadinamąjį išbarstytą erdvėje („backscattered“) ultragarsinį lauką. Tą galima padaryti naudojant hidrofonus – mažų gabaritų ultragarsinius keitiklius. Dėl buvimo matavimo taške keitikliai iškraipo matuojamąjį lauką, skiriamoji geba yra apribota keitiklio matmenimis, taip pat ribota tokių keitiklių darbo dažnių juosta ir didelė jų kaina. Išvardytiems trūkumams eliminuoti pasiūlytas būdas - ultragarsinius laukus matuoti naudojant fokusuotą ultragarsinį keitiklį. Daroma prielaida, jog fokusuotas ultragarsinis keitiklis priima jo fokuso taške esantį ultragarsinį lauką. Taip galima matuoti išbarstytus ultragarsinius laukus ne tik po tiriamojo objekto paviršiumi ar ant jo, bet ir norimu atstumu erdvėje nuo paviršiaus. Tokiu būdu išvengiama keitiklio įtakos ultragarsiniam laukui matavimo taške, nes keitiklis yra nuo jo nutolęs per fokuso atstumą.

Kadangi nėra žinoma, kiek tiksliai tokiu būdu galima išmatuoti ultragarsinį lauką, buvo sumodeliuotas tikrasis laukas matavimo taške, taip pat fokusuotu keitikliu priimtas laukas. Manoma, jog tikrasis laukas yra šaltinio sukurtas. Modeliuojant pasirinktas nefokusuoto keitiklio išspinduliuotas laukas. Toliau buvo skaičiuojama, kiek tikrasis laukas skiriasi nuo lauko, išmatuoto fokusuotu keitikliu. Skirtumai yra gana maži, taigi pasiūlytasis metodas fokusuotu keitikliu matuoti ultragarsinius laukus tinkamas praktiniams tikslams. Eksperimentiniai ultragarsinio lauko matavimai fokusuotu keitikliu skirtingais atstumais nuo nefokusuoto keitiklio paviršiaus taip pat patvirtina šio metodo tinkamumą.

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