ISSN 1392-2114 ULTRAGARSAS (ULTRASOUND), Vol.64, No.1, 2006.

Air – coupled ultrasonic transducers with collimators

A. Vladišauskas, R. Raišutis, E. Žukauskas

Prof. K. Baršauskas Ultrasound Institute,
Kaunas University of Technology, Studentų st. 50, Kaunas, LITHUANIA, E-mail: alfonsas.vladisauskas@ktu.lt.

Abstract

Air – coupled planar ultrasonic transducers with collimators can be effectively used for a wide range of distances when air-coupled focussed transducers are being exploited only at the fixed distance. On the other hand use of attached collimators on the planar transducers allows choosing a relatively wide range of spatial resolutions, what is very important for NDT applications. In this paper investigations of influence of collimators having different diameters of apertures on the width of an ultrasonic beam are presented. The investigations were carried out numerically and experimentally. Experimental investigations of dependence of the width of the ultrasonic beam on a diameter of the collimators were carried out. The experimental investigations were performed using a pair of planar 500 kHz air – coupled ultrasonic transducers.

Keywords: Air – coupled ultrasonic transducers, collimators, diffraction model.

Introduction

The air – coupled ultrasonic investigation methods are very attractive because they enable to avoid disadvantages caused by the liquid coupling materials such as water, oil and gel based materials [1]. However, the large impedance mismatch between the transducers surfaces and air produces an amplitude loss more than 150 dB in a through – transmission technique. In order to decrease the transmission losses many methods are used, such as the impedance matching of piezoelectric transducers [2, 3], piezocomposite transducers [4, 5], backing air – coupled ultrasonic transducers with a thin low impedance front layer [6]. Furthermore, to increase an amplitude of the transmitted ultrasonic signal a high voltage (500 – 1200 V) and a long tone burst excitation signals are used. Using resonant systems for transmitter and receiver can give a typical increase in a sensitivity of nearly 40 dB compared to conventional damped transducers. In order to get the necessary amplitude of the ultrasonic signal for non-destructive testing (NDT) and measurements the air – coupled transducers have large diameters of piezoelectric elements. For example, the air – coupled transducers suggested in [7] have the active diameter from 12,5 mm to 50 mm in the frequency range 0,12 – 0,5 MHz. The near field of this air – coupled ultrasonic transducer for 0,5 MHz frequency is from 57,4 mm to 919,1 mm. It means that a spatial resolution of the planar air – coupled transducers essentially depends on the active diameter of the piezoelement.

This paper presents a simple method to get the narrow ultrasonic beam in the near field or in the collimated zone using the attached shields with different diameter windows for re-radiation of the collimated ultrasonic beam.

Description of the collimators

There are a few papers presenting the construction of the acoustic collimators. There are different methods of collimating of the ultrasonic beam. One of them consists of application of ultrasonic transducers with conical and wedge shaped collimators [8]. Using the conical and wedge shape collimators the minimum beam width of the main lobe of the radiation pattern was obtained. It appears that a simple device-attachment provides radiation of a single narrow beam. The collimators of this type were developed for operation in liquid at the 2 MHz frequency [8].

Investigation of the collimating piezotransducers forming a narrow weakly diverging acoustic beam within the required axial range has been presented in [9]. The collimating piezotransducer consist of piezoelement and acoustic lens which has different logarithmic profiles. This lens forms a narrow weakly diverging acoustic beam throughout the required axial range. The central part of the lens focuses the ultrasonic waves close to the transducer, while the peripheral part of the lens focuses the ultrasonic waves far from transducer. As a result, the acoustic field created by such transducer has a stretched focal zone, where the beam is narrow and collimated. The collimating ultrasonic transducers are intended to operate in an immersion environment at the high frequencies (2–20) MHz. Their sensitivity is 2 – 10 times less than of the standard non focussed transducer [9].

Modern air – coupled transducers usually use a few acoustical impedance matching layers. Manufacturing of such matching layers with logarithmic lenses is rather complicated.

The air-coupled horn collimators were applied successfully in the non-destructive evaluation of the composite materials [10]. This paper has shown that smaller transducers diameters used sometimes in conjunction with apertures increase the contours of the structural detail viewed in a through – transmission imaging of scattering materials. The horn collimators enable to improve imaging of internal structural details and near – edge defects. However, if the horn aperture is large, the horn construction must be long enough in order to avoid the flares in gradual and intermediate reflections. The horn collimators are calculated and fabricated to operate with the constant horn aperture and a fixed acoustic field.

In the non-destructive evaluation and medical diagnostics it is necessary to get high lateral and axial resolutions throughout a large depth of the ultrasonic field. These requirements can be met if the piezoelectric transducer forms a narrow weakly diverging ultrasonic beam within a large axial range (collimated beam). One method to exploit effect of the beam divergence is based on the ultrasonic measurements in the near field of the transducer. For a planar transducer the near field can be calculated as a function of the diameter of the transducer D=2a, the frequency f and the sound velocity in the surrounding medium c:

$$z_a = \frac{a^2}{\lambda} = \frac{a^2 f}{c}, \tag{1}$$

where λ is the wavelength.

The acoustic field of the transducer is presented in Fig.1.

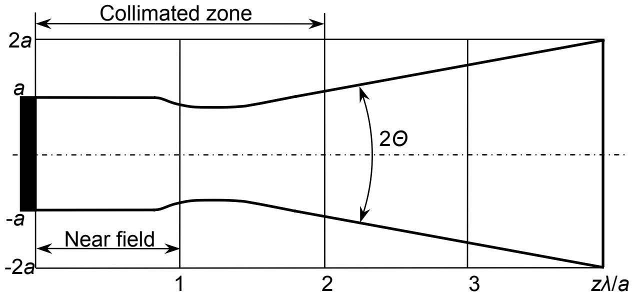


Fig.1. **Acoustic field of the planar ultrasonic transducer**

In practice, there is no beam divergence up to the distance which equals to z_c:

$$z_c = \frac{2a^2}{\lambda} = \frac{2a^2 f}{c}. \tag{2}$$

Due to the fact that the ultrasound velocity in air is very slow and the collimated beam of the air – coupled ultrasonic transducer is sufficiently long. The calculated dependence of the near field and the collimated zone of the air – coupled ultrasonic transducers as a function of the diameter of the active piezoelement for the 500 kHz frequency is presented in Fig.2.

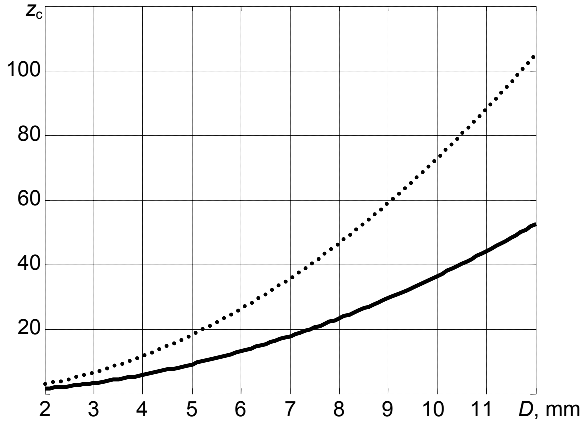


Fig.2. **Dependencies of the near field and collimated zone versus the diameter of planar air-coupled transducer. The solid line denotes the near field, the dotted line denotes the collimated zone**

The collimated zone of the acoustic beam considerably depends on the diameter of a collimator window. Therefore, for the air – coupled ultrasonics NDT applications when the distance between the ultrasonic transducer and the object under investigation can be from 25 mm up to 105 mm, the collimators with the diameter of the aperture (6 – 12) mm can be used. Certainly the amplitude of the signals at the 105 mm distance will be a few time less. However, the modern air – coupled transducers can give the transduction losses 40 – 50 dB. The air-coupled ultrasonic transducer with a collimator having the aperture 2 – 4 mm can be used as a point-type receiver for measurements of acoustic field distribution.

The construction of the air – coupled ultrasonic transducer with a collimator is shown in Fig.3.

The transducer consists of the piezoelement 1, acoustic impedance matching layers 2 and 3 and the damping material 7. All these components are placed in the housing of the transducer 4. Both surfaces of the piezoelement are connected to the connector 5 with wires 4. The collimator 8 with the aperture having the diameter D is placed in front of the radiating surface of the ultrasonic transducer.

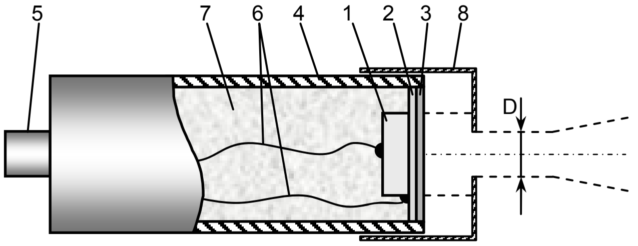


Fig.3. **Construction of the air – coupled ultrasonic transducer with a collimator: 1 – piezoelement; 2, 3 – matching layers; 4 – housing, 5 – connector; 6 – connecting wires; 7 – damping; 8 – collimator.**

The shapes of the collimator apertures can be various – round, rectangle, ellipse, long narrow window and so on. The internal diameter of the collimator attachment is equal to the outer diameter of ultrasonic transducer housing. The collimator was made from 0,3 mm thickness metal plate.

A part of the excited acoustic field of the ultrasonic transducer forms in the matching layers and in the gap between the radiating surface of ultrasonic transducer and the collimator.

Numerical investigation

The excited acoustic field calculation of the circular-shape ultrasonic transducer was calculated using the diffraction approach described in [11].

An acoustic pressure at an arbitrary spatial point x, y away from the surface of the ultrasonic transducer combined with a collimator is found from the convolution of the driving pulse $u(t)$ and the spatial impulse response $h(t)$ of the circular shape ultrasonic transducer. The excitation frequency of the ultrasonic transducer was 500 kHz. The ultrasonic transducer was excited by 2 periods radio burst having the Gaussian shape. The sampling frequency has been assumed to be 10 MHz. During simulation it was assumed that the ultrasound velocity in air is 345.1 m/s at room temperature 22°C and humidity 35 %.

The excited ultrasonic fields of the ultrasonic transducer combined with collimators having different aperture diameters in a pulse mode were calculated for 4 mm, 8 mm, 10mm and 13 mm apertures. The normalized cross-sections of the ultrasonic fields (-3dB) at the distance 20 mm away from the collimator surface in the cases of different diameters of the collimator apertures are presented in Fig.4.

The normalized cross-sections of the ultrasonic fields along the axis of the air-coupled transducer combined with the collimators having different diameters of apertures are presented in Fig.5.

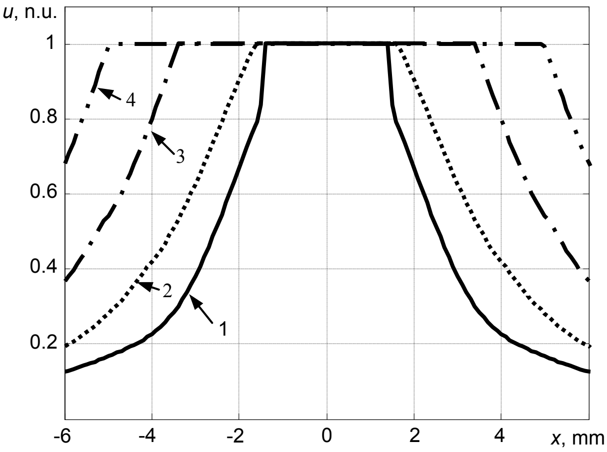


Fig.4. **Normalized cross-sections of the ultrasonic fields (-3dB) at the distance 20 mm away from collimator surface in the cases of different diameters of collimator apertures: 1- 4 mm, 2-8 mm, 3- 10mm, 4- 13 mm**

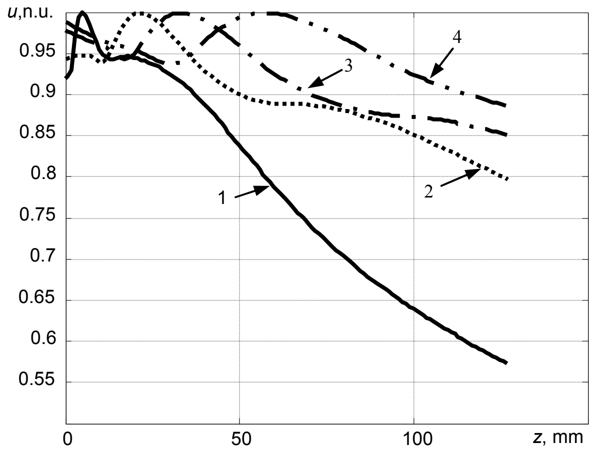


Fig.5. **Normalized cross-sections of the ultrasonic fields along axis of the air-coupled transducer combined with collimators having the different diameters of apertures: 1- 4 mm, 2-8 mm, 3- 10mm, 4- 13 mm**

Experimental investigation

Experimental set-up for investigation of air – coupled ultrasonic transducers with collimators is presented in Fig. 6.

For experimental investigations a pair of air – coupled ultrasonic transducers designed and manufactured in Ultrasound Institute of Kaunas University of Technology was used. The active diameter of the transducers was 12 mm. The ultrasonic transmitter was driven by one period 150 V amplitude pulse. In order to investigate width of the ultrasonic field, the receiver was mounted at a fixed position and the transmitter was moved along the lateral axis with the 0,5 mm scanning step. For experimental investigations the collimators with aperture diameters equal to 10, 8, 6, 4 and 2 mm were used. The distance between ultrasonic transducers was 20 mm. The collimators were mechanically attached to the active surfaces of both ultrasonic transducers: to the receiver and to the transmitter. Thickness of the air gap between the active surface of the ultrasonic transducer and the metal plate of the collimator was equal to 1 mm. During measurements the room temperature was 22°C and the humidity was 35 %.

The experimentally obtained B – scan images without collimators and with collimators having 4 mm diameter of apertures are presented in Fig.7.

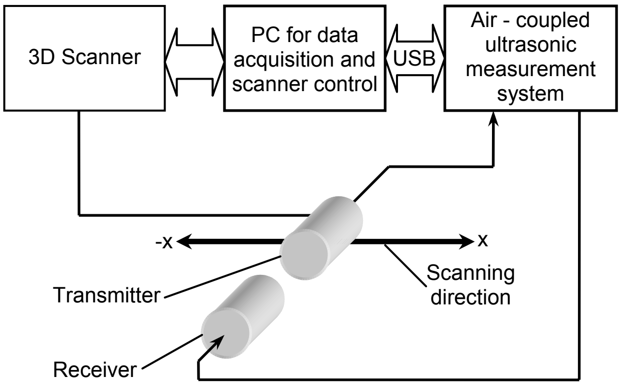
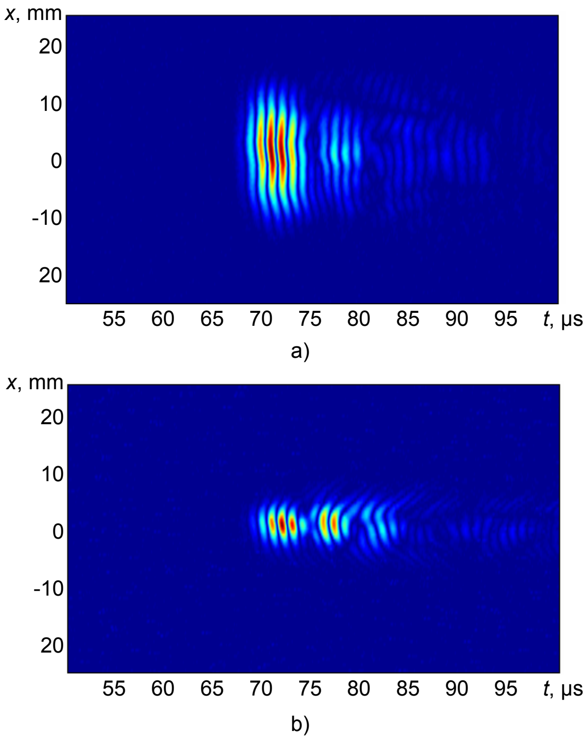


Fig.6. **Experimental set-up**



a)

b)

Fig.7. **Experimentally obtained B – scan images without collimators (a) and with collimators having 4 mm aperture diameter (b)**

The presented B – scan images clearly show that use of collimators allow to narrow the width of the ultrasonic beam without significant distortions of the excited ultrasonic field. Such effect allows increase of the spatial resolution of ultrasonic measurement in NDT applications.

The results of investigations of the influence of the collimators diameter to the width of the ultrasonic beam are presented in Fig.8. The peak – to – peak amplitude of the experimentally obtained signals is presented as a function of the transmitter displacement along the lateral axis (*x* coordinate) according to a fixed position of the receiver.

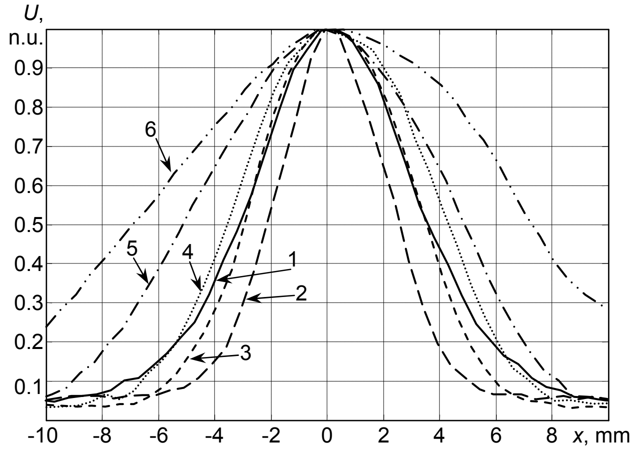


Fig.8. **Normalized peak-to-peak amplitude of the ultrasonic fields in the cases of different diameter collimator apertures: 1 – 2 mm; 2 – 4 mm; 3 – 6 mm; 4 – 8 mm; 5 – 10 mm; 6 – 12 mm (without collimator).**

The presented results show, that significant decrease of the width of ultrasonic beam obtained when the diameters of collimators changes from 12 mm (transducers without collimators, curve No.6) to 8 mm (curve No.4). Changes of the diameters of collimators from 8 mm to 4 mm allow decreasing the width of the ultrasonic beam, but these changes are not so significant (curves No.4, 3, 2). In the case when the collimators with 2 mm diameters were applied, the width of the beam increases. This can be explained by shortening of the near field zone and transition to the far field.

The beam width Δx measured at the -6 dB level as a function of the diameter of the collimator aperture is presented in Fig.9.

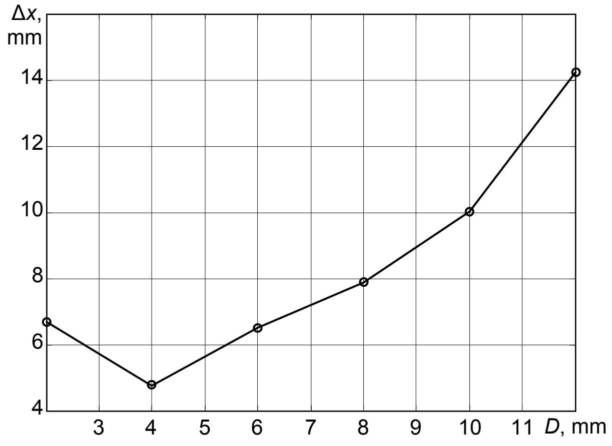


Fig.9. **Beam width as a function of diameter of collimator aperture**

Time diagrams of the signals obtained using air-coupled ultrasonic transducers without and with collimators which had diameters of apertures equal to 8 and 4 mm are presented in Fig.10.

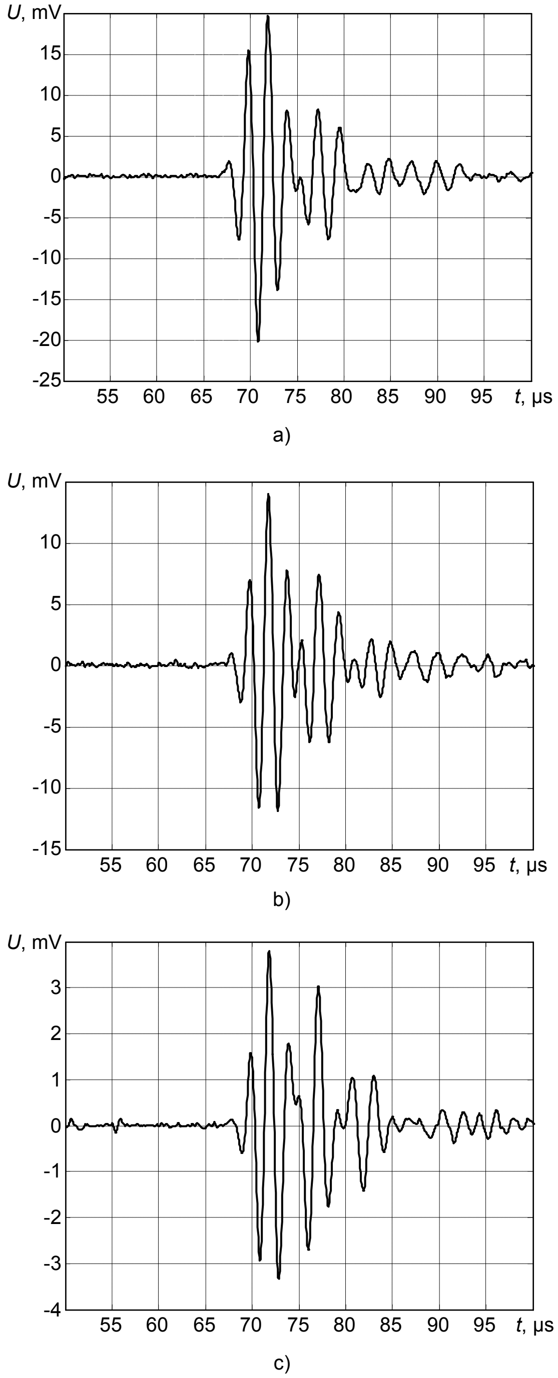


Fig.10. **Waveforms of the signals obtained with transducers without collimators (a) and with collimator having diameters of apertures equal to 8 and 4 mm (b and c)**

Waveforms of the received ultrasonic signals shows, that collimators strongly influence amplitude of the received ultrasonic signals. Influence of collimators to the waveform of the received signals is not so strong. In the case of collimators having 8 mm apertures, additional amplitude losses due to presence of the collimators are -3,8 dB. In the case of collimators having 4 mm apertures the additional losses are almost 4 times bigger, i.e. -15 dB.

These drawbacks can be avoided using a bigger excitation amplitude or using more sensitive transducers.

Conclusions

In the presented study investigation results of influence of collimators having different diameters of apertures on the width of excited ultrasonic beam are presented. Using the numerical simulation based on the diffraction approach and the experimental measurements it was estimated that exploitation of attached collimators having different diameters of apertures on the planar transducers allows choosing a relatively wide range of spatial resolutions. It was estimated that influence of collimators to the waveform of the received signals is not so strong. In the case of the collimators having 12 mm apertures (transducers without collimators), the additional amplitude losses due to presence of the collimators having 4 mm apertures are -15 dB.

The possibility to achieve different spatial resolution of ultrasonic measurements using conventional planar ultrasonic transducers is very important for nowadays NDT applications.

References

1. **Grandia W. A., Fortunko S. M.** NDE applications of air – coupled ultrasonic transducers. 1995 IEEE international ultrasonic symposium. Seattle, Washington, Conf. Proc. 1995. P. 697 – 709.
2. **Gomez Alvarez – Arenas T. E.** Acoustic impedance matching of piezoelectric transducers to the air. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency control. 2004. Vol. 51. No.5. P. 624 - 633.
3. **Kelly S. P., Hayward G., Gomez Alvarez – Arenas T. E.** Characterisation and assessment of an integrated matching layer for air – coupled ultrasonic applications. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency control. 2004. Vol. 51. No. 10. P.1314–1324.
4. **Hossack J. A., Hayward G.** Finite - element analysis of 1 – 3 composite transducers. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency control. 1991. Vol. 38. No. 6. P. 618–629.
5. **Haller M. I., Khuri – Yakub B. T.** Micromachined 1 – 3 composite for ultrasonic air transducers. Rev. Sci. Instrum. 1994. Vol. 65, No. 6. P. 2095.
6. **Loertscher H., Grandia B., Strycek J., Grandia W. A.** Airscan transducers, technique and applications. NDT.net. 1996. Vol. 1. No.9. P.1-4.
7. Modern ultrasonic transducers. Non – contact transducers. Second Wave Systems Corp. 1020 Boal Avenue, Boalsburg PA USA 16827
8. **Shuh – Pan Ying** Single narrow beam ultrasonic transducer with conical and wedge – shaped collimators. IEEE transactions on Sonic and Ultrasonic. 1967. Vol. SU-14. No. 2. P. 67 – 69.
9. **Karpelson A., Hatcher B.** Collimating and wide – band ultrasonic piezotransducers. NDT.net. 2004. Vol. 9. No. 1. P. 1 – 3.
10. **Cotter D. J., Michaels T. E., Michaels J. E., Kass D., Stanton M. E., Kesenko I. V., Frederic H. C.** Squirter, roller probe, and air – coupled ultrasonic transducer techniques for low frequency inspection of advanced composite materials. Proc. 15th World Conference on Non – destructive testing. Rome. 15 – 21 October 2000. P.1 – 10.
11. **Jasiūnienė E., Mažeika L.** The modified method for simulation of ultrasonic fields of disk shape transducer. Ultragarsas (Ultrasound). 1999. Vol.33. No.3. P. 33-37.

A. Vladišauskas, R. Raišutis, E. Žukauskas

Ultragarsiniai keitikliai su kolimatoriais dirbti ore

Reziumė

Nefokusuoti ultragarsiniai keitikliai su kolimatoriais gali dirbti esant įvairesniems atstumams, o fokusuoti keitikliai dirba tik kai atstumas fiksuotas. Be to, naudojant kolimatorius galima pasirinkti daug platesnes erdvinės skiriamosios gebos ribas. Tai ypač aktualu neardomiesiems bandymams. Straipsnyje aprašyti skirtingo skersmens kolimatorių įtakos ultragarsinio spindulio pločiui tyrimai. Teoriškai sumodeliuotas ultragarsinio keitiklio išspinduliuotas laukas. Atlikti eksperimentiniai ultragarsinio spindulio pločio priklausomybės nuo kolimatoriaus skersmens tyrimai naudojant 500 kHz nefokusuotus ultragarsinius keitiklius dirbti ore.

Pateikta spaudai 2009 03 06

DOI: 10.5755/j01.u.64.1.17093