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Application of ultrasonic transducers for investigation of composite materials

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Abstract

In this article the developed low frequency contact type ultrasonic transducers and its application are presented. The special scanner carriage, the adjuster, the single holder and tandem holder were manufactured and used in the measurement carried out on the test sample of composite material. The mechanical system enables to support accurately the stable force pressing the transducer to the composite sample. The characteristics of the low frequency transducers in the time and frequency domains are presented. The composite materials such as CFRP and GFRP were investigated using the developed transducers and a contact technique. It was demonstrated that investigated approach enables to detect non-uniformities in composite materials.

Keywords: contact type transducers, wideband ultrasonic transducers, Lamb waves, composite materials

Introduction

Ultrasonic techniques are widely used in many fields of non-destructive testing and materials characterization. Therefore, use of ultrasonic waves for investigation of composite materials such as carbon fibre reinforced plastics (CFRP) and glass fibre reinforced plastics (GFRP) is very promising. Most of such materials can be investigated using several ultrasonic methods. The first method is based on the placing of the fibre-reinforced plastics in the immersion environment. However, some of materials, such as honeycombs can not be inspected using a coupling liquid due to danger of water ingress. Therefore, the air-coupled methods are widely used [1-3]. Most of the air-coupled ultrasonic investigations are based on through-transmission and pitch-catch configuration of transducers. On the other hand air-coupled ultrasonic investigations have several shortcomings. The main of them is significant mismatch of acoustical impedances between ultrasonic transducers, air and the material under the test. At a single interface between air and carbon fibre reinforced plastic the transmission coefficient is only -60 dB ÷ -70 dB. In addition, the losses in air are increasing with increasing frequency and distance.

In order to overcome these shortcomings there are a few ways. The first of them is to increase the excitation voltage of the transmitter [3]. The second is to use several low noise preamplifiers [4] in such way improving the signal to noise ratio. Additionally, the averaging of signals can be used during experimental investigations. Averaging of the signals can give a significant improvement of the signal to noise ratio, but overall measurement time during the investigations considerably increases.

Due to the big losses of ultrasonic waves propagating in the CFRP and the GFRP plastics the through transmission method is basically used.

The low frequency contact transducers are widely used in acoustic emission applications [5, 6]. In both works the transducers consist of a conical active element and an extended backing. They possess the frequency response which is sufficiently flat in the frequency range from 100 kHz up to 1 MHz. However, the acoustic emission transducers can not be used as the contact type transducers in the scanning device, because they usually do not contain the protector.

Investigation of the composite materials such as CFRP or GLARE applying the contact method requires the ultrasonic transducer with protection of the active surface of transducer. In this paper the constructions of low frequency wide band transducers, which were used in the mechanical scanning device, are presented.

The requirements and the design of the low frequency transducer

The low frequency transducers, designated to operate in the scanning device for investigation of CFRP or GFRP composite materials using the contact method, differ from the transducer discussed above by the three main features. At first`, the matching layer on the front of the transducer has thickness less than a quarter of the ultrasonic wave. The second is the damper, which is attached to the back-side of the piezoelement and is made of the same piezomaterial and is placed in the additional composite damper. The third is a small size of the low frequency transducer's housing, which enables to increase the scanning zone and decrease the weight of the holder of a moving part of the scanning mechanism.

The low frequency transmitter and receiver placed in the one moving unit must be perfectly acoustically insulated from the housing in order to avoid cross-talk. Therefore, a few requirements must be taken into account. At first, the vibrating part of the transducer has a few stages of damping inside the housing. At second, the piezoelement must have good enough acoustic matching with the object under investigation.

In many cases, the active element of the low frequency transducer is made from a single piezoceramic element. The low frequency transducers operating below 1 MHz possess usually a relatively narrow bandwidth, especially in the case when their size is small. In many NDT applications, which are based on Lamb wave excitation or for acoustic emission, the typical size of the piezoelement inside the transducer is less than 3-4 mm and the wavelength of the waves propagating in the object under investigation can be from 10 mm up to 30 mm at the 250 kHz frequency. So, the transmitting transducer can be analysed as a point source of ultrasonic waves. The active element of the transducer can have different shape; however, the most usable is a conical transducer [5-7]. The shape of the active piezoelectric element essentially determines the transducer bandwidth. Therefore, it was proposed to use the shape and size of the piezoelement which is shown in Fig.1.

The piezoelement has two parallel surfaces with electrodes on them. The sizes of the electrodes are different. One of them has the size of 4×4.5 mm (upper), another of 3×3.5 mm (lower).

The direction of the piezoelectric element's polarization is normal to the surfaces coated by electrodes. Due to the different sizes of front and back surfaces of the piezoelement the side walls are inclined. The absence of parallel sides means that the radial modes of vibration are essentially reduced.

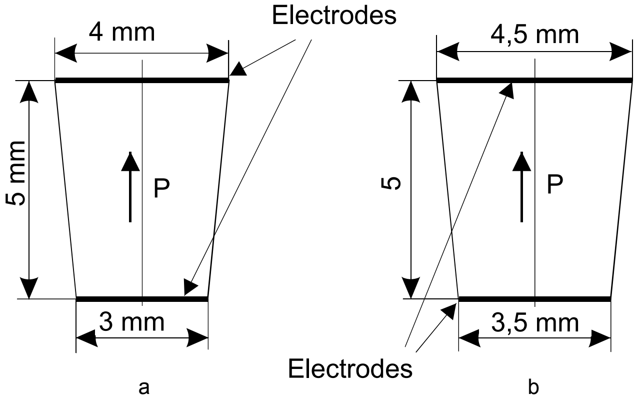

Fig.1. **The shape of the piezoelement: a – the front view, b – the side view. P with arrow denotes direction of polarization**

Fig. 2 shows the overall design of the low frequency transducer. It consists of the protector 1, the conical piezoelement 2 and damper 3. The damper is four-sided cone with an electrode on the surface, which is solidly connected with the electrode of the piezoelectric element 2 using soldering.

Two types of the protector of the low frequency transducer were used: a convex (Fig. 2a), and a planar (Fig. 2b). In both cases, the protector was made from glass fibber plastic. Thickness of the protector was less than a quarter of the wavelength.

The mechanical stability of the protector's shape depends on the hardness of the material from which the protector is made as well as an the surface roughness and hardness of the material of the investigated object. In order to improve the mechanical resistance of the protector, the hard materials such as steel, quartz, glass can be used. However, if the investigated object is made of plastics, the mismatch of the acoustic impedances between the protector of the transducer and the test object will give the reduction of the through transmission of ultrasonic signal.

The schematic cross-section of the low frequency transducer is shown in Fig. 3. Three vibration parts 1, 2 and 3 are connected with the two wires 4 and are filled with a damping compound 5, which consist of an epoxy and a lead oxide. This arrangement was swivelled around by a layer of soft material 6 and mounted into housing 7. The wires are connected to the connector 9 which is attached to the housing using the support 8.

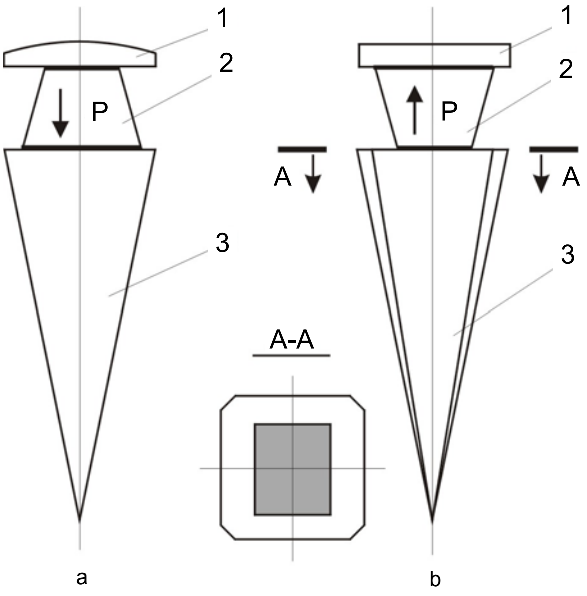

Fig. 2. **Vibration part of the ultrasonic transducer with: a - convex protector; b - with planar protector; 1 – protector; 2 – piezoelement; 3 - damper**

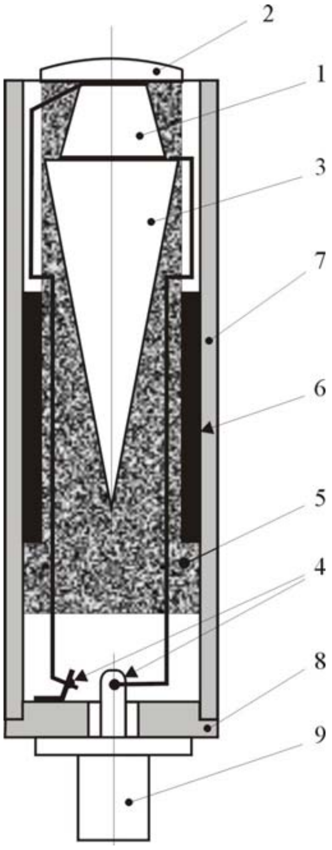

Fig.3. **Schematic drawing (cross-section) of the low frequency ultrasonic transducer: 1 – piezoelement; 2 – protector; 3 – damper; 4 - connection wires; 5 - damping compound; 6 - soft material layer; 7 – housing; 8 – support; 9 - connector**

Characterisation of the contact type ultrasonic transducer

At first the characteristics of the transducers developed have been determined. The characteristics were measured for different pair of transducers by attaching transducers to each other as shown in Fig. 4. The acoustic contact was provided by a coupling liquid. Two different methods were used to get the frequency responses of the transducers. According to the first one, the transmitter was excited by the three periods burst of the 350 kHz frequency. In the second one, the short excitation pulse (0.5 μs) was used in order to get the pulse response of the transducer.

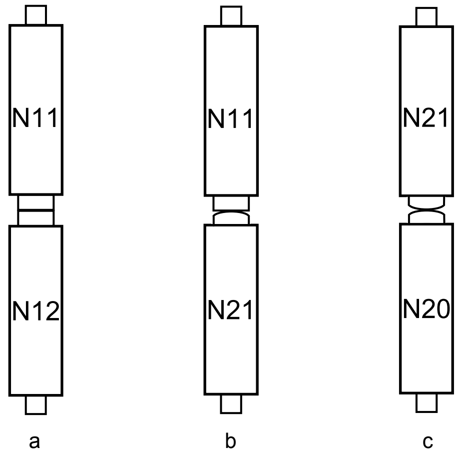

Fig. 4. **The arrangement for characterisation of the transducers: a - both with flat protectors; b -one with a flat protector (N11); an other with convex protector (N21); c - both with convex protectors**

In order to determine an influence of the shape of the protectors on characteristics of the transducer the different pairs of transducers were tested (Fig. 4). The transducers with flat protectors N11 and N12 are presented in the Fig. 4a, one transducer with the flat protector N11, an other the with convex protector N21 – in Fig. 4b, and both convex transducers N21, N22 in Fig. 4c.

The transducers (N12, N21, N20) were used as transmitters of ultrasonic waves and the transducers (N11, N21) as receivers.

The received ultrasonic signal from the transducers with flat protectors is shown in Fig. 5. The transducer was excited by the 350 kHz rectangular shape three periods burst with the amplitude of 20 V. The estimated losses of the electroacoustic channel were close to 57 dB.

It should be noted, that the transmission losses of the air-coupled ultrasonic transducers are 65 ÷ 70 dB [4]. The diameter of the transducer is 15 mm and it has two matching layers on the front face. But, if the tested object is located between the air-coupled ultrasonic transducers, the losses incredibly increase up to 120 ÷ 140 dB. For the contact type ultrasonic transducers the losses at the boundary between transducer surface and surface of the test object are close to 10 dB. Of course, it depends on acoustic properties of the material of the object under a test.

As it can be seen, the low frequency transducer can operate from 20 kHz up to 1 MHz (Fig. 6). The variations of the frequency response do not exceed 20 dB. It means that the low frequency transducers can be used as a transmitter or receiver for investigation of different modes of the Lamb waves in a relatively wide frequency range.

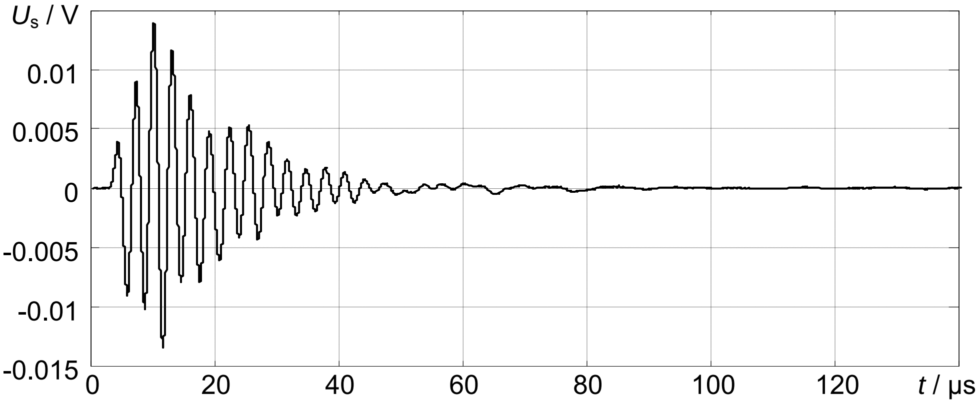

Fig. 5. **The ultrasonic signal in the case of both transducers having flat protectors**

The results obtained in the case when one of the transducers have convex protector show, that the ultrasonic signal becomes shorter and the amplitude of the signal decreases approximately by 2 dB (Fig. 7). The frequency response presented in Fig. 8 demonstrates very small changes, may be better flatness in the frequency range 0.1-0.6 MHz.

In the third case (Fig. 4c) both transducers with convex protectors were used in the investigation. The results of investigation are presented in Fig. 9 and 10. The losses are very similar (58 dB) and the frequency response does not possess essential changes also.

The analysis of the low frequency transducers characteristics shows that the transmission losses are approximately 60 dB lower than in the case of the air-coupled transducers. It also demonstrates that the shape of the protector of the transducer does not affect essentially transmission characteristics. It is very important, because the protector wears out during the contact type scanning what leads to changes of the thickness, shape and surface roughness of the protector.

The presented above characteristics in general are related to the bulk waves. In the case of application of these transducers for excitation of guided waves their

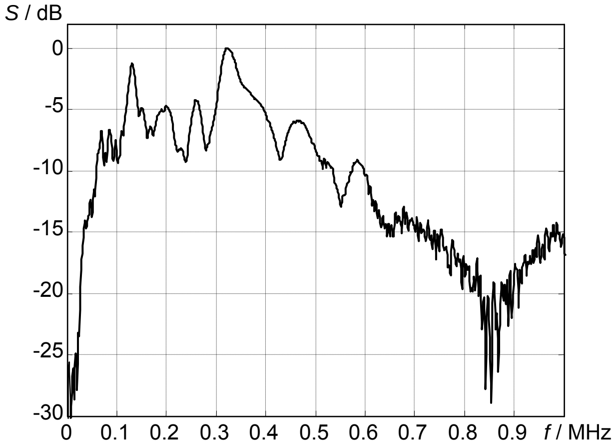

Fig. 6. **The frequency response of the transducer with the flat protector**

characteristics can be different. Of course, in such a case the characteristics depend on the object under investigation. However in order to verify the efficiency of these transducers for guided wave applications the experiments were carried out on the sample of CFRP plastic. The test object was the plate with dimensions of 150×60 mm and the thickness of 7 mm.

The transducers N11 and N12 were attached to the surface of CFRP plate from one side. The distance between the centres of transducers was 84 mm. The transmitter was excited by the 1.43 μs pulse which corresponds to the half period for 350 kHz frequency. The received signal is shown in Fig. 11. The waveform of very complicated signal which contains patterns of several propagating guided waves modes can be observed. The analysis of this signal in the frequency domain is shown in Fig. 12. It can be seen that different signal segments correspond to different frequency ranges.

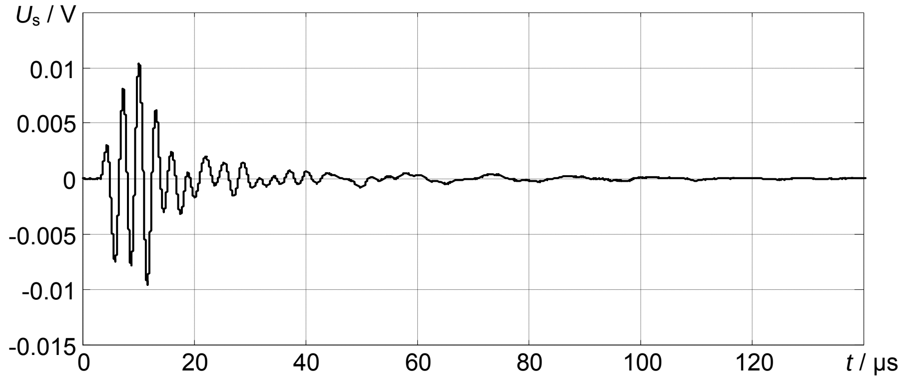

Fig. 7. **The ultrasonic signal in the case of the transmitter with the flat protector and the receiver with the convex protector**

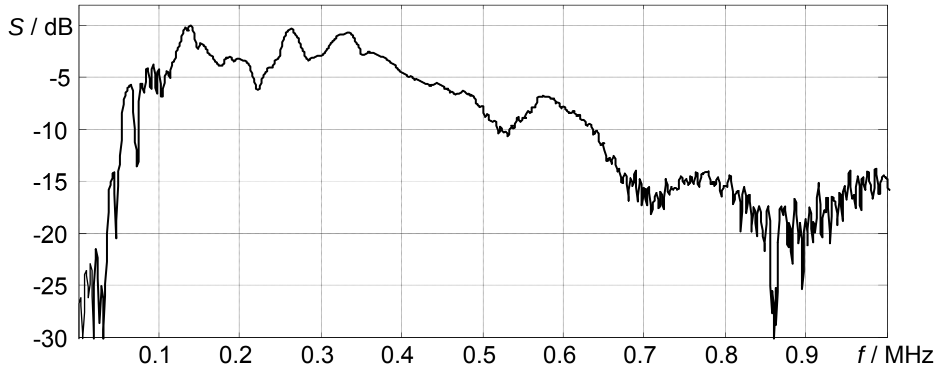

Fig. 8. **The frequency response in the case of the transmitter with the flat protector and the receiver with the convex protector**

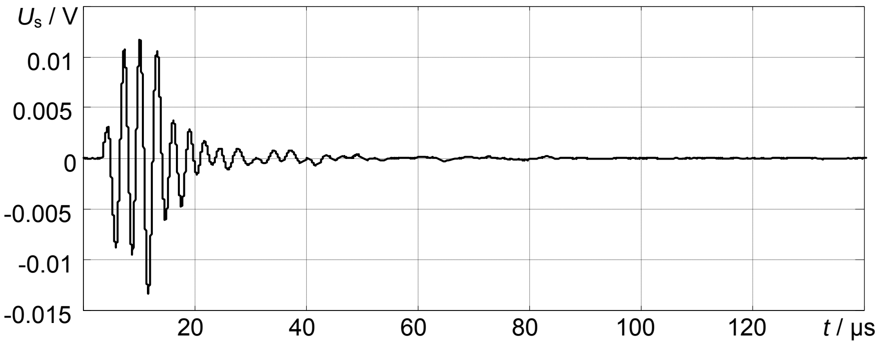

Fig.9. **The ultrasonic signal in the case of the two transducers with the convex protector**

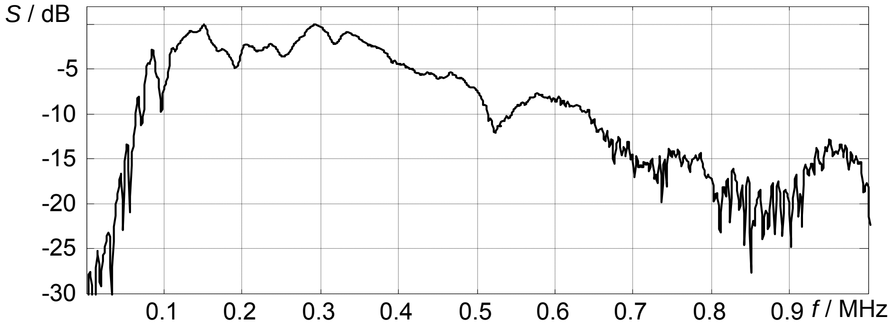

Fig. 10. **The frequency response of the two transducers with the convex protector**

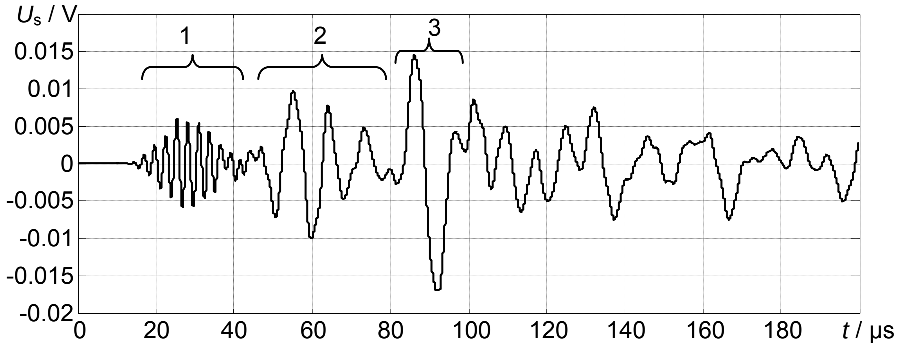

Fig.11. **The signal measured on the CFRP plate: 1, 2, 3 are the segments of the signal corresponding to different modes of guided waves**

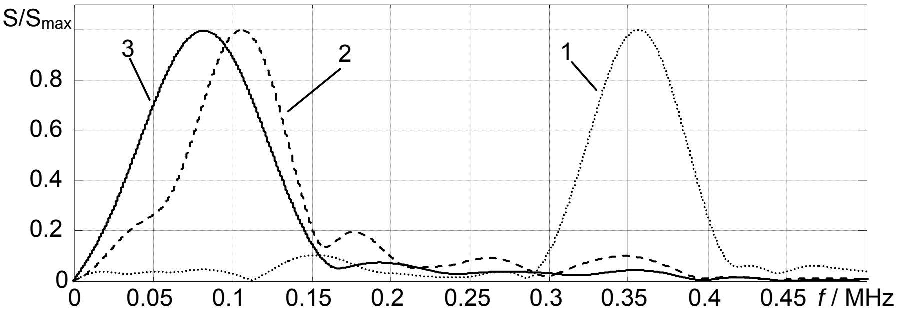

Fig.12. **The frequency spectrums of the signal segments corresponding to different modes of guided wave. The central frequencies are: 1 - 360 kHz; 2 - 110 kHz; 3 - 80 kHz**

Holders and adjusters for the ultrasonic transducers

The method of contact scanning of various objects using the low frequency ultrasonic transducers requires the devices, which provide the constant acoustical contact when the ultrasonic waves are transmitted into and received from the object under investigation. Therefore, the devices must fulfil the following requirements:

- the constant pressure force of the ultrasonic transducer to the test object;
- perpendicular position of the ultrasonic transducer with respect to the surface of the test object;
- the holder of the tandem transducers must provide a good acoustic insulation between the ultrasonic transmitter and receiver in order to avoid the effect of cross-talk;
- resistance of the protector to abrasive and rough surfaces during long term scanning;
- the holder of the tandem transducers must enable the rotation by 90° degree;
- the whole assembly of holders and adjusters must have a small weight and size.

During the experimental investigations the two types of transducers holding devices were used: a single transducer holder and the tandem holder. The main part of this device is the adjuster with a mounted different holder. The single transducer holder is presented in Fig. 13. The adjuster 1 is attached to the *x-y* mechanical scanner through a fastening element. The drive bushing 3 is fixed to the adjuster 1. The slippers 4 are moving in the drive bushing 3. The slippers are connected together by a transversal traverse 5 and adjuster support 6. This mechanical solution ensures stiffness of the construction and as result the sufficient accuracy of the positioning of the transducers. The necessary force *F* is provided by a screw spring 9 which is fixed between traverse 5 and adjuster 1. The lower end of the spring 9 is fastened through the adjustment screw that allows changing the initial tension of the spring. The contact type transducer is mounted in the holder 7.

The contact ultrasonic transducer can be successfully used in the scanning systems if a few requirements are fulfilled. At first, the good acoustic coupling between ultrasonic transducers and the surface of the object under investigation should be guaranteed. In this case it is very important that the pressure force of the transducers is constant and enables transmission of the ultrasonic waves into the object under investigation. Determination of the required force is very important also. If the pressure force is too big, the surfaces of the transducers (protectors) will be wearied off very fast. If the pressure force is too small, the ultrasonic signal can be lost when the transducer moves on the rough surface of the object. Therefore, the pressure force of the spring must be carefully evaluated. The results of the experimental investigation of the spring force are presented in Fig. 14. The experimentally determined spring force for testing of CFRP and GFRP test samples varies in the ranges from 4 N to 9 N.

The second is the weight of the holder and adjuster. They create the load on the mechanical scanner and their weight should be minimized. Therefore, the components of the holder and adjuster were manufactured using the light metal such as a duralumin. The view of the holder of the single ultrasonic transducer is presented in Fig. 15.

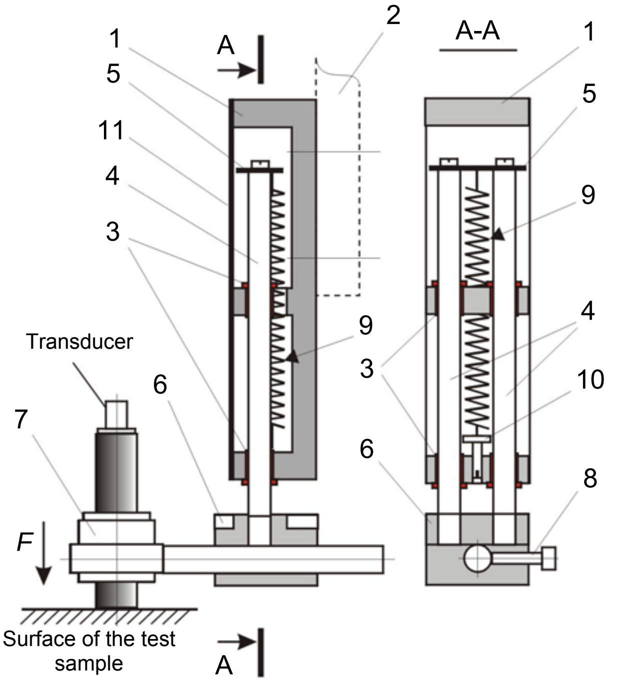

Fig.13. **The holder of single transducer:1 – adjuster; 2 - fastening element; 3 - drive bushing; 4 – slippers; 5 - transversal traverse; 6 - adjuster support; 7 - single holder; 8 – screw; 9 – spring; 10 - adjustment screw; 11 - cover**

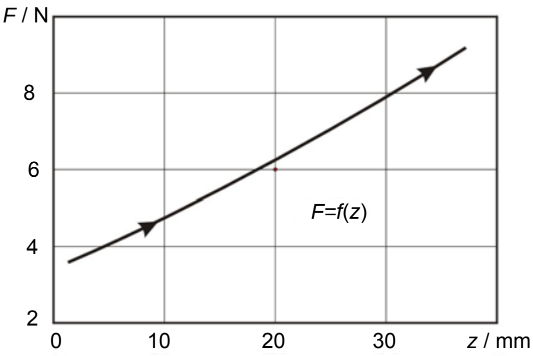

Fig.14. **Dependence of the spring force versus the adjuster position**

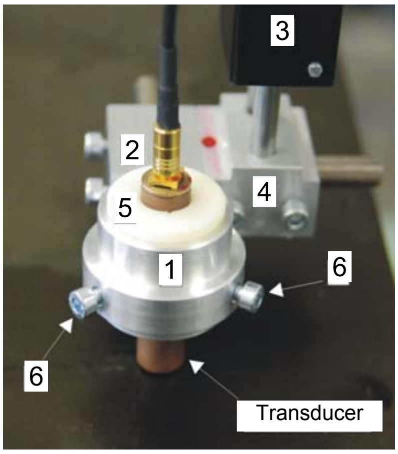

Fig.15. **The view of the holder for a single ultrasonic transducer: 1 – holder; 2 – connector; 3 – adjuster; 4 - adjuster support; 5 - insulation material; 6 - fixing screws**

The technical characteristics of the moving part with holder and adjuster are the following:

- dimensions (H×W×L) – 125x35x25 mm;
- weight:
  adjuster – 0.354 kg (with a fastening element);
  holder of the transducer – 0.077 kg;
  adapter – 0.055 kg;
  transducer – 0.023 kg.

The tandem transducers system was used for investigation of CFRP and GFRP plates. The transmitting and receiving ultrasonic transducers were moved together at a fixed distance between them. The distance between centres of ultrasonic transducers was of 50 mm. The drawing of the construction of the tandem transducers system is presented in Fig. 16.

Two low frequency ultrasonic transducers 1 and 2 are mounted to a damping bushing 3, which increase an acoustic insulation of the housings of the ultrasonic transducers. Both damping bushings are placed in a support 4 and fixed by screws 5. This construction is located on a rotation axis 6 and can freely rotate depending on a geometry of the surface of the object under investigation. Another end of the axis is mounted to the adjuster support which is shown in Fig. 13.

The view of the moving part of the tandem transducers system is presented in Fig. 17. In this figure a flexible cables, which connect the transducers with the low frequency ultrasonic measurement system are visible also.

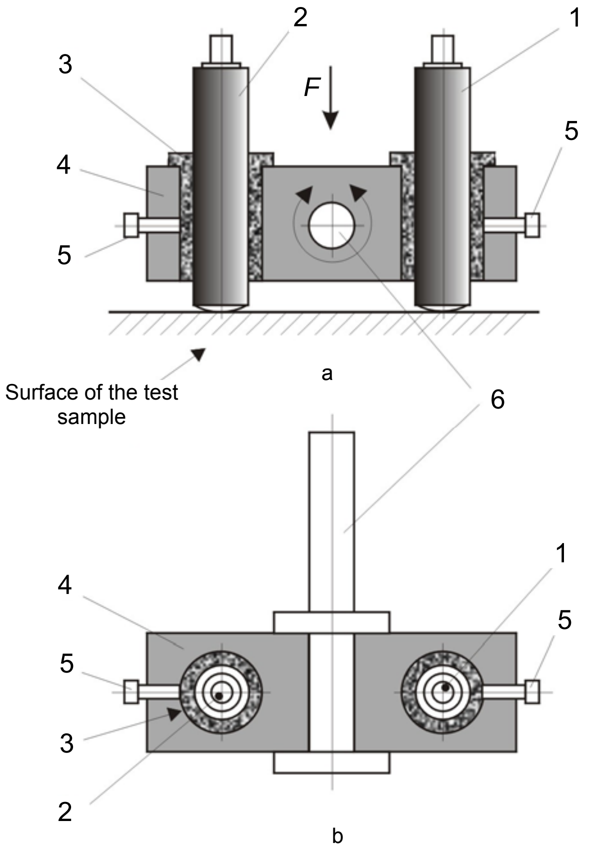

Fig. 16. **The drawing of the construction of the tandem transducers system: a - front view; b - top view; 1, 2 - transmitting and receiving low frequency transducers; 3 - damping bushing; 4 – support; 5 - screws, 6 - rotation axis**

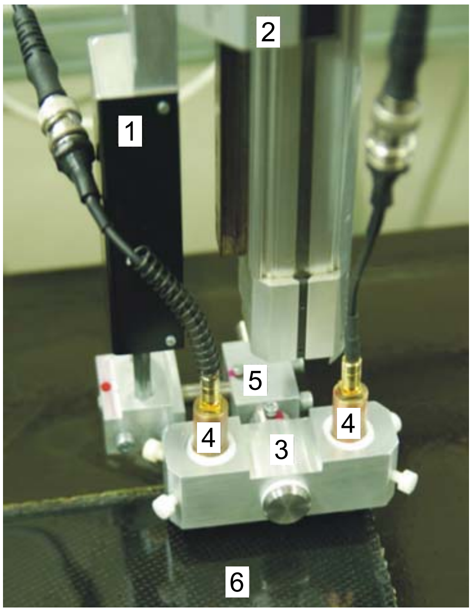

Fig. 17. **The view of the moving part of the tandem transducers system: 1 – adjuster; 2- scanner carriage; 3 – support; 4 -the transmitting and receiving transducers; 5 - rotation axis; 6 - object under investigation**

Investigation of the defect detection in the CFRP and GFRP plates

The developed low frequency contact type ultrasonic transducers are very attractive to use them in many configurations of a contact NDT method. They were used to investigate the possibility of defects detection in CFRP and GFRP plates using guided waves. In the experiments 8.4 mm thickness CFRP and 6 mm thickness GFRP plates were used.

As it is known, some non-uniformity (virtual defect) can be simulated by attaching some mass to the surface of the test sample. By such artificial obstacle the guided waves are reflected. The mode conversion of the incident wave mode occurs also. So, the experiment in which the mass attached to one side of the plate and scanning performed over opposite surface demonstrates that it is possible to “see” through the plate and to detect such non-uniformities. In our case the defect was simulated by gluing of 6 mm diameter Plexiglas cylinder to the surface of the test sample. The generalized experimental set-up for both CFRP and GFRP plates is presented in Fig. 18. The positions of the defects in CFRP and GFRP samples were slightly different.

The transmitter was attached to the edge or to the top surface of the plate at one position. The receiver was scanned over rectangular areas shown in Fig. 18 with 1 mm step in *x* and *y* directions. At each scanning position, the received signals were recorded and stored for further investigations.

The peak-to-peak amplitude C - scan images obtained for CFRP and GFRP plates are presented in Fig. 19 and Fig. 20.

As it can be seen, the glued defect was detected in both cases. In the case of the CFRP plate the image presented in Fig. 19 was obtained without any additional processing. In the case of GFRP (Fig. 20) the time window corresponding to the signal of the higher (and faster) modes of Lamb waves was used before calculating peak-to-peak amplitude of the received signal. The experiments have demonstrated also that the more stable acoustic contact can be obtained using the convex protector.

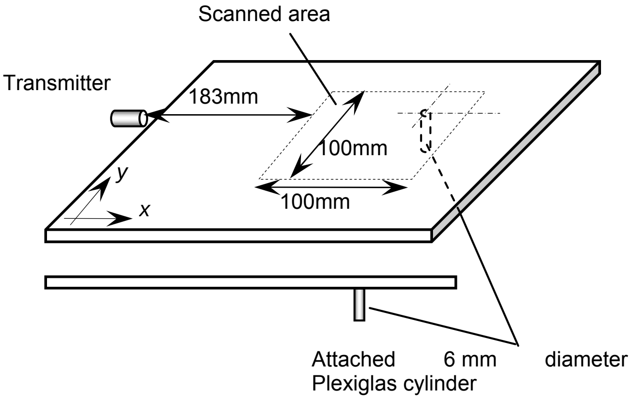

Fig. 18. **Set-up of the experimental investigation of possibility to detect defects in a composite plate**

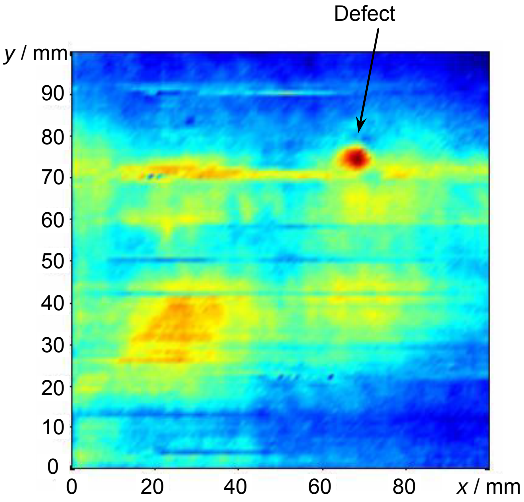

Fig. 19. **Amplitude C - scan image of the CFRP test sample with artificial defect**

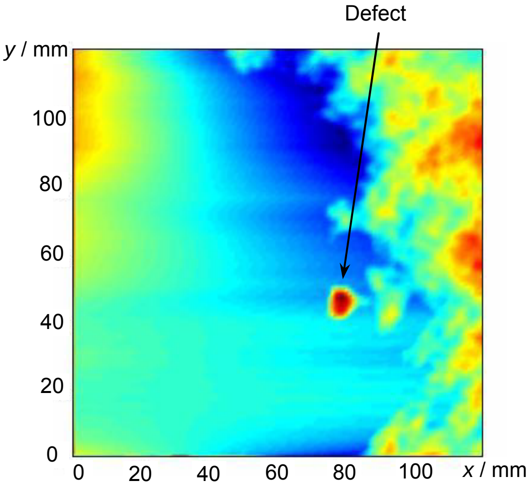

Fig. 20. **Amplitude C- scan image of the GFRP test sample with artificial defect**

Conclusions

The wide band low frequency contact type ultrasonic transducers were developed. They possess bandwidth from 20 kHz up to 1 MHz. The losses of the pair of the transducers do not exceed 60 dB.

The holder system was developed to be suitable for simultaneous scanning of the object using two transducers.

The application of the transducers developed for inspection of GFRP and CFRP samples demonstrated their efficiency in defect detection.

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Ultragarso bangų naudojimas kompozitams tirti

Reziumė

Atlikta žemojo dažnio kontaktinių ultragarsinių pjezoelektrinių keitiklių ir žemojo dažnio kontaktinių pjezoelektrinių keitiklių laikiklių komplekto, naudojamo precizinėse skenavimo sistemose, analizė. Pateiktos pjezoelektrinių keitiklių su plokščiuoju ir sferiškai išgaubtu protektoriais principinės schemos. Atlikti pjezoelektrinių keitiklių charakteristikų matavimai ir apskaičiuotos įvairių formų protektoriams skirtos jų dažninės charakteristikos. Nustatyta, kad esant protektoriui mažesnio storio kaip ketvirtis ultragarso bangos ilgio, ultragarso signalo amplitudės plokščiajam ir sferiškai išgaubtam protektoriui nedaug skiriasi. Ištirtas ultragarso signalas, gautas siunčiant ir priimant ultragarso bangas per kompozito sluoksnį. Gautosios ultragarso signalo dažninės charakteristikos parodė, kad plačiajuosčiai kontaktiniai pjezoelektriniai keitikliai turi pranašumų, kai taikomi neardomajai kontrolei ir medžiagų struktūrai tirti.

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