ISSN 1392-2114 ULTRAGARSAS, Nr.1(54). 2005.

Application of air – coupled ultrasonic technique for sizing of delamination type defect in multilayered materials

E. Žukauskas, V. Cicėnas, R. Kažys

Prof. K. Baršauskas ultrasound institute

Kaunas University of Technology

Introduction

Ultrasonic testing using couplants is most popular technique for non destructive testing of solid materials. In the most non – destructive evaluation tasks such as investigation of materials whose properties may be changed by liquid contact this technique can not be used. Use of contact technique can be restricted for complex geometry structures. Also, liquid couplants cannot be used when materials under investigation are hot, or when water can fill defects and the detectability of the defects may be reduced. Air – coupled ultrasonic technique is very attractive for non destructive testing and evaluation, because it avoids the disadvantages caused by liquid couplants. Many authors present results of air–coupled ultrasonic investigation of solid materials [1 – 7], but mostly it is qualitative evaluation. Objective of this work was to check possibility to use air - coupled ultrasonic technique to measure the dimensions of defects in aluminum and carbon fiber reinforced plastic multilayered structures.

Experimental setup

The block diagram of the experimental system is presented in Fig.1.

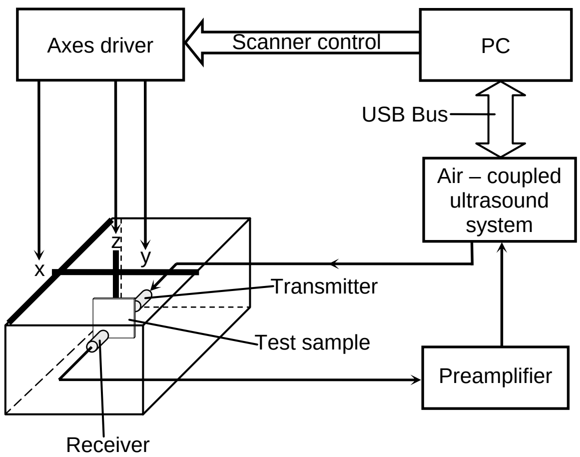

Fig.1**. Block diagram of the experimental system**

The whole system is controlled using personal computer. Two channel air–coupled ultrasonic system consists of the high voltage generator, the low noise amplifier and the analog – to – digital converter. The maximal output voltage of the generator is 750 V. Gain of the amplifier can be changed from 10 dB to 50 dB. The low noise 13.4 dB preamplifier is connected directly to the receiver in order to improve the signal to noise ratio. Experimental signals are collected and stored in the PC. Also there is possibility to real time presentation of B – scans and amplitude C – scans.

The scanning system is designed in such a way that the ultrasonic transducers are at the fixed position and the test sample is moved during the scanning process by a spatial step 0.1 mm. Scanning was carried out using the 445 kHz air - coupled focused priezocomposite transducers in the through – transmission mode. The focal spot of the transducers is 1 mm.

Experiments were performed using two types of the test samples: the reference test sample and carbon fiber reinforced plastic (CFRP) test sample. The reference test sample was produced from 0.6 mm aluminum sheet. As the defect 6×6 mm square hole was made. The CFRP test sample contains inner artificial delamination defects made of folded and sealed teflon. The size of the defect is 6×6mm.

Experiments were carried out using two configurations of the reference test sample: scanning of the single layer test sample (Fig.2a) and scanning of the double layer test sample with an additional aluminum sheet of the same thickness which was bonded using grease (Fig.2b).

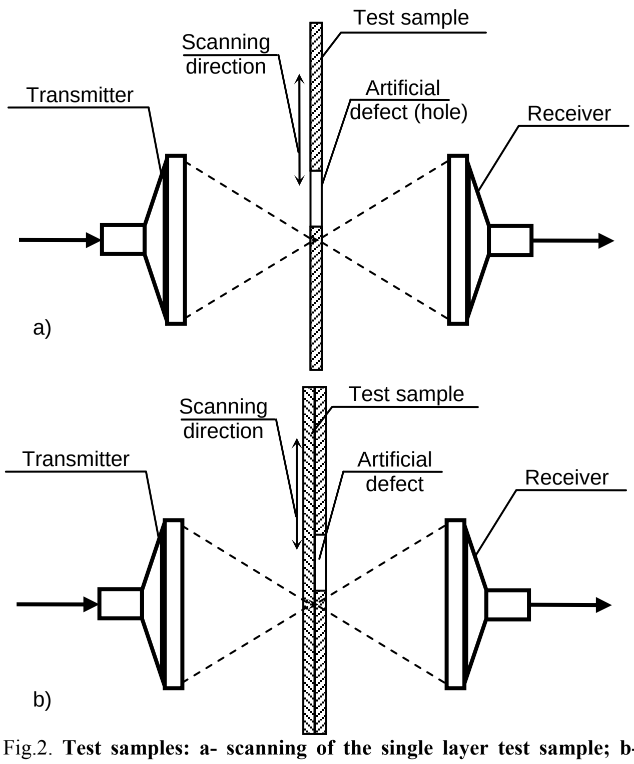

Fig.2. **Test samples: a- scanning of the single layer test sample; b- scanning of the test sample with a bonded additional aluminum sheet**

Results of experiments

The amplitude C – scan of the single layer reference test sample is presented in Fig.3. Due to the high signal to noise ratio the defect can be easy distinguished without averaging of the signals.

The amplitude C – scan of the test sample with an additional bonded aluminum sheet is shown in Fig. 4. Due to low signal to noise ratio the experiment was carried out using signal averaging. 32 signals were averaged at each scanning step. Periodical fluctuations of peak to peak amplitude of collected signals were noticed around the defect. To explain this phenomenon, simulation of the wave propagation through the aluminum test sample was performed. The simulation results are presented in the next chapter.

The amplitude C – scan of the CFRP test sample with the artificial delamination defect is shown in Fig. 5. Experiment was carried out using signal averaging due to the low signal to noise ratio. 32 signals were averaged at each scanning point. Periodical fluctuations of the peak to peak amplitude of the signals around defect were noticed as well as in the previous experiments. Some bright spots are visible in the area of the artificial defect. Origin of these spots can be explained by bonding of the defect to the carbon fiber reinforced plastic.

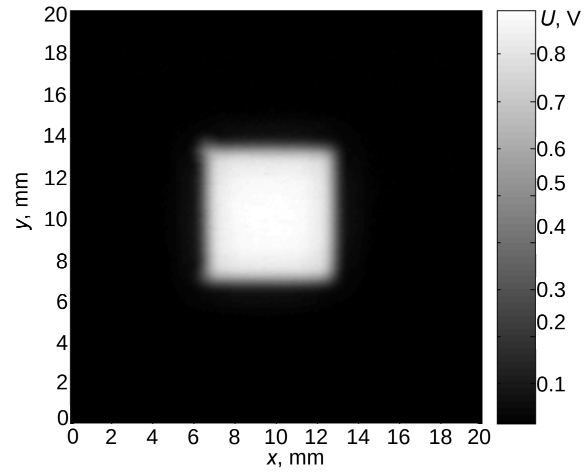

Fig.3. **Amplitude C – scan of the reference test sample**

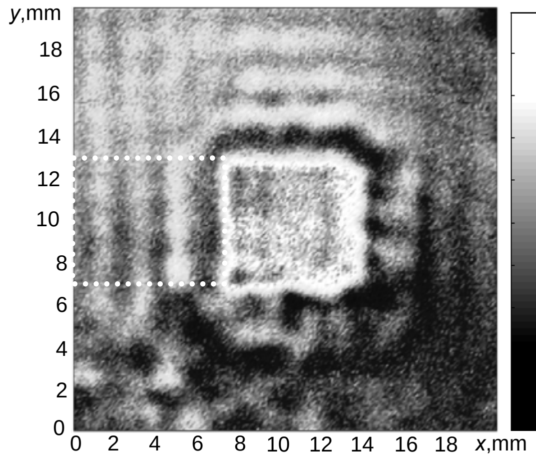

Fig.4. **Amplitude C – scan of the test sample with the bonded additional aluminum sheet**

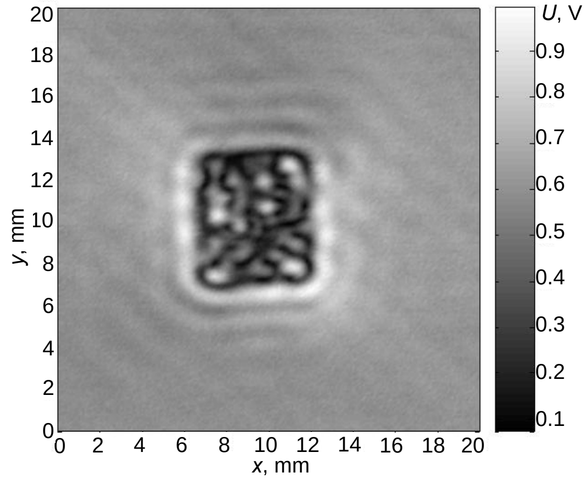

Fig.5. **Amplitude C – scan of the CFRP test sample with an artificial delamination defect**.

Simulation results

The finite differences Wave3000 Pro software package was used to create the 3D model of the bonded aluminum plates in order to simulate wave propagation through these bonded plates. The model consists of two aluminum plates bonded together: the first is the 100x100 mm square shape and 0.6 mm thickness plate, the second plate is of the same thickness and 40x40 mm dimensions with the 6x6 mm square hole at the centre (Fig.6).

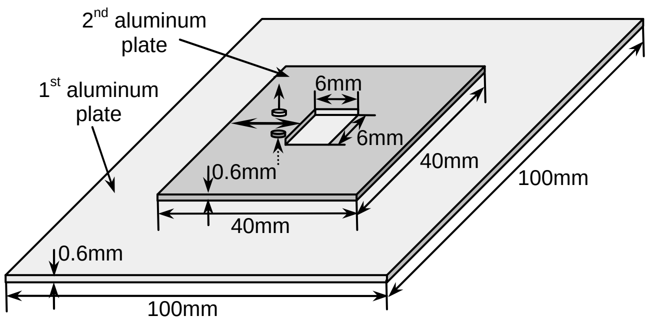

Fig.6. **The configuration and the dimensions of two bonded aluminum plates**

There is no possibility to run simulation with the focused transducers due to the lack of computer resources even using the high – end computer, because of the relatively long distance between transducers (more then 100 mm) at the 445 kHz excitation frequency. The real case was simplified. For excitation and detection of ultrasonic waves two small 1 mm diameter transducers contacting with the test sample were used in the model. The diameter of the circular transducers matches the diameter of the focal point – 1 mm. They were placed on both sides of bonded plates directly opposite to each other.

The following parameters used in the simulation were selected: the excitation frequency 445 kHz; the excitation signal nine periods burst with the Gaussian envelope. The simulation was carried out at the plane *y*=50 mm, scanned region from x_1=30.5 mm to x_2=46.5 mm, with the scanning step 0.25 mm (Fig.7).

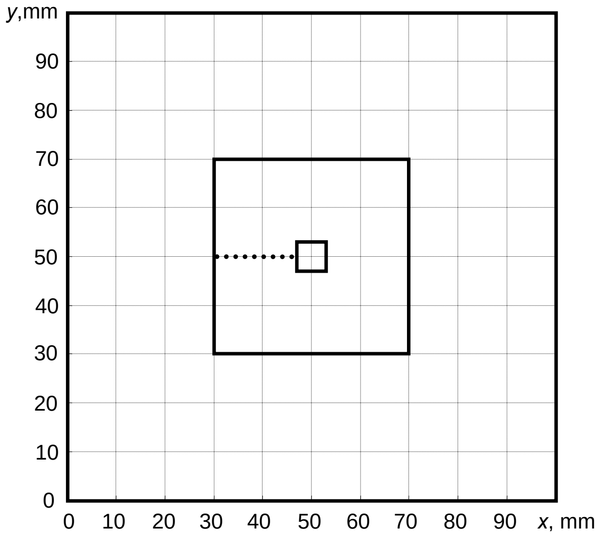

Fig.7. **Wave300 Pro model and marked axis of modeling**

The normalized modeling results are presented in Fig.8. Normalization of the simulation and experimental results were performed according to maximal value of the results. The oscillations amplitude near the edge of the second aluminum plate is larger and then decreases moving farther from the edge. The reason of these oscillations is due to the finite dimensions of the test sample, the direct signal and the signal reflected by the nearest edge overlap. The spatial oscillation period is quite close to the half wavelength of the a_0 mode ultrasonic Lamb wave which in our case is 2.2 mm.

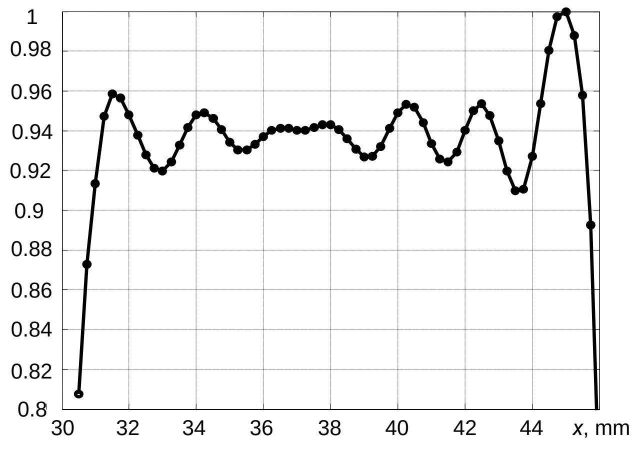

Fig.8. **The simulation results (acoustical pressure) obtained by the finite difference model. The simulated region is from 30mm to 46.5mm**

To get the clearer signal from the experimental results the average signal was taken. The averaging was performed using the results of experimental measurements of C-scan. The signals from y=7.5 mm to y=12.5 mm (Fig.4) was combined by averaging along one line (Fig.9). Modeling results of the same zone are presented in Fig.10.

Fig.9 and 10 show that modeling results corresponding to the experimental. The coordinate x corresponds to the dimension of the aluminum sample used in the experiments.

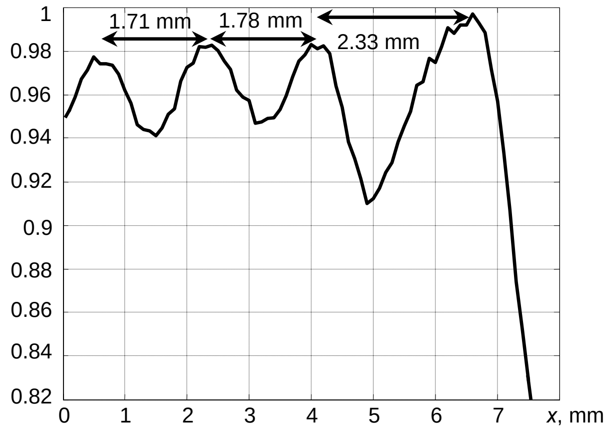

Fig.9. **The averaged measurement results; normalized amplitude of the signal versus coordinate**

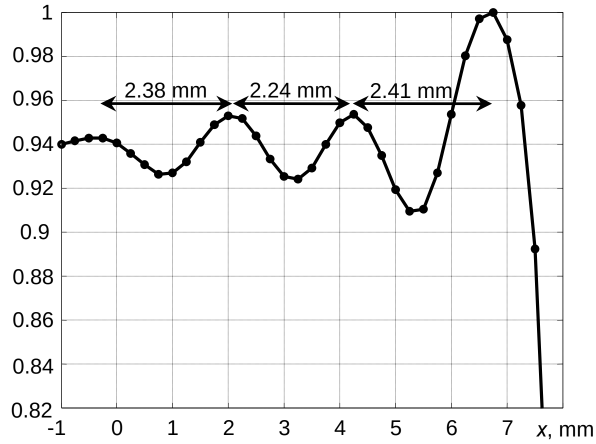

Fig.10. **Modeling results; normalized acoustical pressure versus coordinate.**

Estimation of the accuracy of measurements

The cross section of the amplitude C – scan of the single layer aluminum test sample at -6 dB level is shown in Fig.11. In the same figure the defect dimensions, measured using optical microscope MBS - 9 are presented. In order to estimate accuracy of the measurements, the distance between the opposite sides of the defect mock - up was measured. Corners of the contour are rounded due to the finite dimensions of the transducers focal spot.

The calculated distances between the opposite sides of the defect from the measurement results are presented in Fig.12 and 13. The rounded areas of the corners were not taken into account. The mean distance measured by the air-coupled ultrasonic technique between *A* and *C* sides of the defect (Fig.11) is 6.39 mm. The standard deviation of the measurement results is 17.7 µm. The distance between the sides *A* and *C*, measured by the optical microscope is 6.5mm. The measurement error is -0.11 mm or 1.7%. The mean distance measured by the air-coupled ultrasonic technique between *B* and *D* sides of the defect (Fig.11) is 6.24 mm. The standard deviation of the measurement results is 27.19 μm. The distance measured by the optical microscope is 6.35 mm. In this case the measurement error is -0.11 mm or 1.7%.

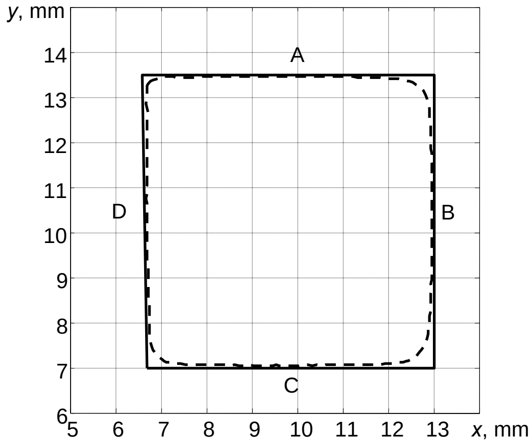

Fig.11. **Cross – section of the amplitude C – scan at the -6db level (dashed line) and the dimensions of the defect measured using the optical microscope (solid line)**

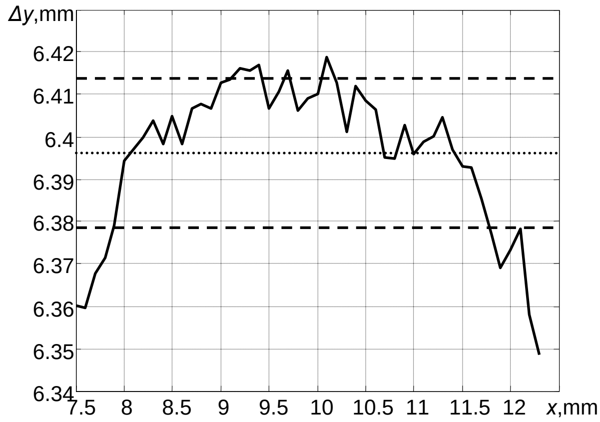

Fig.12. **Measured results of the distance between A and C sides of the artificial defect along *x* axis. The mean value is 6.39mm (dotted line), the standard deviation is 17.7 μm (dashed line)**

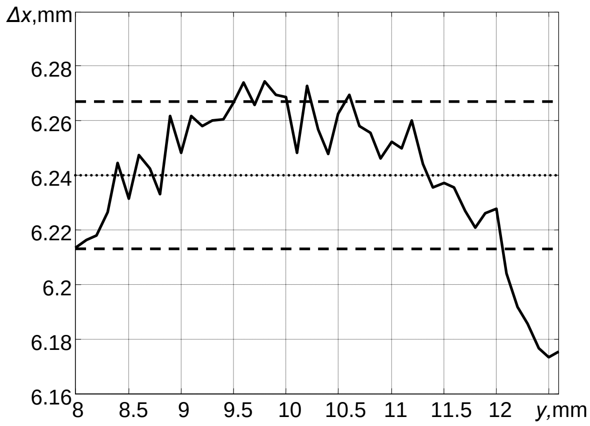

Fig.13. **Distance between B and D sides along *y* axis. Mean value 6.24mm (dotted line), standard deviation 27.19·10^{-3}mm (dashed line). (zoomed x axis)**

The cross – section of the amplitude C – scan of the double layer aluminum test sample at the -6 dB level and results of measurements using the optical microscope are presented in Fig.14.

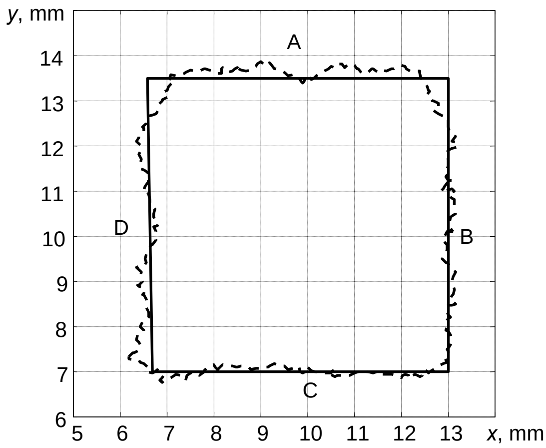

Fig.14. **Cross – section of the amplitude C – scan at the -6db level (the dashed line) and dimensions of the defect measured using the microscope (the solid line)**

As well as in the previous case the rounded areas of the corners of the defect were not taken into account. The mean distance measured by the air – coupled ultrasonic technique between the opposite *A* and *C* sides of the artificial defect is 6.64mm. The measurement error is 0.14mm or 2.1%. The mean distance between the *B* and *D* sides of the defect is 6.47mm. The measurement error is 0.12mm or 1.9%. Due to the low signal to noise ratio the standard deviation of the measurement results for the double layer test sample is 0.13mm.

The cross – section of the amplitude C – scan of the CFRP test sample of the 1 mm thickness at the -6dB level is shown in Fig.15. The artificial defect lies in the 0.5 mm depth. The contour of the defect is distorted (*B* and *D* sides) probably due to bonding points of the defect at some points to the plastic material. These distorted sides were not taken into account in estimation of accuracy of the measurements.

Because the defect is between the inner layers of the test sample, it was not possible to measure dimensions of the artificial defect using the optical microscope. The radiographic image of the CFRP test sample with the defect is shown in Fig.16. Due to low image quality it is almost impossible to measure dimensions of the defect. It is only known that defect dimensions should be 6×6 mm.

The mean distance measured between the *A* and *C* sides of the artificial defect is 6.52mm. The measurement error is 0.52mm or 8%. The standard deviation of measurement results is 61·μm.

Measurement errors could be caused by the following sources:

1) the finite dimensions of the focal point of the ultrasonic transducers;
2) diffraction effects at the edges of the defects;
3) variations of the distance between the transducers and the test sample;
4) alignment errors of the transducers and accuracy of axial symmetry of beam field;

5) influence of vibrations of the test sample;
6) electrical noise of electronic circuits;

The biggest influence on the measurement error has the finite dimensions of the ultrasonic transducers and diffraction effects. Variations of the distance between the ultrasonic transducers and the test sample, alignment errors, influence of the vibrations of the test sample can be reduced and influence of these sources can be neglected. The influence of an electrical noise can be neglected as well because it is random and can be eliminated using signal averaging.

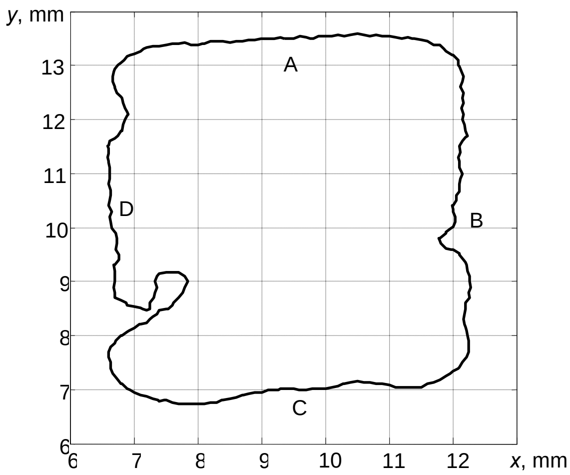

Fig.15. **Cross – section of the amplitude C – scan of CFRP test sample at the -6db level dashed line and dimensions of the defect measured using microscope (solid line)**

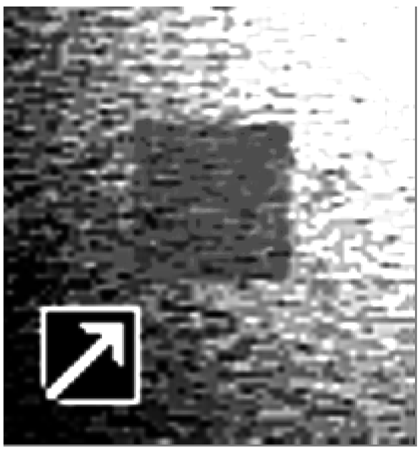

Fig.16.**Radiographic image of the 6×6mm^2 artificial defect in CFRP test sample**.

Conclusions

Possibility to use air- coupled ultrasonic technique for sizing of delamination type defects in multilayered structures was investigated. The experiments were carried out using two types of materials: aluminum and CFRP test samples.

It was discovered that around the rectangular defects amplitude oscillations of the wave transmitted through the sample exists. The amplitude of oscillations is decreasing moving farther from the edge of the defect. In order to get explanation of this phenomenon, numerical simulation of the aluminum plate with a rectangular defect was performed. These oscillations are due to interference of two waves: the direct wave and the wave reflected from the plate edge.

For estimation of dimensions of defects, the distance between opposite sides of the contour of the defects was measured. For the single layer aluminum test sample the measurement error is -0.11mm. For the double layer aluminum test sample measurement error is 0.13mm. The measurement error of dimensions of the defect of CFRP test sample is 0.52mm. Experimental results show, that the measurement of the dimensions of defects in multilayered structure using air – coupled ultrasonic technique can be performed with a relatively high accuracy.

References

1. **Buckley J.** Principles and applications of air - coupled ultrasonics. Insight. November 1998. Vol. 40. No.11. P. 755 – 759.
2. **Blome E., Bulcaen D., Declerq F.** Air – coupled ultrasonic NDE experiments in the frequency range 750 kHz – 2 MHz. NDT&E International. 2002. Vol.35. P. 417 – 426.
3. **Rogovsky A. J.** Development and application of ultrasonic dry – contact and air – contact C – scan systems for nondestructive evaluation of aerospace composites. Materials evaluation. December 1991. P. 1491-1496.
4. **Schindel D. W**. Air coupled ultrasonic measurements of adhesively bonded multi – layer structures. Ultrasonics 37. 1999. P. 185-200.
5. **Kelly S. P, Hayward G**. Real time through transmission inspection of aircraft composites using air – coupled ultrasonic arrays. IEEE ultrasonic symposium. 1995. P. 711 – 714.
6. **Bhardwaj M. C., Neeson I., Stead G**. Introduction to contact – free ultrasonic characterization and analysis of consolidated materials. NDT.net. June 2000. Vol.5. No.6.
7. **Hillger W., Meier R., Heinrich R**. Inspection of CFRP components by ultrasonic imaging with air coupling. NDT.net. October 2002. Vol.7. No.10.

E. Žukauskas, V. Cicėnas, R. Kažys

Ultragarsinių matavimų per oro tarpą metodo taikymas delaminacijos defektų matmenims nustatyti daugiasluoksnėse struktūrose

Reziumė

Bandomas ultragarsinių matavimų per oro tarpą metodas defektų matmenims matuoti. Pateikta ultragarsinės matavimo per oro tarpą sistemos struktūrinė schema, matavimo metodas, aprašyti tiriamieji aliuminio plokštelių ir anglies pluoštu sutvirtintos plastmasės bandiniai, pateikti jų erdvinio skenavimo rezultatai. Amplitudės fliuktuacijų aplink defektą prigimčiai patikrinti atliktas bangos sklidimo per tiriamąją struktūrą modeliavimas baigtinių skirtumų metodu. Defektų matmenims nustatyti išmatuotas atstumas tarp priešingų defektų briaunų. Ultragarsinių matavimų per oro tarpą rezultatai palyginti su optiniu mikroskopu nustatytais matmenimis.

Pateikta spaudai 2005 03 25