ISSN 1061-8309, Russian Journal of Nondestructive Testing, 2024, Vol. 60, No. 4, pp. 368–377. © Pleiades Publishing, Ltd., 2024.
Russian Text © The Author(s), 2024, published in Defektoskopiya, 2024, No. 4, pp. 16–27.

ACOUSTIC METHODS

Detection of Hidden Defects in Composite Material Using the Standing Waves Method

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Received November 29, 2023; revised April 7, 2024; accepted April 12, 2024

Abstract—As a result of measurements carried out using the standing waves method, hidden defects were detected inside the prosthetic feet details made of composite material. When comparing the obtained amplitude-frequency spectra of intact samples and samples with defects based on the first peaks corresponding to the first bending wave modes, it was revealed that the values of the resonant frequencies of defective samples were lower relative to the frequency values of the spectra of the intact ones. That observation indicated that the material of defective products might have reduced strength characteristics. Also, when studying some samples, the presence of additional peaks was noted, which indicated the appearance of new reflection boundaries corresponding to the appearance of defects in the test samples. The maps of amplitude distributions in the studied samples were obtained. A preliminary comparison was made with the results of examining samples using the OmniScan X3 device manufactured by OLYMPUS company. The results obtained indicated the presence of an increased number of reflection boundaries, as well as an increased bulges content, which probably arise during the process of products gluing. The analysis confirms the possibility of successfully using the standing waves method as a method for detecting hidden defects in composite material.

Keywords: standing waves, hidden defects, composite material, prostheses, diagnostic system

DOI: 10.1134/S1061830924601752

INTRODUCTION

At the stage of testing the strength characteristics of products under cyclically repeated loads on the prosthetic feet details made of composite material, there is a problem of inhomogeneity of the results obtained: some number of products breaks, withstanding a load of ~1 000 000 repetitions but another one withstands a load of an order of magnitude less. Since each specific foot detail is manufactured in small batches from layers containing about 50 products, such significant differences in the withstandable loads indicators at the strength testing stage may indicate the problems existing in the technological chain and leading to such inhomogeneities in the results.

This problem can be voiced as a problem of diagnosing products at all stages of their manufacture in order to identify and localize possible defects, visually indistinguishable to the naked eye, in order to meet the requirements for the quality and safety of their operation.

Defects identified in composite materials may include: cracks, delaminations, foreign inclusions, cavities, etc. To detect defects in composite materials, it is possible to use various non-destructive testing methods: acoustic, optical, thermal, radiation, magnetic, etc. [1].

For example, the shadow ultrasonic method of non-destructive testing is as follows: the emitting transducer supplies waves to the test object, passing through which, low-frequency waves hit the receiving transducer located coaxially with the emitting one. There are amplitude and time shadow transmission methods. The amplitude shadow method is based on measuring the amplitude of an ultrasonic wave passing through an object. If there is a defect that is encountered along the path of the wave, the amplitude of the wave either increases or decreases, and is also accompanied by the appearance of additional values of resonant frequencies, which correspond to characteristic peaks. The time shadow method is based on measuring the time it takes for an ultrasonic wave to travel through an object: if there is a defect in the wave's path, the travel time increases.

The advantages of the shadow ultrasonic method include: high accuracy and sensitivity to defects, the ability to test objects without destroying them or stopping the manufacturing process, the ability to check objects in hard-to-reach places. However, the problems may arise associated with the inability to accurately determine the depth of a defect, the need for specialized equipment and skills to use [2, 3].

The optical-acoustic method of non-destructive testing is based on the principle of converting acoustic energy into optical energy and vice versa. It includes three main stages: generation of acoustic waves by a sound source that penetrate into the test object, conversion of acoustic energy into thermal energy, which leads to a local change in temperature, which in turn causes a change in the refractive index of the material, detection of changes in the refractive index by the optical system caused by acoustic waves and converting them into an electrical signal. Or, in turn, laser pulses are used to generate acoustic waves. In these systems, a short laser pulse is focused on the surface of the material, and part of the pulse energy is converted into thermal energy, which creates an acoustic wave. This acoustic wave then propagates within the material and can be detected using an optical system that measures the changes in refractive index caused by the wave.

The optical-acoustic method has a number of advantages: the optical system allows one to accurately determine the location of the defect, since it can record changes in the refractive index with high accuracy, the optical system can operate in a wide range of temperatures and humidity, which makes it very universal, this also includes the absence of the need for direct contact with the object, ease of use and the ability to integrate with automated systems.

However, this system also has disadvantages. One of them is the high cost of equipment. In addition, an optical-acoustic system requires certain skills and experience for proper configuration and use [4, 5].

The thermographic method of non-destructive testing is based on the analysis of infrared radiation emitted by the test object. Since thermography is based on the principle that all objects with a temperature above 0 K emit thermal radiation, it is also possible to record this radiation using special equipment — infrared cameras, which convert infrared radiation into a visible image.

Using the thermographic method, the following defects can be detected: breaks and incorrect laying of reinforcing fibers, inhomogeneities in the material caused by poor-quality impregnation or the formation of air bubbles, uneven distribution of resin or filler, determination of layer boundaries, as well as various mechanical damage. All this affects the thermal waves propagation speed in defective and defect-free areas of the test object.

The advantages of the thermographic non-destructive testing method are its simplicity, speed and the ability to carry out testing in real time. However, this method may be less sensitive compared to other methods, such as, for example, ultrasonic flaw detection, and requires certain skills and experience in interpreting the data obtained, as well as the need to provide optical access to the surface of the test object [6, 7].

Radiation methods of non-destructive testing are based on the use of ionizing radiation to obtain information about the internal structure and properties of test objects. For example, X-ray flaw detection is based on the use of X-rays to illuminate objects and detect internal defects such as cracks, pores and delaminations.

The principle of X-ray flaw detection is that X-rays pass through a material and interact with its atoms. When an X-ray tube generates a beam of X-rays that passes through the test object, then if there are defects inside the object (cracks, pores, delaminations, etc.), the X-rays will be absorbed differently in different places of the object, which can be detected using radiation detector, which converts them into an electrical signal.

In composite materials, X-ray flaw detection is commonly used to check the quality of the joints between different layers of material, for example to detect defects in the joints between carbon fibers and the polymer matrix, and to detect cracks and other defects. If there is a defect inside an object, then the rays will be absorbed more at that location than at locations without the defect due to the difference in densities or compositions compared to the intact area of the object.

Radiation methods are highly sensitive and can detect defects down to several microns in size. However, they also have a number of disadvantages, including the need to use sources of ionizing radiation, which requires special safety measures. In addition, radiation methods may not be applicable to the inspection of objects sensitive to ionizing radiation, such as electronic components or optical elements [8, 9].

The eddy non-destructive testing method is based on recording eddy currents arising in the test object under the influence of an electromagnetic field. These currents create their own magnetic field, which can be measured using a special sensor.

If there is a defect in the composite material, such as a crack or delamination, then the intensity of the magnetic field in this area will be higher compared to the undamaged part of the material. The sensor can detect this change and determine whether there is a defect. To determine a defect, it is necessary to measure the magnetic field in several areas of the product. If the field change in one area is significantly greater than the change in other areas, this may indicate the presence of a defect. A comparison can also be made with a reference sample having known characteristics.

The advantages of the method include: high speed of testing, the ability to control products of complex shapes and high sensitivity. However, there are a number of disadvantages, the most significant of which is its superficiality. The disadvantages also include: limitations on the material, limitations on the size of the defect and the difficulty of interpreting the results [10, 11].

In the process of developing the method used, in particular, in this work, it became clear that noise vibrations can carry useful information. As is known, bounded bodies are characterized by a certain set of natural frequencies. If there are forced harmonic oscillations in the environment, then when their frequency coincides with one of the natural frequencies of the test object, resonance phenomena are observed, which can be used, for example, to solve problems of monitoring and diagnostics of products made of composite material. Thus, if the environmental noise influencing the test object has the spectral components that coincide with any natural frequencies of this object the field of standing waves can be formed in the latter with each frequency coinciding with one of the natural frequencies of the test object. Despite the relatively small amplitude of these waves, a technique has been developed that allows them to be isolated from the noise field [12–15].

To study the natural vibrations of details, a method based on isolating standing waves from acoustic noise was used. The essence of the method is the accumulation of amplitude spectra of noise recordings, as a result of which regular sequences of peaks corresponding to standing waves appear on the averaged spectra. Next, we shall present the results of physical modeling of standing waves formed in products made of composite material with and without defects under the influence of a noise field.

The purpose of using a method based on standing waves is to determine the possibility of diagnosing the presence of hidden defects inside composite material. The purpose is also to show that it is possible to detect defects in the shortest possible time using the proposed method, saving the resources and time spent on this, and once they are detected, it is advisable to use alternative control methods, studying them in more detailed manner.

MATERIALS AND METHODS

The objects of the study were a batch of prosthetic foot details made of composite material. The composite material of the test details was a carbon fiber reinforced prepreg with epoxy resin, in which a suspension with nanotubes was mixed in order to increase the strength characteristics of the product.

The experimental setup diagram is shown in Fig. 1. An acoustic speaker generating “white noise” was used as a source of acoustic noise. The amplitude-frequency response of the speakers according to the passport works up to 20 kHz. In Fig. 2 one can see the degree of unevenness in the characteristics of the white noise source. Then a mobile receiver, based on a TsTS-19 piezoceramic disk with a diameter of 2 mm and a thickness of 1 mm, recorded the noise field (Fig. 3). The receiver moved over the test object using the following “grid” of measurements: 2 longitudinal tracks with 10 points were passed along with a step of 2 cm and 2 transverse tracks with 3 points were passed with a step of 1 cm (Fig. 4). The time spent obtaining data at each point does not exceed 10 s. Signals from the sensor were fed to one channel of a two-channel digital oscilloscope V-421 then digitally recorded onto a personal computer hard drive for subsequent processing. Next, the data was entered into the software developed by the team, which made it possible to obtain a map of the amplitude distribution from the obtained spectra. The results were also compared with the amplitude distribution maps obtained by the OmniScan X3 device manufactured by OLYMPUS.

The standing waves diagnostic method was as follows:

(1) Measuring intact samples from a batch:

(a) Registration of noise records on the test object in order to identify standing waves in them using a piezoceramic sensor moved along the measurement “grid”;

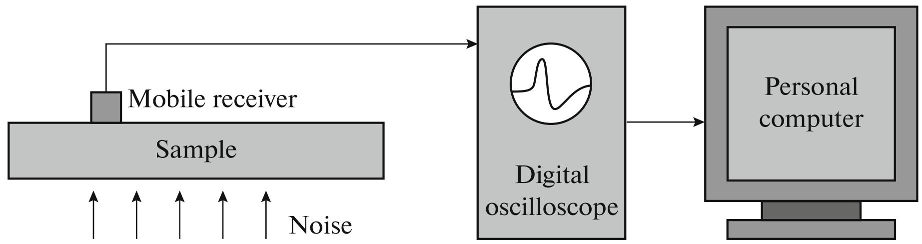

Fig. 1. Experiment scheme.

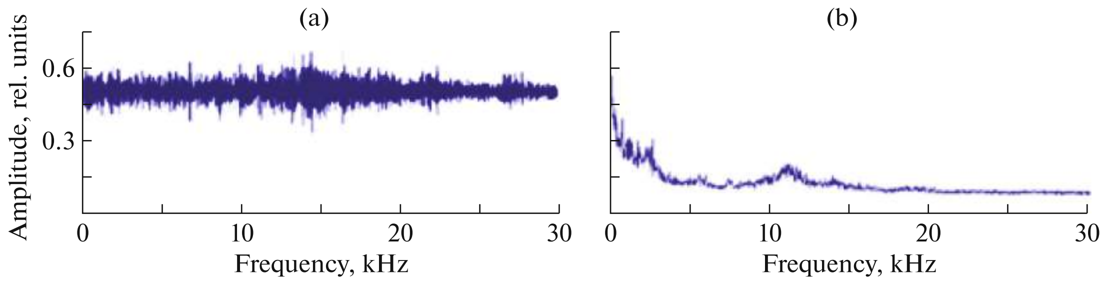

Fig. 2. Examples of amplitude spectra of electrical noise signals applied to the sample (a) and noise acoustic signals recorded on the surface of the sample (b).

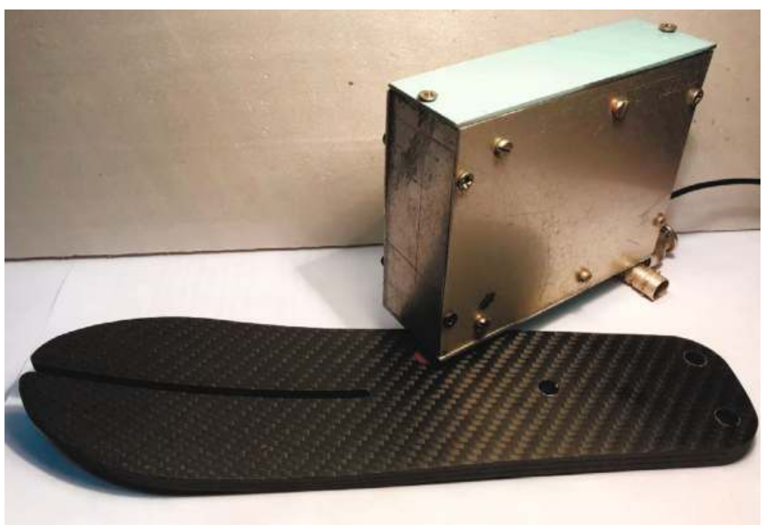

Fig. 3. Test object (prosthetic foot detail) with a piezoceramic sensor.

(b) Splitting noise records into blocks of 65 536 samples (the maximum number of samples in the V-421 oscilloscope);

(c) Fourier transform for each block and averaging of the resulting amplitude-frequency spectra by summing them.

(2) Construction and comparison of total spectra with each other in order to identify a shift in amplitude-frequency spectra as a preliminary assessment of the uniformity of frequency values for intact samples.

(3) Creation of a crack by squeezing one intact sample with a vice and breaking it with pliers until a characteristic crunch of the product; a crack was not visually observed.

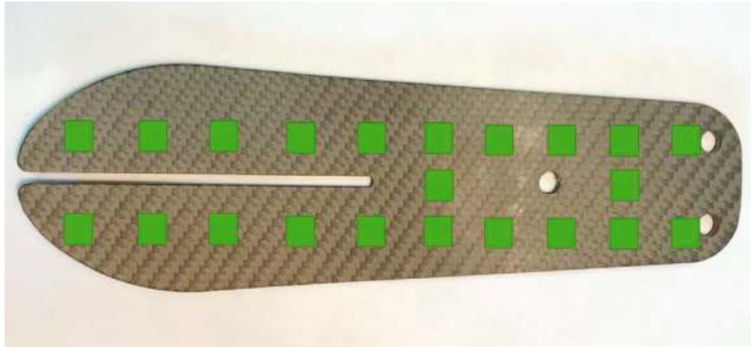

Fig. 4. “Grid” of measurements of the test object.

(4) Construction and comparison of the total spectra of a sample with a crack and the intact one in order to identify a shift in the amplitude-frequency spectrum and the formation of new resonance peaks as an assessment of the presence of defects.

(5) Also repeating the above procedure for a sample in single specimen in order to show a clear example of the formation of additional values of resonant frequencies in the presence of a defect in the product. Here we note that the “grid” of the sensor passage was slightly different due to the difference in the geometric dimensions of this specimen with samples from another batch: 2 longitudinal tracks with 9 points were passed along with a step of 1 cm and 1 transverse track with 3 points – with a step of 1 cm.

(6) Obtaining a map of the amplitude distribution in a sample presented in a single specimen, with an assessment of the sizes of defects detected.

(7) Obtaining a map of the amplitude distribution of two intact samples using the OLYMPUS OmniScan X3 device and analyzing the resulting map in order to assess the possibility of applicability of the standing waves method as a system for detecting and diagnosing hidden defects and as evidence of the presence of defects such as discontinuities in the studied composite material.

(8) Providing images of defects directly on the sample presented in a single copy.

RESULTS

Next, the amplitude–frequency spectra and the maps of amplitude distributions will be considered as informative parameters proposed for monitoring the test objects.

Note that if the geometric dimensions, material of the samples, as well as the noise characteristics are constant from batch to batch, the area of occurrence of antinodes of standing waves will appear in the same areas of the test samples. To localize these areas, in particular, the above-mentioned “grid” of measurements is necessary. Consequently, by designating the area of antinodes for different waves modes and installing a reading piezoceramic sensor in this area, it becomes possible to obtain data from one single point, located, for example, in the center of the test sample which will significantly speed up the data acquisition procedure for the purpose of localizing hidden defects in large batches of samples. However, in the presence of hidden defects, the antinode area may shift from sample to sample in a single batch. Therefore, for the first sample in a single batch, it is necessary to go through a “grid” of measurements, localizing these areas for, for example, the first and second waves modes, and then for subsequent samples within a single batch, select 3 points corresponding to the antinodes of these waves modes. This procedure can significantly reduce the data acquisition procedure to ~30 min per batch of 50 details.

Figure 5 shows the results of obtaining amplitude-frequency spectra for two intact samples. The names “intact_2” and “intact_3” correspond to the 2nd and 3rd samples, which belonged to the same batch.

Figure 6 shows the results of obtaining amplitude-frequency spectra for the intact sample and a sample with a crack. The names “intact_1” and “with crack_1” correspond to the 1st sample in its intact state and to the same sample, but with a crack created. The sample is from the same batch as the samples which spectra are shown in Fig. 5.

Figure 7 shows the results of obtaining amplitude-frequency spectra for the intact sample and a sample with a crack (single specimen).

Next, the following procedure was carried out:

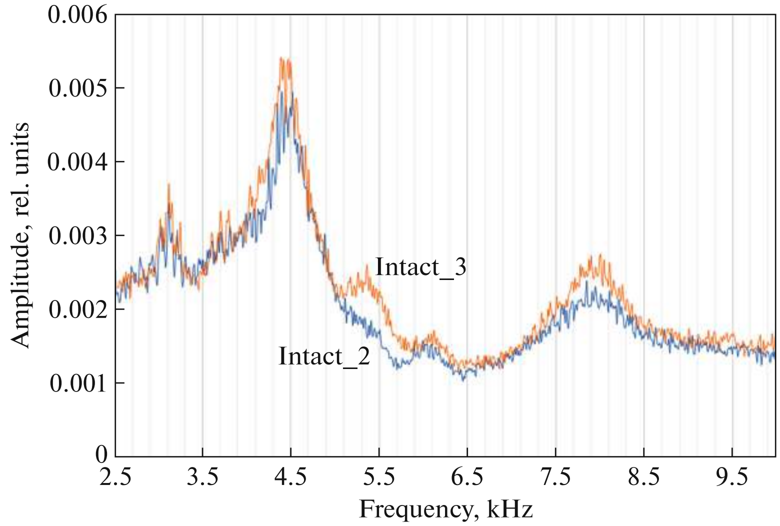

Fig. 5. Comparison of amplitude–frequency spectra of two intact samples.

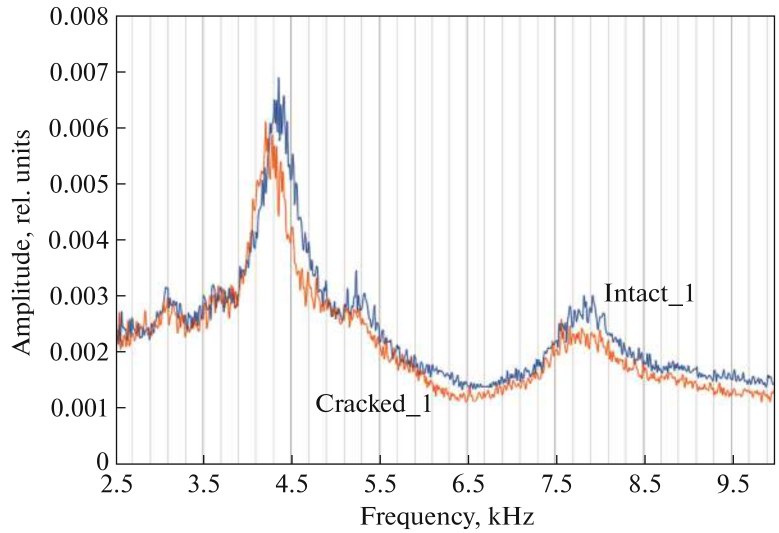

Fig. 6. Comparison of amplitude–frequency spectra of an intact sample and a sample with a crack.

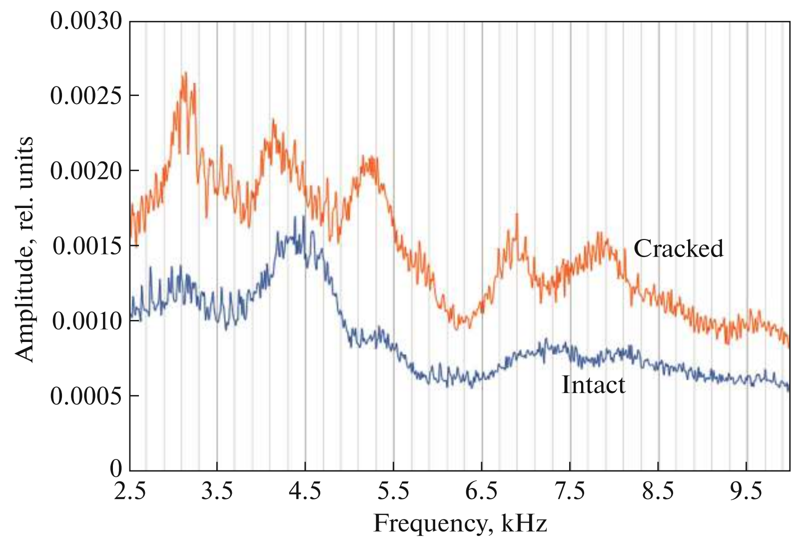

Fig. 7. Comparison of amplitude–frequency spectra of an intact sample and a sample with a crack (single specimen).

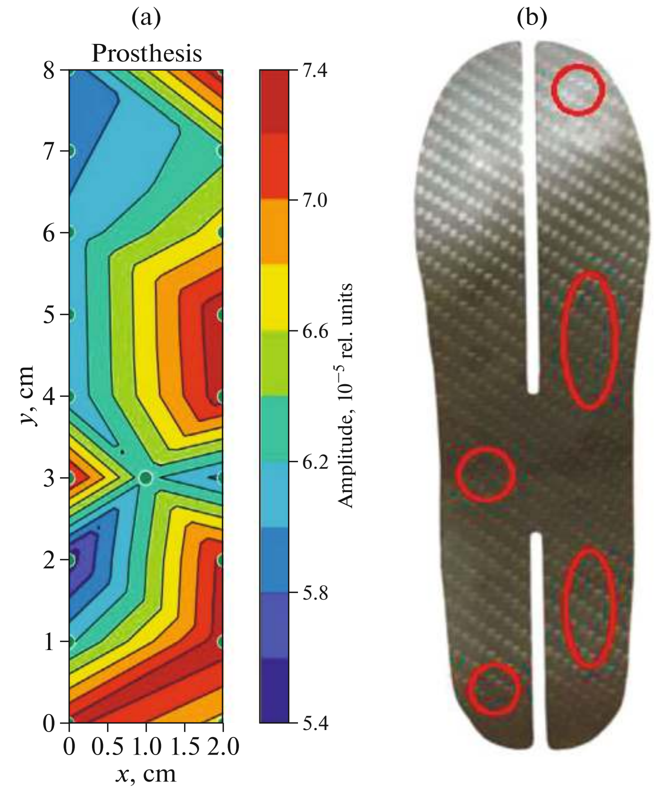

Fig. 8. Amplitude distribution of a sample presented as a single specimen. On the left the areas with increased amplitude values, corresponding to areas with defects in the sample after a fracture are shown; on the right is an approximate display of these areas directly on the sample.

The sample was cut along the right longitudinal axis, according to a known reference system, in order to clearly demonstrate the presence of defects in the test sample, because before cutting the sample, the presence of these defects was not proven, since after the fracture they were not visually observed. We emphasize that the cut was made along the right side, since, referring to the amplitude distribution map in Fig. 8, the greatest content of increased values of amplitude stresses could be observed precisely from this side. In Figs. 10a–10d the images of the sample after fracture with visually indistinguishable defects, as well as with visually distinguishable defects are shown.

In Fig. 5, by comparing the total spectra of two intact samples, one can see the difference in the height and width of the peaks, which may indicate a reduced quality factor and strength characteristics of one sample compared to the other. However, we can assume such reduced characteristics in the third sample in relation to the second, which may be indicated by the formation of an additional peak corresponding to the manifestation of an additional resonant frequency due to the possible appearance of an additional reflection boundary in the third sample and absent in the second one (between two clearly visible peaks).

In Fig. 6, using the example of comparing the total spectra of an intact sample and a sample with a crack, we can conclude that a shift in the values of the resonant frequencies downward for one of them may be due to the fact that this sample has a lower quality factor compared to the other, which may indicate the fact that the object may contain defects that can cause energy loss, because they can lead to increased losses due to friction, vibration, etc., and, as a result, to reduced strength of the product.

In Fig. 7, in turn, by comparing the total spectra of an intact sample and a sample with a crack in a single specimen, one can observe the appearance of additional peaks corresponding to the resonant frequencies of the defective product, which indicates the appearance of additional reflection boundaries due to the occurrence of breaks in its structure.

According to the amplitude distribution shown in Fig. 8, one can see the areas of increased amplitude values, which may indicate problem areas in which hidden defects are present. The sizes of areas with the highest values of amplitude stresses, marked in red, can indicate the size of defects in the test sample (of the order of 1–2 cm).

(a) (b)

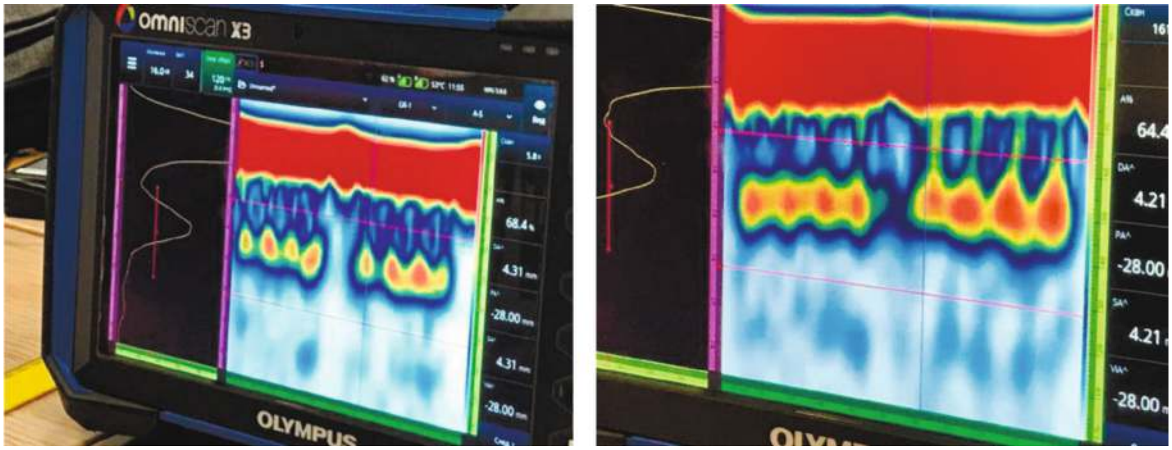

Fig. 9. Amplitude distribution of two intact samples obtained with the OLYMPUS OmniScan X3 device. On the left is the 2nd sample (more durable), on the right is the 3rd one (less durable).

(a) (b) (c) (d)

Fig. 10. (a) Image of a sample after a fracture with visually indistinguishable defects (top view); (b) image of a sample after a fracture with visually indistinguishable defects (side view); (c) image of the sample after fracture with visually distinguishable defects (top view); (d) image of the sample after fracture with visually distinguishable defects (side view).

According to the amplitude distribution shown in Fig. 9, one can see a comparison of the amplitude distribution maps, where a pair of intact feet details from one batch was visible: one, as we knew from the analysis of the spectra, was the strongest of all and one with a crack:

– without paying attention to the “dead zone” at the top of the map, we can say that the brightest areas indicate the presence of some reflection boundaries in the products, and the intensity of their expression indicates their larger size and quantity in a less durable sample in comparison with a more durable one;

– a larger area of blue zones at the bottom of the map in a less durable sample compared to more durable one indicates an increased number of bubbles in the first sample, which is most likely due to the formation of swelling areas during the gluing process of products.

Figures 10a, 10b show 2 images of a defective sample obtained as a result of the fracture procedure (top view and side view). The images are shown to indicate the visual indistinguishability of defects.

Figures 10c, 10d show 2 images of a defective sample obtained as a result of the fracture procedure and subsequent cutting with a cutting disk 1.2 mm thick (top view and side view). On the sample (side view), one can observe defects approximately localized in zones according to the obtained amplitude distribution map in Fig. 8.

CONCLUSIONS

During the research, experiments were conducted to study the composite material using the standing waves method. The purpose of the work was to study the possibility of detecting defects in the foot details made of composite material using this method. As a result of the experiments, it was found that the amplitude-frequency spectra of the composite material have different shifts depending on the presence of defects: the values of the resonant frequencies of defective samples were lower than the frequencies of the spectra of the intact ones, which may indicate that the defective material has reduced strength indicators. Also, when studying some samples, the presence of additional resonance peaks was noted, which indicates the appearance of new reflection boundaries corresponding to the manifestation of defects in the test samples.

The obtained maps of amplitude distributions indicate the possibility of localizing defects in the test samples. Obtaining maps of amplitude distributions using the OmniScan X3 device manufactured by OLYMPUS company confirms the presence of hidden defects in the test samples. These findings may indicate the possibility of successful application of the standing waves method as an alternative method of non-destructive testing of products made of composite material, through which it becomes possible to detect and localize hidden defects in the shortest possible time, saving the resources and time spent on this, and when they are detected, it is advisable to use other control methods, studying them in more detail, in particular, with the purpose of clarifying the characteristics of the defects sought.

The resulting images after cutting the defective sample clearly demonstrate the presence of defects in it with approximate localization in areas according to the amplitude distribution map.

So, to determine the suitability of an object, it is advisable to use the following approach: use an ultrasonic device that allows one to view an arbitrary set of details, for example, 5–10 samples from a batch and make sure that the samples can be considered sufficiently intact. Then determine points on the sample, usually antinodes, at which the resonance characteristic will have maximum amplitude. Compare the resulting spectrum, where frequency and amplitude values can serve as informative parameters, with the spectrum of the next sample, and if they coincide (within up to 2% in frequency and amplitude at the discretion of the details manufacturer), then these samples can be considered identical.

This approach will allow one to quickly and accurately determine which object is suitable and which needs to be replaced or additionally checked.

FUNDING

This study was performed as the part of the basic project FWZZ-2022-0017.

CONFLICT OF INTEREST

The authors declare no conflict of interest related to this work.

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