

# Influence of Geometry and Boundary Conditions in Area of the Cohesion between Materials on the Reflection of an Ultrasonic Beam. Part 2. Features of Experimental Simulation

A.R. Baev<sup>1</sup>, N.V. Levkovitch<sup>2</sup>, M.V. Asadchaya<sup>1</sup>, A.L. Mayorov<sup>1</sup>, G.I. Razmyslovich<sup>1</sup>, A.Y. Burnos<sup>1</sup>

<sup>1</sup>*Institute of Applied Physics of the National Academy of Science of Belarus,  
Akademicheskaya str., 16, Minsk 220072, Belarus*

<sup>2</sup>*Belarusian State University,  
Nezavisimosti Ave., 4, Minsk 220030, Belarus*

Received 21.10.2021

Accepted for publication 09.12.2021

## Abstract

Improving the efficiency of diagnostics of objects with layered structure as applied to detection of poorly detectable material bonding defects is an important production task. The aim of the work was to experimentally simulate ultrasonic scattering by samples of proposed defect simulator designs with discretely and smoothly varying boundary conditions correlating with the phase response of longitudinal waves during their interaction with the defect boundary of contacting materials.

A brief analysis of some methods and means for experimental simulation of the volume and surface wave scattering at the interfaces of contacting materials as applied to improvement of method of detection of poorly detectable adhesion defects of materials proposed earlier was carried out. For this purpose an immersion installation working in the shadow mode and allowing for simulation the spatial fields of scattered longitudinal waves at inhomogeneous or defective adhesion boundaries was developed and constructed. It is assumed that the waves interacting with such a boundary acquire a discrete or smoothly varying phase shift which significantly affects the formation of the scattering field in its peripheral zone. The greater this shift, the stronger these changes are, which can significantly increase the sensitivity of detection of poorly detected defects.

In order to increase the efficiency of such inspection and to develop its methodology a new principle of simulation of such defects has been proposed.

Experimental study of longitudinal waves scattering using the developed installation and defect simulators, simulating discretely and smoothly changing boundary conditions which are consistent with a change in the phase shift of the scattered waves is carried out. The amplitude dependences of the scattering field vs. the receiving angle received mainly in the range from  $-20^\circ$  to  $+20^\circ$  and the displacement of the simulated defect relative to the axis of the probing acoustic beam were obtained.

As it has been established, there is a quality conformity between the calculated and experimental data. The present study is of interest for solving a number of tasks of increasing efficiency of ultrasonic testing of modern objects with layered structure and will contribute to practical application.

**Keywords:** ultrasonic wave scattering, non-uniform boundary conditions, defect simulator, phase shift, acoustic load.

**DOI:** 10.21122/2220-9506-2021-12-4-301-310

---

### Адрес для переписки:

Баев А.Р.  
Ин-т прикладной физики Национальной академии наук Беларуси,  
ул. Академическая, 16, г. Минск 220072, Беларусь  
e-mail: baev@iaph.bas-net.by

### Address for correspondence:

Baev A.R.  
Institute of Applied Physics of the National Academy of Science of Belarus,  
Akademicheskaya str., 16, Minsk 220072, Belarus  
e-mail: baev@iaph.bas-net.by

---

### Для цитирования:

A.R. Baev, N.V. Levkovitch, M.V. Asadchaya, A.L. Mayorov,  
G.I. Razmyslovich, A.Y. Burnos.  
Influence of Geometry and Boundary Conditions in Area  
of the Cohesion between Materials on the Reflection of an Ultrasonic  
Beam. Part 2. Features of Experimental Simulation.

Приборы и методы измерений.

2021. – Т. 12, № 4. – С. 301–310.

**DOI:** 10.21122/2220-9506-2021-12-4-301-310

---

### For citation:

A.R. Baev, N.V. Levkovitch, M.V. Asadchaya, A.L. Mayorov,  
G.I. Razmyslovich, A.Y. Burnos.  
Influence of Geometry and Boundary Conditions in Area  
of the Cohesion between Materials on the Reflection of an Ultrasonic  
Beam. Part 2. Features of Experimental Simulation.

*Devices and Methods of Measurements.*

2021, vol. 12, no. 4, pp. 301–310.

**DOI:** 10.21122/2220-9506-2021-12-4-301-310

# Влияние геометрии и граничных условий в области сцепления материалов на рассеяние ультразвуковых волн. Ч. 2. Особенности экспериментального моделирования

А.Р. Баев<sup>1</sup>, Н.В. Левкович<sup>2</sup>, М.В. Асадчая<sup>1</sup>, А.Л. Майоров<sup>1</sup>, Г.И. Размыслович<sup>1</sup>, А.Ю. Бурнос<sup>1</sup>

<sup>1</sup>Институт прикладной физики Национальной академии наук Беларуси,  
ул. Академическая, 16, г. Минск 220072, Беларусь

<sup>2</sup>Белорусский государственный университет,  
пр-т Независимости, 4, г. Минск 220030, Беларусь

Поступила 21.10.2021

Принята к печати 09.12.2021

Повышение эффективности акустической диагностики объектов со слоистой структурой применительно к выявлению слабо выявляемых дефектов сцепления материалов является важной производственной задачей. Цель работы состояла в экспериментальном моделировании рассеяния ультразвуковых волн на образцах предложенных конструкций имитаторов дефектов с дискретно и плавно изменяющимися граничными условиями, коррелирующими с фазовой характеристикой продольных волн в процессе их взаимодействия с дефектной границей контактирующих материалов.

Проведён краткий анализ некоторых методов и средств экспериментального моделирования рассеяния объёмных и поверхностных волн на границах контактирующих материалов применительно к совершенствованию метода обнаружения слабо выявляемых дефектов сцепления (адгезии) материалов. Для этого разработана и изготовлена иммерсионная установка, работающая в теновом режиме и позволяющая моделировать пространственные поля рассеянных продольных волн на неоднородной или дефектной границе сцепления материалов. Как предполагается, взаимодействующие с такой границей волны приобретают дискретный или плавно изменяющийся фазовый сдвиг, существенно сказывающийся на формировании поля рассеяния в его периферийной зоне. Увеличение же этого сдвига позволяет значительно повысить чувствительность обнаружения слабо выявляемых дефектов.

Проведено экспериментальное исследование рассеяния продольных волн на разработанной установке и имитаторах дефектов, моделирующих дискретно и плавно изменяющиеся граничные условия, которые согласуются с изменением фазового сдвига рассеиваемых волн. Получены амплитудные зависимости поля рассеяния в зависимости от угла их приема в диапазоне от  $-20^\circ$  до  $+20^\circ$  и смещения центра моделируемого дефекта относительно оси зондирующего акустического луча. Как установлено, наблюдается качественное соответствие между расчётными и опытными данными.

Настоящие исследования представляют интерес для решения ряда задач по повышению эффективности ультразвукового контроля современных объектов со слоистой структурой и будут способствовать расширению возможностей использования предложенного метода.

**Ключевые слова:** ультразвуковые волны, рассеяние ультразвука, неоднородные граничные условия, имитатор дефекта, фазовый сдвиг.

**DOI:** 10.21122/2220-9506-2021-12-4-301-310

**Адрес для переписки:**

Баев А.Р.

Ин-т прикладной физики Национальной академии наук Беларуси,  
ул. Академическая, 16, г. Минск 220072, Беларусь  
e-mail: baev@iaph.bas-net.by

**Address for correspondence:**

Baev A.R.

Institute of Applied Physics of the National Academy of Science of Belarus,  
Akademicheskaya str., 16, Minsk 220072, Belarus  
e-mail: baev@iaph.bas-net.by

**Для цитирования:**

A.R. Baev, N.V. Levkovitch, M.V. Asadchaya, A.L. Mayorov,  
G.I. Razmyslovich, A.Y. Burnos.

Influence of Geometry and Boundary Conditions in Area  
of the Cohesion between Materials on the Reflection of an Ultrasonic  
Beam. Part 2. Features of Experimental Simulation.

Приборы и методы измерений.

2021. – Т. 12, № 4. – С. 301–310.

**DOI:** 10.21122/2220-9506-2021-12-4-301-310

**For citation:**

A.R. Baev, N.V. Levkovitch, M.V. Asadchaya, A.L. Mayorov,  
G.I. Razmyslovich, A.Y. Burnos.

Influence of Geometry and Boundary Conditions in Area  
of the Cohesion between Materials on the Reflection of an Ultrasonic  
Beam. Part 2. Features of Experimental Simulation.

Devices and Methods of Measurements.

2021, vol. 12, no. 4, pp. 301–310.

**DOI:** 10.21122/2220-9506-2021-12-4-301-310

## Introduction

Ensuring high sensitivity of the poorly non-destructive testing of sound-reflecting defects in the area of material joints, including sticking defects, during welding, powder spraying, brazing, bonding operations, etc., is an actual problem. In this case, a small change in the structure of the contacting material boundary may have an impact on the strength and performance characteristics of the products.

Currently, there are a number of approaches to solve such problems analyzing the amplitude and phase shift of the acoustical signal passed or reflected from the materials boundary [1], the change in the signal spectrum, or the resonant frequency of the waves excited in the layered objects [2–4] and etc.

So, traditional inspection techniques are usually based on amplitude methods of reflected (once or repeatedly) or passed acoustic pulses through the boundary of the materials to be joined (BMJ). In this case the echo or the echo-through method is used to create of optimal conditions for propagated through BMJ acoustic signal in time, that leads to change of signal amplitude in  $A/A_0 \sim (D_{12}D_{21})^m$  times, where  $D_{12}$  and  $D_{21}$  are coefficients of sound propagation through materials boundary in forward and backward direction respectively.

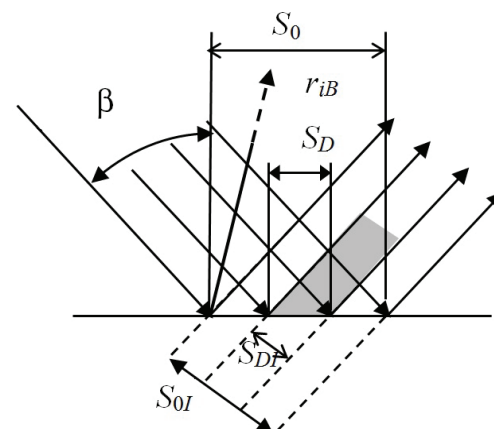
If the ultrasonic waves (UW) emitting surface  $S_0 > S_D$  and there is a phase shift for the acoustic beam passing through the fault area of the edge of the materials to be joined, then the estimation of its quality can be significantly affected by the instability of the acoustic contact due to the specific working conditions of the UW probe, geometry and surface roughness of the object under inspection. All these factors will also influence the above-mentioned ways of object sounding.

Significant difficulties arise at diagnostics of welded seams of plastic materials of rather large items nomenclature, including gas polyethylene pipes of low and medium pressure, that have low velocity and high attenuation of UW bonding [5–7]. It was suggested to use possible correlation between detected pores and most dangerous adhesion defects (of “kiss-bond” type) to find defective zones of poor bonding of joined materials, which should be achieved by echo-mirror sounding of the object using a so-called the chord probes of longitudinal waves, incident at the maximum possible angle to the normal of the welding surface [7]. However, conclusive data on this correlation are lacking.

It should be noted that not only volume but also highly efficient elastic modes propagating along the boundary of contacting materials, including Rayleigh waves, Stoneley waves, and plate waves, are used to control layered objects. In this case, the violation of the quality of adhesion of materials is accompanied in one way or another by a change in the amplitude or velocity of the wave, measured by the change in the time delay or phase of the wave. Some features of changing these parameters are presented, for example, in [8–12].

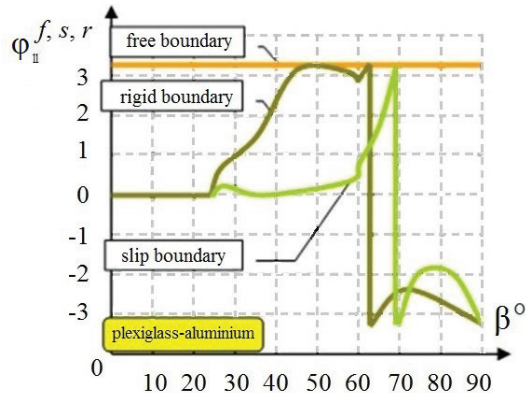
Based on theoretical and experimental simulation the determination of optimal conditions to emit and receive of scattered waves, including the angles of wave receiving and emitting, dynamic changes in the aperture and position of the wave source, etc., contributes to establishing the relationship between the state of the contact layer structure, its physical and mechanical characteristics and the acoustic parameters of the scattered mode. On the other hand, it is of scientific interest for acoustics of layered media too.

In paper [13] was proposed the method to find poorly detectable defects of material bonding where, all other things being equal the phase shift  $\Delta\varphi = \varphi_N - \varphi_D$  between waves passed or reflected from defective ( $S_D$ ) and non-defective ( $S_N$ ) place of BMJ is used as the most significant and sensitive acoustical parameter, depending on mechanism of the elastic wave interaction with the interface boundary region of the materials bonding. (Explanation of ultrasonic waves reflection from interface boundary of materials, where  $S_{0I}$  and  $S_{DI}$  are the surfaces of imaginary wave sources is in Figure 1).



**Figure 1** – Explanation of ultrasonic waves reflection from interface boundary of materials, where  $S_{0I}$  and  $S_{DI}$  are the surfaces of imaginary wave sources

In turn,  $\varphi_N$  and  $\varphi_D$  depend on the angle of incidence of the wave on the respective material bond areas which our calculations show as an example in Figure 2 to demonstrate the calculated dependences  $\varphi(\beta)$  for classical variants – when a longitudinal wave reflects from a free, sliding and rigid boundary of contacting materials.



**Figure 2** – Typical example of reflected wave phase change when varying the angle of incidence  $\beta$  of an acoustic beam on a material interface with different acoustic impedances and classical boundary conditions

For example, when gluing materials, the area in the form of a thin layer of air is a local free boundary or defective one. In this case, if the specific acoustic resistance of the specimen or substrate  $Z_0 > Z_K$ , where the  $Z_K$  is resistance of the material contacting it, and angle of incidence of the wave is close to normal then  $\Delta\varphi \rightarrow \pi$ . So, the discontinuity is easily detected by the traditional method when the dimensions of  $S_D$  and  $S_N$  are comparable. However, at  $S_{DN} = S_D/S_N \ll 1$  and the instability of the acoustic contact of the order of  $\approx 1\text{--}2$  dB and more, caused by the influence of the roughness and curvature of the object surface, as well as the “humanity factor”, which takes place in real conditions of production control, the reliability and validity of the control significantly decreases.

It should be noted that in practice, the evaluation or testing of the adhesion of materials is significantly complicated due to the following. Firstly, it is caused for example by the peculiarities of mutual penetration of materials as a result of mixing, diffusion processes and etc., significantly affecting the structure and the boundary layer thickness, its elastic modulus. Secondly, which is very important and is the subject of our studies, the problem of determination places with insufficient adhesion, in probing of which the amplitude of reflected or transmitted

waves from the defective and defect-free BMJ differ within  $\approx 1\text{--}2$  dB, and is nearly  $\Delta\varphi \approx \pi/2$  and lesser.

In [14] a non-mirror variant of ultrasonic testing of an object by a surface wave taken in the vicinity of the angle of the first minimum of the directional diagram of surface acoustic waves scattered by reflection  $\phi \approx \phi_{\text{min}1}$  has been tested in the echo mode ( $f = 5$  MHz). In this case, the phase shift between the waves reflected from the defective ( $-d < x < d$ ) and defect-free boundary  $\Delta\phi/\pi \approx 0.5$ . It has been found that the change of the signal amplitude  $A(x)$  during the motion of the acoustic beam spot parallel to the simulated surface of materials has reached a maximum value up to  $\approx 25\text{--}30$  dB, when the acoustic axis of the beam is moved in a vicinity of the simulated defect coordinate  $x \rightarrow d$  or  $x \rightarrow -d$ , which is determined by a scanning direction.

It should be noted that the development of testing techniques for objects requires the use of defect samples or defect simulators (DS) that adequately simulate the acoustic path of the measuring system. This is particularly true for the development of DS for detecting poorly detectable material bonding defects. The purpose of this work was to develop a methodology for experimental simulation of ultrasonic scattering processes by a heterogeneous boundary as applied to the detection of defects with poor detectability and to compare the experimental data with the calculated ones.

### Analysis and development of methodology and experimental setup for simulation and study of ultrasonic wave scattering fields by inhomogeneous boundary

#### Analysis of some schemes for simulation of ultrasonic wave scattering processes on the inhomogeneous boundary

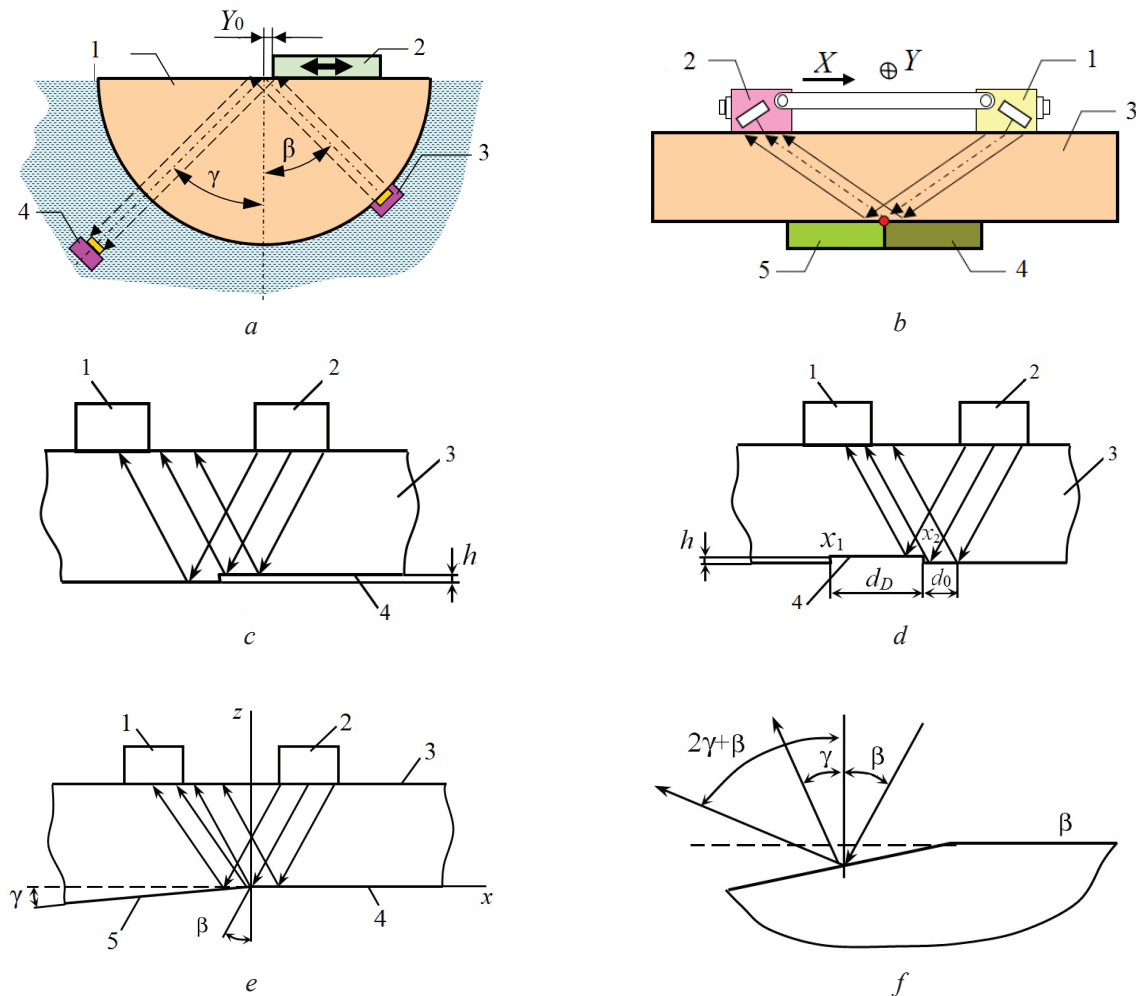
As it was mentioned above, the phase shift  $\Delta\varphi$  between the defect-free ( $S_N$ ) and defect ( $S_D$ ) interface regions, is the most significant, sensitive parameter, characterizing the adhesion processes at material bonding. By selecting optimum conditions of excitation-reception (angles of input-receiving of UW, apertures of probes, operating frequency, etc.) it is possible to provide maximum sensitivity in relation to detection of “minimum defectiveness” of the materials to be joined. According to the proposed model the phase shift between waves interacting with defect and non-defective surface can be not only constant and small enough value, but (as practice shows) change smoothly, i. e.  $\Delta\varphi = \Delta\varphi(x)$ .



I. e., the amplitude of imaginary sources field generated by each local section of surface  $dS$  in the vicinity of spatial coordinate  $x_i$  can be represented as  $A \sim dS \exp[-ikx_i \sin\theta + \Delta\varphi(x_i)]$ , where  $\theta$  is angle between selected vertical direction  $z$  and radius-vector.

In developing of the procedure of modeling of ultrasonic scattering at the inhomogeneous boundary we considered variants, explained by Figure 3, where the presented schemes *a, b, c, d* correspond to condition of detection of defects, separated from each other by clear boundary or by discrete change on it phase shift. And schemes *3e* and *3f* are conditions, when this phase shift changes smoothly, that often

takes place in practice for number of technologies of joining materials and not giving proper attention to developing of non-destructive techniques. When simulating the process according to the diagram in Figure 3*a*, it is possible to determine the spatial distribution of ultrasonic scattering field by easily varying the angle of incidence  $\beta$  of the wave on the sample boundary with acoustic load, although the ability to control the geometry and simulation of a “rigid boundary” and its probing by a transverse mode in the simulation is difficult. These limitations are not present with the other schemes shown in Figure 3.



**Figure 3** – Some simulated schemes of the ultrasonic waves scattering by a non-uniform boundary with discrete (*a, b, c, d*) and smoothly varying (*e, f*) boundary conditions. *a*: 1 – waveguide solid UW specimen; 2 – acoustical load to simulate of UW reflection; 3 – emitting and 4 – UW receiving probes; *b*: 1 – is an UW emitting and 2 – receiving probe, 3 – solid sample, 4 and 5 as a composite solid to reflect UW; (*c, d, e*): 1 is an UW emitting and 2 is receiving probe; 3 – is an waveguide solid sample with simulated defect region on opposite surface 4

As for measurement schemes of Figure 3 (*c, d, e*), the principle of their operation is based primarily on the presence of correlation between the quality

parameters of adhesion of materials and the phase of the reflected wave, which in the general case is a function distributed along the wave front.

It can be easily shown that for the correct use of the proposed model, it is necessary to set restrictions on the geometrical parameters of the simulated defect area, such as  $h_d = \frac{h}{d}$  and  $\lambda_h = \frac{\lambda}{h}$ ,

where  $\lambda$  is the wavelength of the bulk mode;  $h$  is the height of the slit or protrusion. The condition that  $h_d < h_d^*$  and  $\lambda_h < \lambda_h^*$ , where  $h_d^*$  and  $\lambda_h^*$  depends ultrasonic incidence angle on the boundary with the defect, should be observed (Figures 3c and 3e). Their values are determined experimentally from the condition that the scattering energy ( $W_d$ ) of a part of the ultrasonic flux exactly in the vicinity of the lateral boundaries of the model defect  $x \rightarrow \{x_1, x_2\}$  is such that  $W_d \ll W_0$ . In this case the value of simulated acoustic beam phase shift between propagated or reflected UW from defect and non-defective surface  $\Delta\varphi \approx 4\pi h_\lambda (\cos\beta)^{-1}$ . If, on the other hand, the boundary conditions in defect area change smoothly (Figures 3e and 3f), then:

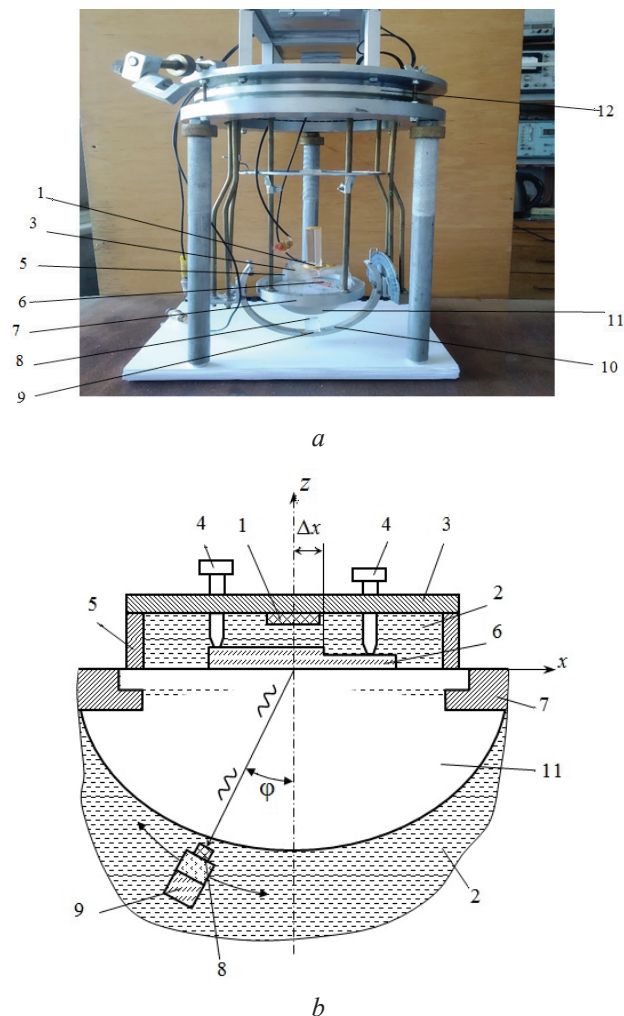
$$\Delta\varphi = \pi \frac{x}{\lambda} \frac{\sin 2\beta \tan \gamma}{(\cos^2 \beta - \sin^2 \beta)} \left( \frac{1}{\cos(2\gamma + \beta)} + \frac{1}{\cos \beta} \right).$$

It should be noted that the above simulation schemes of ultrasonic scattering processes by a heterogeneous boundary are based on the use of an echo mode of object sounding, which is connected with a number of limitations and errors caused by the difficulties of accounting the interaction features of elastic mode with the surface of acoustic load – that has a limited surface and geometry. Although the ultimate goal of the research is to identify precisely the weakly detectable defects, which in the simulation should introduce minimal distortions in the geometry of the reflecting (basic surface) of the body, the losses of ultrasonic modes to the transformation of other modes that create the noise background, etc.

#### Installation for simulation of ultrasonic wave scattering

On the basis of analysis of the acoustic measuring path and the above considered measurement schemes the possibility of simulation of both the ultrasonic propagation and reflection on the types of inhomogeneous boundaries shown in Figure 3. To study, an installation realizing the shadow method of sounding has been developed that is explained by Figure 4 and Figure 5, where an acoustic part and an electronic scheme of experimental setup of the installation are presented, respectively.

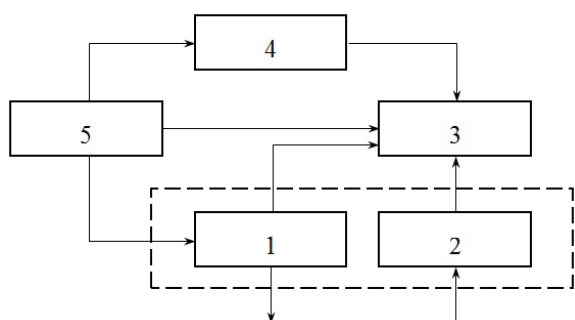
Figure 4 shows the photo of the acoustic part and a scheme explaining the measuring procedure of the spatial field of ultrasonic scattering on the boundary simulated by DS and UW receiving. Data about DS construction are in Figure 4a, b (6 and 7).



**Figure 4** – A photo of the acoustic part the experimental installation (a) and scheme (b) for measurement of the ultrasonic waves field as a result of wave scattering on the simulated defect boundary of joined materials: 1 – ultrasonic waves emitting probe; 2 – water with wetting agents; 3 – base plate; 4 – fixing screws; 5 – supporting pillars; 6 – defect simulator; 7 – base support; 8 – ultrasonic waves receiving probe; 9 – holder mounted on rotating frame; 10 – rotating frame; 11 – hemispherical specimen or body-substrate simulator; 12 – equatorial angle setting mechanism

DS is located on the flat surface of the specimen in the form of a hemisphere and has possibility to move relative to the acoustic axis of the emitting probe, where water with wetting additives and controlled within 0.5 degrees temperature is used as an

immersion liquid to create acoustical contact along the entire path of acoustic signal propagation Plexiglas hemisphere of 86 mm in diameter (specimen) placed on the fixed support is used as a substrate-acoustic conductor through which an acoustic signal is transmitted to the receiver for measurement of the acoustic signal passing through the DS body. A longitudinal wave source with an operating frequency of  $f = 1$  MHz and a diameter of 13.5 mm is placed at a distance of 20 mm from flat surface of the hemisphere. Non-directional ultrasonic prober of 3 mm in diameter is made with possibility of rotation both in horizontal and vertical planes and angles fixing with an error not more than 1 degree.



**Figure 5** – Electronic scheme of experimental installation: 1 – bell-shaped pulse generator; 2 – amplifier; 3 – double-beam oscilloscope; 4 – measuring generator; 5 – time-shift meter

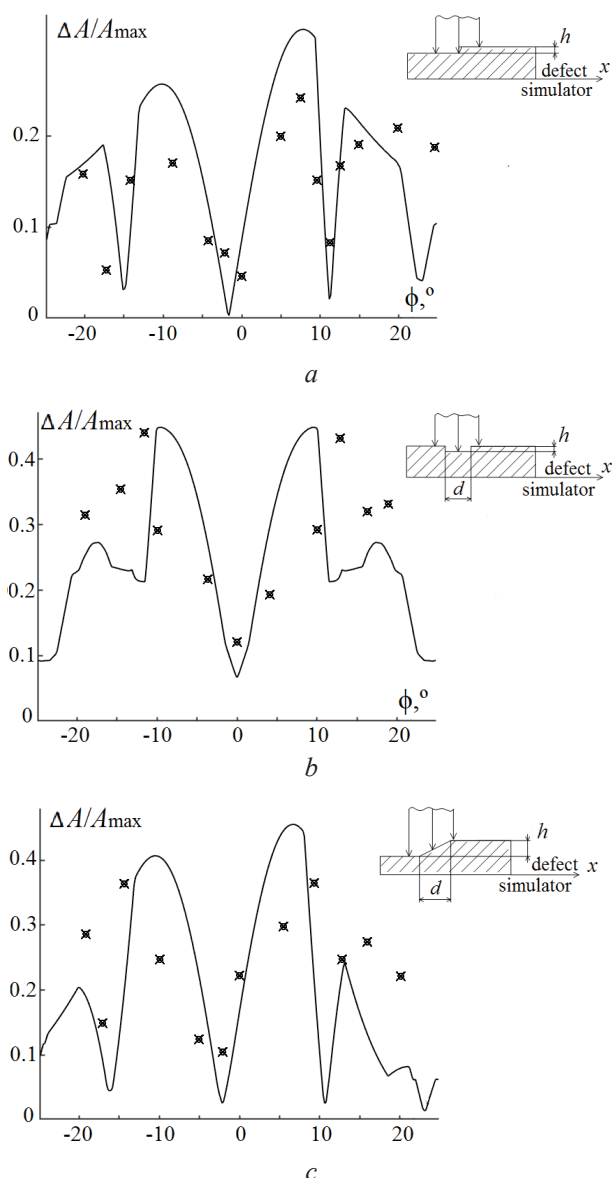
The electronic scheme of experimental setup is in Figure 5 and used to receive and excite of UW described in contains a generator of bell-shaped pulses with the number of oscillations  $N = 5$  and an electric signal receiver. The measuring complex is based on standard devices. As a source 1 and amplifier 2 of the probing signal are the corresponding units of an ultrasonic flaw detector UD2-12. From the output of the amplifier 2 signals go to one of the screens of the two-beam digital oscilloscope. On the second scan the reference signal from the measuring generator 4 is fed to determine the amplitude of the probing signal by comparison method. Simultaneously, by giving an electrical pulse from the output of the flaw detector generator 1 to the second scanning channel of the oscilloscope 3 (through a divider), the stability of the amplitude and shape of the pulse in time is controlled. Synchronization of the circuit operation is performed by the device I2-26 (5). With its help a delay and sweep of a probing impulse and measurement of time intervals are performed on the oscilloscope screen. This scheme allows during measurements to make complex observations of

pulse parameters, including amplitude, waveform, phase, as well as to obtain spectral characteristics of the signal, changes in which are caused by scattering of UW from an inhomogeneous boundary.

## The results of study and discussion

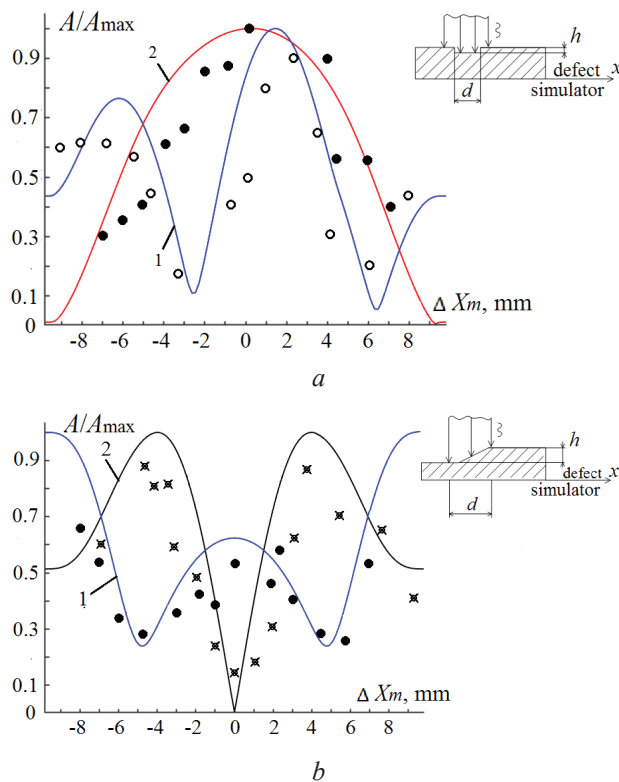
The results of analysis of the given schemes of experimental simulation, the researches of peculiarities of ultrasonic scattering of elastic waves on the inhomogeneous boundary and the data of the first (theoretical) part of this work, indicate the possibility of using the method based on optimization of apertures and phases of imaginary ultrasonic sources, scattered by inhomogeneous boundary to determine weakly detectable defects. Thus, attention is paid to necessity of researches connected with simulation of features of ultrasonic scattering on the DS. The latter are characterized that as objective parameter correlating with quality of material joining and determined beforehand is used exactly phase shift  $\Delta\phi$  of scattered waves on defects with homogeneous ( $\Delta\phi = \text{const}$ ) or varying  $\Delta\phi = \Delta\phi(x)$  in their area boundary conditions. This enables the identification of optimum conditions for maximum sensitivity of the method, including the wave mode and its frequency the angles of wave incidence on the media boundary and receiving in the meridian and equatorial planes of the scattering field cross section diagram directivity as applied to the non-destructive testing of a particular object.

The main results of investigations or simulations of acoustic path are shown in Figures 6 and 7, where the dimensionless amplitude characteristics of the scattering field at the defect simulators are studied with respect to conditions of ultrasonic scanning. It is realized by displacement of DS plate relative to acoustic axis of wave source. As can be seen, in this case, three types of defects are simulated with the DS: two discrete and one with smoothly varying boundary conditions, which is characterized by a linearly varying phase shift along the wave front. The experimental and calculated dependencies presented in Figure 6 correspond to the condition when amplitude parameter is to study,  $A/A_0 = (A_{\max} - A_{\min})/A_0$ , where  $A_{\max}$  and  $A_{\min}$  are the extreme values of amplitudes of scattered UW during the whole period of DS movement relative to the acoustic beam spot for fixed receiving angles whose range of variation is  $-20^\circ - +20^\circ$  and  $A_0$  corresponds to the reference signal measured without the simulated defects with UW receiving angle  $\phi = 0$ .



**Figure 6** – Calculated and experimental data of the maximum difference of amplitudes of the acoustic scattering field on the defect simulator with the geometry shown in the figure, depending vs. angle of receiving of ultrasonic waves, where  $A_0$  corresponds to the reference signal measured for  $\phi = 0^\circ$  and  $h = 0$ :  $h$ , mm = 0.41 (a), 0.43 (b), 0.83 (c);  $d$ , mm =  $\infty$  (a), 4.95 (b), 5.1 (c)

Figure 7 illustrates the characteristic dependencies of scattered wave amplitudes vs. distance of the simulated defect from the acoustic axis of the incident acoustic beam. As it was found that as a result of acoustic wave diffraction at DS there are angles of ultrasonic wave receiving lying in the range of  $10^\circ < \phi < 25^\circ$  or  $-25^\circ < \phi < -10^\circ$  where the value of  $A/A_{\max}$  can reach up to 15–20 dB and more, exist, which is qualitatively consistent with the calculated data.



**Figure 7** – Calculated and experimental dependencies characterizing changes of normalized amplitude of ultrasonic waves scattering field vs. displacement of the defect simulator relative to the axis of the acoustic beam falling on it for two angles of wave receiving: a)  $20^\circ$  (1);  $13^\circ$  (2); b)  $20^\circ$  (1) and  $-20^\circ$  (2);  $h$ , mm = 0.43 (a), 0.83 (b);  $d$ , mm = 4.95 (a), 5.1 (b)

At the same time, it is necessary to pay attention to some difference between the experimental and calculated data obtained. Apparently, it is first of all related to a different form of the emitted signal, which in the experimental simulation is pulsed (5 oscillation per pulse), while in the calculations is continuous. In addition, no attention was paid to the fact that  $H/R = 0.07-0.08$ , where  $H$  is the thickness of the DS plate in contact through the contact lubricant with the flat surface of a hemispherical specimen with radius  $R$ . It naturally may affect the character of interference phenomena and formation the resulting field of the longitudinal waves scattered at DS. In this case, according to [1] there is a widening of the diagram directivity and “smoothing” of the course of the curves outside the angle of the main lobe of the diagram directivity opening.

Thus, the above distinction must be taken into account when simulation of the acoustic path in relation to improving the methods of testing of poorly detectable defects in the adhesion of materials.



Nevertheless, the obtained research data confirm the possibility of using the proposed method of experimental modelling and means of imitating defects at the preliminary stage of preparing the methodology of control of fixed joints. It should be noted that in modelling the above phase shift, caused by the difference between the interaction of elastic vibrations with defective and defect-free surface (and, as expected, correlated with the effectiveness of adhesion of materials), the minimum value of  $\varphi^* = \Delta\varphi/\pi \approx 0.22$ . Additional experimental investigations have shown that reducing the value of  $\Delta\varphi$  with respect to those mentioned above by a two time or more makes it possible to select the optimum conditions under which the level of change in the scattering field amplitude of UW of the simulated defects is quite sufficient for their detection.

The experimental data obtained confirm the possibility of using the proposed method of experimental simulation and the use of defect simulation tools at the preliminary stage of developing a method of testing weakly detectable defects in permanent joints made by soldering, welding, spraying, gluing and etc.

## Conclusion

A brief analysis of some methods and means for experimental simulation of longitudinal waves scattering at the interfaces of contacting materials with reference to the improvement of the previously proposed method for detection of poorly detectable adhesion defects of materials is given. Some patterns of ultrasonic wave reflection from inhomogeneous boundary created by an acoustic load, including those modeled by changing the geometry of the reflecting surface, are analysed.

For the first time the principle and designs of defect imitators have been proposed with regard to the development of a technique that allows significantly increasing the efficiency of detecting poorly detectable defects in the adhesion of materials, which is based on the idea of a stable relationship between the bonding quality of materials and the phase shift between waves reflected or passed through the defective and non-defective sections of the bond interface.

The installation and technique of measurements of the longitudinal wave scattering field in the pulse mode, realized by the shadow method at an operating frequency of 1 MHz when the spot of the probing acoustic beam moves relative to the defect si-

mulators of semi-infinite and finite width in the presence of a discrete and linearly variable in the defect area phase shift of up to  $\approx 40^\circ$ , have been developed. For the above defect simulators in the scanning mode the amplitude dependences of the longitudinal wave scattering field on the value of their reception angles have been obtained, principally in the range from  $-20^\circ$  to  $+20^\circ$ , and changes in the distance between the acoustic beam spot and the defect simulator. It was found that the maximum change in signal amplitude, characterizing the presence of a simulated defect, changes by 15–20 dB and more, and is observed in the peripheral region of the scattering field angles.

The experimental simulation data have been compared with the calculated dependences obtained in the axial approximation. It is found that there is a qualitative correspondence between them, and the existing difference is supposed to be caused by different forms of the probing signal (continuous and pulse), by the influence of the thickness of the defect simulator plate placed on the hemispherical sample and the attenuation of ultrasound in it, as well as by the hardware error.

The experimental data obtained confirm the possibility of using the proposed method of experimental simulation and the use of defect simulation tools at the preliminary stage of developing a method of testing weakly detectable defects in permanent joints made by soldering, welding, spraying, gluing.

## References

1. Nondestructive Testing: Handbook: In 7 vols. Ed. V.V. Klyuev. Moscow: Mashinostroenie Publ., 2003, vol. 3, 864 p.
2. Lavrentyev A.I., Rochlin S.I. Ultrasonic spectroscopy of imperfect interfaces between a layer and two solids. *J. Acoust. Soc. Amer.*, 1998, vol. 103, pp. 657–664.
3. Santo J.B., Santon M.J. Ultrasonic interferometry for the evaluation of thickness and adhesion of thin layers. Abstracts of 4<sup>th</sup> International Conference on NDT, China, Greece, 2007, p. 22.
4. Chambers J.K., Tucker J.R. Bound line analysis using swept-frequency ultrasonic spectroscopy. *Insight*, 1999, vol. 41, no. 3, pp. 151–155.
5. Kruger S.E., Lord M., Levesque D., Bakker A.J. Detection of kissing bond in extruded aluminum by laser-ultrasound. *Review of Progress in Quantitative Nondestructive Evaluation*. Golden, Colorado, 2007, vol. 975, pp. 279–285.
6. Bostrom A., Wikcham G. On the boundary conditions for ultrasonic transmission by partially closed crack.

DOI: 10.1063/1.2902670

*Journ. Non-Destruct. Eval.*, 1991, iss. 10, pp. 139–149.

**DOI:** 10.1007/BF00567096

7. Giller G.A., Mogilner L.Yu., Khomenki V.I. Ultrasonic chord probes for flaw detection of welded butt pipelines. *Testing. Diagnostics*, 2000, no. 9, pp. 22–47.

8. Pecorary C. Scattering of a Rayleigh wave by a surface-breaking crack with faces in partial contact. *Wave motion*, 2001, vol. 33, pp. 259–270.

**DOI:** 10.1016/S0165-2125(00)00070-6

9. Drinkwater B., Dwyer-Joyce R., Cawley P. A study of the transmission of ultrasound across solid-rubber interfaces. *J. Acoust. Soc. Amer.*, 1997, vol. 101, iss. 2, pp. 970–981. **DOI:** 10.1121/1.418055

10. Kim H.-J., Song S.-J., Kim D.-Y., Kwon S.-D. Evaluation of thin coating layers using Rayleigh-like waves. *Review of Progress in Quantitative Nondestructive Evaluation*. Golden, Colorado, 2007, vol. 975, pp. 1066–1073. **DOI:** 10.1063/1.2902550

11. Abbakumov K.E., Konovalov R.S. Influence of violation of acoustic contact on the distribution of

Stoneley waves near the boundary of solid half-spaces. *Russian Journal of Nondestructive Testing*, 2008, no. 44, pp. 196–201. **DOI:** 10.1134/S1061830908030054

12. Jerzak W., Siegman W.L., Collinz H.D. Modeling Rayleigh and Stoneley Waves and other Interface and Boundary Effects with the Parabolic Equation. *J. Acoust. Soc. Amer.*, 2005, vol. 117, iss. 6, pp. 3497–3503.

**DOI:** 10.1121/1.1893245

13. Baev A.R., Asadchaya M.V. Features of the reflection of an acoustic beam from a surface with non-uniform boundary conditions. Part 1. Theoretical analysis. *Russian Journal of Nondestructive Testing*, 2010, vol. 46, no. 8, pp. 547–558.

**DOI:** 10.1134/S1061830910080012

14. Baev A.R., Levkovich N.V., Mayorov A.L., Asadchaya M.V. [Scattering of Elastic Waves by an Inhomogeneous Boundary in the Acoustic Testing of Permanent Joints]. *Devices and Methods of Measurements*, 2019, vol. 10, no. 4, pp. 360–372 (in Russian).

**DOI:** 10.21122/2220-9506-2019-10-4-360-372