**DOI:** 10.21122/2220-9506-2025-16-2-109-120

# Distant Excitation of Rotating Surface Waves in Bodies with Cylindrical and Spherical Surface as Applied to Ultrasonic Control

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*Received 24.04.2025*
*Accepted for publication 17.06.2025*

**Abstract**

Increasing the efficiency of ultrasonic diagnostics and objects with curved surfaces, including cylindrical, spherical, etc., is an important scientific and technical task. The aim of the work was to develop a technique and experimentally investigate the excitation of surface rotating waves on cylindrical and spherical samples in contact with a metal substrate (support) using the proposed remote sounding method, where the substrate serves as an acoustic delay line for transmission-reception of signals between transducers and the object of investigation. The acoustic path of the suggested measuring scheme operating in shadow and echo modes has been analyzed and the dependences of the amplitude and velocity of the surface rotating waves excited in cylindrical steel and dural samples on their radius $r$, wave frequency $\nu$ and the number of revolutions $n$ of the wave, while varying the angular wave number in the range $p = 2\pi r/\lambda = 20–125$ have been experimentally revealed. The quasi-linear growth of the wave attenuation coefficient from the sample diameter at frequencies $\nu = 1–5$ MHz has been experimentally established. The growth of the distance travelled by the wave is accompanied by a drop in the amplitude of the wave according to a law close to the exponential law, reaching the greatest attenuation with a decrease in $r$. The change in the surface rotating waves velocity in the specified range of variation $p$ did not exceed 1.5–2 %, increasing with decreasing sample radius and wave frequency. The obtained experimental data on the peculiarities of changes in the parameters of acoustic impulses during the passage of surface rotating waves through the crack and the model coatings of the specimens indicate the possibility of using the proposed method for the control of objects of the specified shape.

**Keywords:** distant acoustic control, surface rotating waves (SRW), wave scattering (SAW) and coefficients of their passage and reflection, acoustic load body (ALB), wave amplitude and velocity

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***Для цитирования:***
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***For citation:***
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# Дистанционное возбуждение вращающихся поверхностных волн в телах с цилиндрической и сферической поверхностью применительно к ультразвуковому контролю

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*Поступила 24.04.2025*
*Принята к печати 17.06.2025*

Повышение эффективности ультразвуковой диагностики объектов с криволинейной поверхностью, включая цилиндрическую, сферическую и др., является важной научно-технической задачей. Цель работы состояла в разработке методики и экспериментальном исследовании возбуждения поверхностных вращающихся волн на контактирующих с металлической подложкой (опорой) образцах цилиндрической и сферической формы, используя предложенный дистанционный способ прозвучивания, где подложка служит в качестве линии акустической задержки для передачи-приёма сигналов между преобразователями и объектом исследования. Проанализирован акустический тракт предложенной измерительной схемы, работающей в теневом и эхо режимах, и экспериментально выявлены зависимости амплитуды и скорости возбуждаемых в цилиндрических стальных и дюралевых образцах поверхностных вращающихся волн от их радиуса $r$, частоты волны $\nu$ и числа оборотов $n$ волны, при варьировании углового волнового число в диапазоне $p = 2\pi r/\lambda = 20–125$. Экспериментально установлен квазилинейный рост коэффициента ослабления волны от диаметра образца на частотах $\nu = 1–5$ МГц. Рост пройденного волной расстояния сопровождается падением амплитуды волны по закону, близкому к экспоненциальному, достигая наибольшего ослабления с уменьшением $r$. Изменение же скорости поверхностных вращающихся волн в указанном диапазоне варьирования $p$ не превысило 1,5–2 %, возрастая с уменьшением радиуса образца и частоты волны. Полученные опытные данные об особенностях изменения параметров акустических импульсов при прохождении поверхностных вращающихся волн через трещину и модельные покрытия образцов свидетельствуют о возможности применения предложенного способа для контроля объектов указанной формы.

**Ключевые слова:** дистанционный акустический контроль, поверхностные волны (ПАВ), включая вращающиеся (ПВВ), рассеяние волн и коэффициенты их прохождения и отражения, тело акустической нагрузки (ТАН), амплитуда и скорость волны

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## Introduction

A significant number of objects of modern industrial production have curvilinear surface, including cylindrical, spherical, etc., non-destructive testing of which can be carried out by electromagnetic, current-vortex, ultrasonic and other methods, including visual and thermal [1]. So, the solution of a number of problems associated with the establishment of physical and mechanical properties of the surface layer of the object subjected to surface hardening [1], the presence of sinks, cracks, both emerging on the surface and located under it, as a rule, is carried out by placing the primary transducers near the object of control. Then the transducers move or scan the surface of the object, which affects the quality and reliability of control, its productivity. In particular, this applies to quite effective acoustic contact or immersion methods of control, using weakly damped Rayleigh surface waves (RW) or similar to them (in structure) as probing and excited by transducers with the angle of the piezoelectric transducers (PETs) prism $\beta = \arcsin(C/C_R)$, where $C$ and $C_R$ are the velocities of the longitudinal wave in the PET prism and Rayleigh wave in the substrate, respectively [1].

In addition, in some works carried out both abroad [1] and in Institute of Applied Physics of the National Academy of Science of Belarus, small aperture PETs have been successfully used for wave scattering (SAW) excitation-reception [1]. With their help it is possible to determine the quality of the layer hardened by thermal or chemical-thermal treatment or its depth regardless of the ratio of SAW velocities in the base of objects having curved surfaces, as well as to assess the degree of damage to metals, the quality of coatings, etc. using correlation characteristics. Nevertheless, the disadvantage of the mentioned methods and means of control is that at "local" movement of the above transducers on the curved surface of the object the productivity and reliability of control is not high enough due to the need to ensure quality acoustic contact, orientation of the transducers, etc., as well as the need to ensure the quality of the acoustic contact. Despite the successes achieved through the use of new techniques and devices, including, for example, phased arrays [2, 3], as well as methods of mathematical processing of scattering fields on the defective structure, the expansion of technical capabilities and efficiency of SAW for the control of a wide range of objects with curved surfaces is an important scientific and technical task.

Note also that the application of non-contact methods of control, including electromagnetic-acoustic and pulse-laser [5, 6], also have limitations due to the properties of the object and the complexity of the application of measuring instruments, for example, when coating the product, soldering, welding, hardening of the surface layer, etc. [5]. In this paper we suggest the idea of controlling objects with curved surfaces using surface rotating waves (SRW) by their distant excitation by Rayleigh waves. The latter are transmitted through a sound-conducting substrate (base) serving as a delay line between PETs and the object under investigation, which is an acoustic load body (ALB). It should be noted that a similar sounding scheme was previously applied by us to study the peculiarities of SAW passage through the boundary of sliding and rigid contact of the substrate surface and prism (also ALB) having different angles of inclination of side faces [7]. We studied the peculiarities of the influence of boundary conditions on the acoustic path with respect to the process of joining materials and showed that the shape of the prism has a significant influence on the function of SAW passage through the sliding contact region of these bodies and their "reflectivity" determined by the ratio of reflection coefficients from the above mentioned ALB contact boundaries.

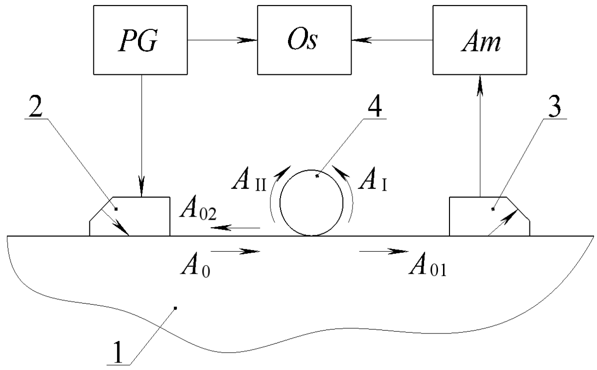
In addition, scattering of SAW on the mentioned boundaries is accompanied by the appearance of SAW fluxes propagating along the side surfaces in the vertical plane of the prism towards each other. As it is supposed, a similar effect should appear in the case considered below – at the contact of a substrate with ALB having the form of a cylinder and a sphere. This area of acoustic contact in the main plane of section is similar to a liquid wedge. And one of its surfaces is curvilinear, which, naturally, should affect the amplitude parameters of scattered waves.

Thus, the results of our earlier studies concerning mainly the SAW passage through the sliding boundary of the substrate with ALB in the form of a prism [7, 8], as well as other works, for example [9, 10], aimed at studying the SAW propagation on a cylindrical surface with a source and receiver of waves located on it, served as a basis for the development of the proposed method of remote ultrasonic control of objects with a curved surface.

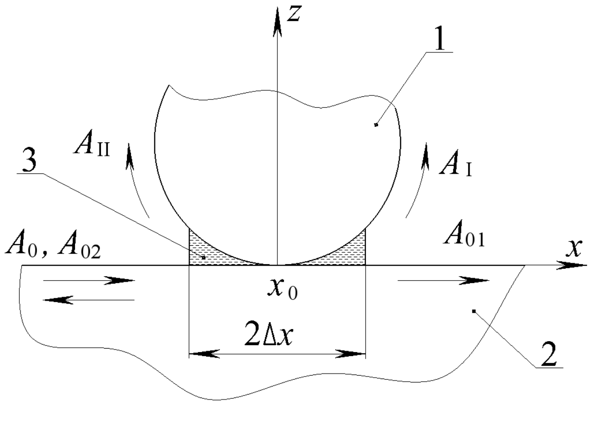
## Experimental study setup and schemes

The scheme of experimental studies for modelling the distant method of excitation of rotating waves in objects with cylindrical and spherical surfaces for use in ultrasonic control is shown in Figure 1, where as sources and receivers of RW used PETs with a prism angle β = 65°. For this purpose the shadow or echo method of object sounding can be used. So, in the first case for carrying out researches on a steel substrate 4 cm thick two PETs directed towards each other and operating at frequencies ν, MHz = 1, 2.5 and 5 are installed. To increase the reliability of acoustic contact and orientation of the PETs, they are held by a pair of magnets installed on both sides of the PETs. The samples serving as ALBs of cylindrical shape are placed symmetrically with respect to the acoustic axis, which is perpendicular to the main axis of the sample. Their orientation is achieved by using special stops, including magnetic ones. In this case, the surfaces of the samples are processed to the roughness class Ra not more than 1.6 μm, and machine oil is used as a thin sound-conducting layer providing acoustic contact between the contacting bodies.

The electronic part of the scheme of the experimental setup contains as a source and receiver of SAW electric pulses the blocks of a standard flaw detector, including a generator with a pulse repetition rate of 1 kHz, their amplification block with the output of both undetected and detected informative signals on a RigolDS7024 device with a sampling frequency of 200 MHz and measurement of time intervals with an error up to ≈ 5 ns. As it was mentioned above, at realization of echo-mode of sounding the reference signal created by reflection of RW from the SAW reflector developed for this purpose in the form of a prism of a special form, installed in opposition to the source-receiver of SAW, between which the object of control is placed [7], It is also very important to note that at preparation of the measuring process it is necessary to pay attention to creation of acoustic contact between a substrate and ALB for transfer of RW energy to ALB and back, which is made through a thin layer of liquid. In this application of the sound conductive layer, rotating waves are excited. In this case, by analogy with the data obtained by us earlier, we should expect some peculiarities of the transfer of the RW flow energy into the energy of rotating modes, depending on a number of factors, including the contact layer of the liquid.




*a*




*b*

**Figure 1** – Experimental scheme explaining the method of excitation by Rayleigh wave of rotating waves on objects with cylindrical and spherical surface (*a*) and peculiarities of Rayleigh wave propagation through the area of acoustic contact of contacting bodies (*b*). *a*: 1 – substrate; 2 and 3 – emitting and receiving transducers; 4 – research object or body of acoustic load of cylindrical, spherical or other similar shape; *PG* – pulse generator; $O_s$ – oscilloscope; $A_m$ – amplification unit of the received signal. *b*: 1 – acoustic load body; 2 – steel substrate; 3 – contact lubricant layer; surface wave amplitudes resulting from Rayleigh wave scattering with amplitude $A_0$ at the contact boundary of the bodies: amplitudes of the passed ($A_{01}$) and reflected ($A_{02}$) modes of the Rayleigh wave's, $A_I$ and $A_{II}$ – excited surface rotating waves, rotating counterclockwise and clockwise, respectively

The studies will be carried out in the following way. At first, the PETs are installed in opposition to each other, achieving optimal conditions of RW passage between them, if the sounding mode is shadow. In the other case, the PET, combining the function of an emitter and a receiver of RW, is orientated relative to a special reflector of surface waves, the principle of which is described in the paper [7], and then the ALB is installed to study the object according to the data of amplitude and time characteristics of the signal.

In order to study the possibility of excitation of SAW on spherically shaped objects, a similar installation to the one mentioned above was used as a basis, improved in order to study the amplitude and angle characteristics of scattered SAW, which is explained in Figure 6. As research objects demonstrating the possibilities of the method of controlling the defectiveness of objects of cylindrical shape were used metal samples with cracks and imitators of coatings and in the form of different thicknesses, made on a polymer base and covering half of the surface area of the samples with thicknesses from 22 to 430 μm.

## The results of experimental studies and their discussion

The main results of experimental studies devoted to the study of the acoustic path and possibilities of remote control of objects with cylindrical and spherical surfaces with the help of SRW are explained in Figures 2–8. Thus, Figure 2 shows a characteristic oscillogram of a series of SRW pulses excited as a result of Rayleigh mode pulse scattering when it passes the area of acoustic contact of a cylindrical sample with a substrate. The peculiarities of changes in the amplitude characteristics of the SRW mode from the sample radius, wave frequency, number of revolutions, and distance travelled are illustrated in Figures 3 and 4.

Data on the influence of the angular wave number $p = 2\pi r/\lambda$ on the change of the SRW velocity in steel and duraluminium samples are shown in Figure 5, where λ is the Rayleigh wavelength. In Figure 6 shows the amplitude-angle dependences of the SAW scattering field of a spherical shaped sample, the surface of which is bypassed by the SRW in different directions. Figures 7 and 8 illustrates the possibility of detecting surface cracks remotely by both shadow and echo methods.

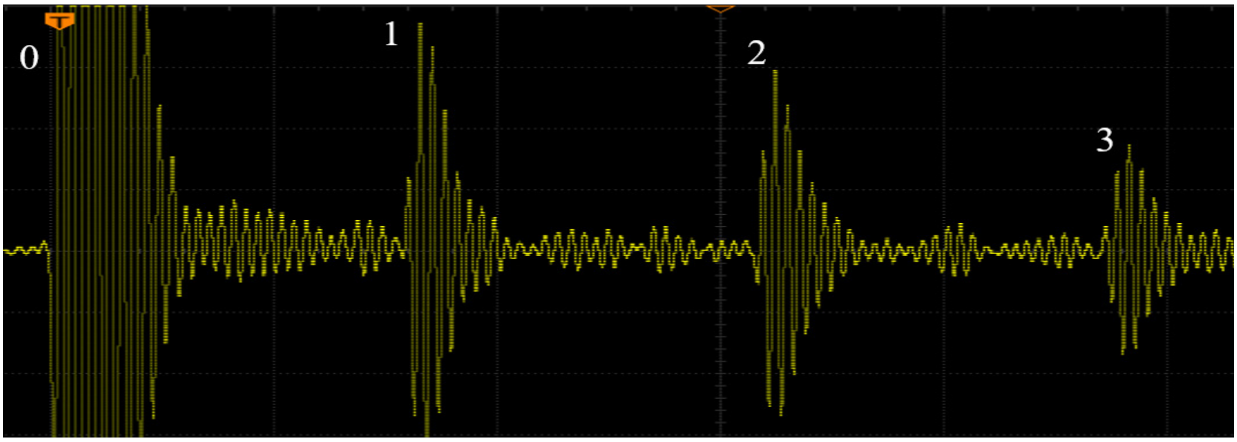



**Figure 2** – Characteristic oscillograms of surface rotating wave pulses excited by the proposed "distant" method by Rayleigh wave on cylindrical samples in contact with steel substrate; sample diameter 15.08 mm, operating frequency of transducers ν = 1.8 MHz; signs 1, 2 and 3 – correspond to pulses of the surface rotating wave with numbers – 1, 2 and 3, and sign 0 – corresponds to the reference signal received in the shadow mode of object sounding

*Amplitude characteristics of the surface rotating waves*

Experimental investigations were carried out on steel and dural samples of cylindrical and spherical shape depending on their diameter $d = 6.98$–25.1 mm and PET operating frequency ν, MHz = 1, 1.8, 2.5 and 5 MHz. So the main range of variation of the angular wave number was $p = 2\pi r/\lambda \approx 20$–125, which allowed to reveal a number of features of both excitation and propagation of SRW. Thus, in the whole investigated range of wave number variation, the RW passing through the contact boundary of an object or ALB with the substrate is accompanied by the excitation of two surface rotating waves (modes) directed towards each other, which is illustrated in Figure 1*a*). In the direction of the source propagates reflected from the region $\Delta x_0 < x^* < x_0 + \Delta x_0$ mode with energy $W_0 K_{ref}$. Thus, the formula for describing the energy balance is as follows:

$$\Delta W = W_0 - W_{pr} = W_0(1 - K_{pr}) = W_0(K_0\uparrow + K_0\downarrow + K_{ref}), \quad (1)$$

where $W_{pr}$ is the energy of the RW mode passed through the contact region of the bodies; $K_0\downarrow$ and

$K_0$↑ are the conversion coefficients RW→SRW for rotating modes clockwise and counterclockwise; $K_{pr}$ and $K_{ref}$ are the corresponding coefficients of the RW mode passage and reflection by energy from the specified region.

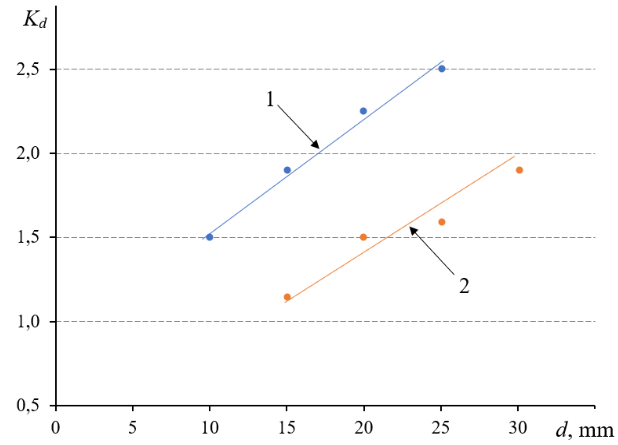



**Figure 3** – Dependence of the attenuation coefficient of the relative amplitude of the rotating mode pulse amplitude $K_d = A_n /A_{n–1}$ on the cylinder diameter at the piezoelectric transducer operating frequency ν, MHz = 5 (1); 1 (2)

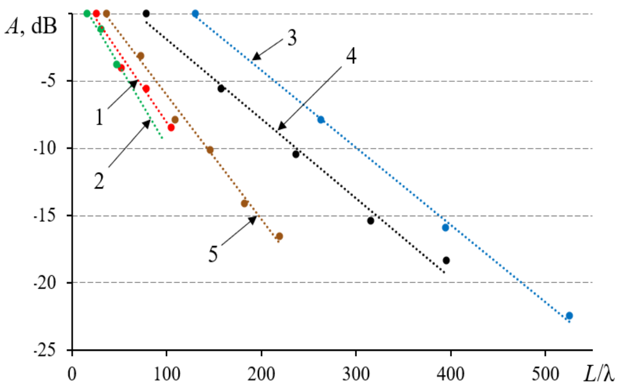



**Figure 4** – Relative change of the surface rotating waves pulse amplitude propagating on the surface of steel cylinders depending on the traveled distance determined by the number of revolutions and the cylinder diameter: dependencies obtained at ν = 1 MHz at $d$, mm = 25.1 (1) and 15.08 (2), and at ν = 5 MHz at $d$, mm = 25.1 (3), 15.08 (4) and 6.98 (5)

It should be noted that, under certain conditions, the amplitude of the scattered RW modes, including SRW, can be influenced by the contact layer of the liquid, whose profile is similar to a wedge with a changing curvature of one of the surfaces. In this case, in the first approximation, the profile of the contact layer is determined by the surfaces limiting it – $z = 0$ and $z = z(x^*)$, dimensionless height of which

$$h_\lambda = h(\lambda_{in})^{-1} = r(\lambda_{in})^{-1}[1–[1–(\Delta x/r)^2]^{0.5}], \quad (2)$$

where $\lambda_{in}$ is the length of excited elastic waves. In the case when $\Delta x/r << 1$, then $h_\lambda \approx \Delta x^2(\lambda_{in}r)^{-1}$. Thus, when optimizing the conditions of acoustic measurements it is necessary to take this parameter into account in order to reduce the noise background and increase the stability of measurements.

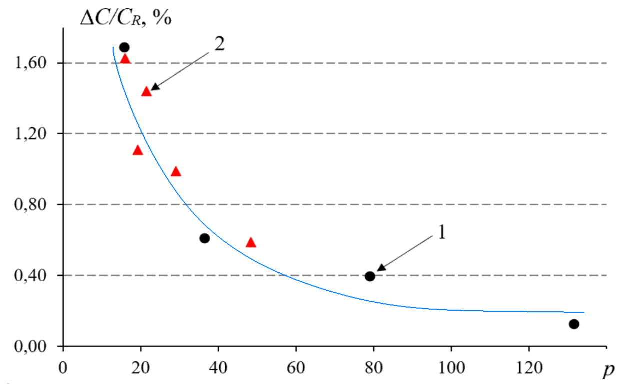



**Figure 5** – Variation of the velocity of the rotating surfactant according to the data of the time it circles the surface of a cylindrical sample as a function of the angular wave number $p = 2\pi r/\lambda$; sample material steel (1) and dural (2)

It has been experimentally established that at achievement of optimum conditions providing the minimum noise background at maximum amplitude of SRW impulses circling the ALB surface and maintenance of a certain ratio between amplitudes, stability of readings, it is the mode rotating counterclockwise that prevails. In most cases its amplitude $A_{\mathrm{I}}$ exceeds the amplitude of $A_{\mathrm{II}}$ by 5 and more times. Experimental estimation of $A_{\mathrm{I}}$ and $A_{\mathrm{II}}$ was carried out by using developed small aperture and miniature inclined PETs placed directly on the surface of ALB or near its substrate. At realization of the mentioned conditions, Figure 2 serves as a confirming example, where an oscillogram of SRW mode impulses registered by the receiving PET at making the next turn and passing of waves through the area of contact between ALB and substrate is given.

It should be noted that similar oscillograms are observed in the case when steel spheres serve as ALBs. However, as it is established, there is a difference between them caused by inversion of the wave phase by the value Δφ→π when a cylinder serves as a ALB. If the object is a sphere, on the other hand, there is no shift. Obviously, it is necessary to take this into account when making measurements using the phase characteristics of the probing signal.

The investigations of amplitude dependences of SRW on the ALB diameter (Figure 3) and the passed distance (Figure 4) at the operating frequencies of 1 and 5 MHz allowed to establish the following. First of all, the amplitude of impulses of the rotating mode depending on the traveled distance $L = 2\pi rn$ decrease according to the law close to the exponential one, which is illustrated by dependences 1–5 in Figure 4, where $A$ is the normalized amplitude and $\lambda$ is the RW wavelength.

Note also, the measured wave amplitude attenuation coefficient as a function of diameter is a linearly increasing function, i. e., $K_d = A_n / A_{n-1} \sim d$, or $K_d / d = \text{const}$ at operating frequencies of 5 and 1 MHz. Moreover, as can be seen, the attenuation of the wave amplitude with lower frequency is significantly lower, by ≈50–80 %. From the analysis of the mechanism of energy losses (formulas 1 and 2) and experimental data, it should be concluded that the amplitude of the surface wave that has passed the path $L = 2\pi rn$, having made $n$ revolutions, can be represented in the form:

$$A_n \sim A_0 D_p \varepsilon \left( \prod_{n=1}^{n} D_n f_n \right), \tag{3}$$

where $A_0$ and $D_p$ are the RW amplitude emitted by the PET and the coefficient of its passage of the ALB-substrate contact boundary when moving along $x$ to the receiving PET, respectively; $\varepsilon$ is a correction factor characterizing the peculiarities of the mechanism of transferring part of the RW energy to the rotating wave directly when the initial RW pulse moves along the substrate; $D_n$ is the coefficient of passing by the rotating wave of the acoustic contact area of $x \subset x_0 \pm \Delta x_0$ bodies, and $f_n$ is the coefficient of attenuation of the wave amplitude caused by the wave front divergence during the $n^{\text{th}}$ rotation. It follows from (3) that $K_d = D_n f_n$.

Analyzing peculiarities of the mechanism of interaction of the rotating mode at passing the area of acoustic contact of ALB-substrate, it should be assumed that the most significant mechanism of attenuation of the wave amplitude is caused exactly by dissipation of its energy at passing each time the area of acoustic contact of ALB with substrate. And the more turns the wave makes, the more these losses are, which follows from formula (3).

*On the change of the surface rotating waves velocity*

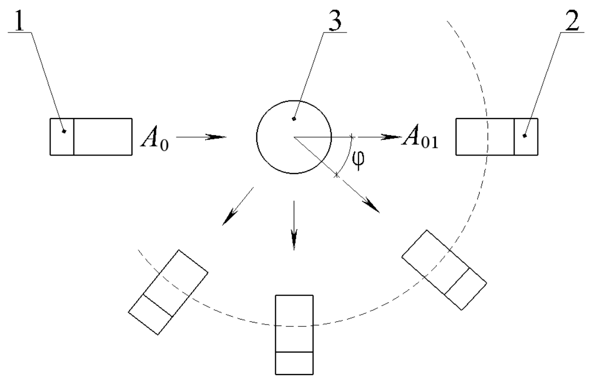
To study the possibility of using as an informative parameter the velocity $C$ of SRW propagation using the proposed remote sensing method and to compare these data with the known (mainly theoretical) data [11], the shadow mode of sounding at frequencies ν, MHz = 1, 2.5 and 5 MHz, and varying the angular wave number almost 6 times – $p = 2\pi r/\lambda = 20–125$ was used. The material of the samples was steel and dural. The experimental scheme shown in Figure 1 was used for measurements, where the object was placed between the emitting and receiving PETs. Moreover, the signal reception and processing was performed with the help of RIGOLLS7024 device with integrated electron beam tube. Figure 5 presents the results of the study of the SRW velocity estimated from the data of the time $\Delta t$ between the pulses received by the PET when the wave makes one or several revolutions of the cylinder surface. In this case, each time the wave velocity was measured 3–4 times, and it was determined by the formula: $\Delta C = L/\Delta t – C_R$, where $C_R$ is the Rayleigh wave velocity measured on a flat sample with an error not worse than 0.2 %. It was found that $\delta = \Delta C/C_R$ is an increasing function with decreasing numerical parameter $p$ for both steel and dural samples.

However, the value of δ did not exceed 1.5–2 %, which qualitatively agrees with the theoretical conclusions of work [11], where it is shown that the additional change (growth) of the velocity $\Delta C/C_R \sim p^{-2} \sim \lambda^2 r^{-2}$ measured by us is due to the effect of wave dispersion.

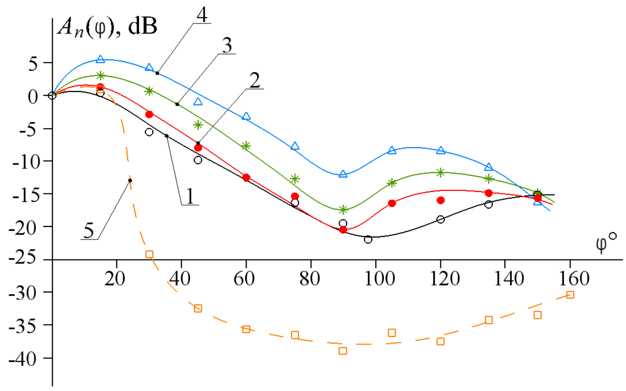
According to known theoretical data [11], it was found that when propagating along a convex cylindrical surface, SAW has dispersion – the dependence of velocity on frequency. In [11], a theoretical analysis of the dependence of phase and group velocities is carried out and states their dependence on the angular wave number $p = 2\pi r/\lambda$ ($r$ is radius of the cylinder; $\lambda$ is length of the ultrasonic wave). According to [11], a Rayleigh-type surface wave propagates along a convex cylindrical surface, and when the diameter of the convex surface tends to infinity, the phase and group velocities tend to the Rayleigh wave velocity, all particle displacements are also identical. Accordingly, as the frequency increases, the phase and group velocities also tend to the Rayleigh wave velocity. In the first approximation, the phase velocity of a propagating ultrasonic wave on a convex cylindrical surface is proportional to $1/(k_R r)$, where $k_R$ is the wave number.

*Surface rotating waves in a spherically shaped sample*

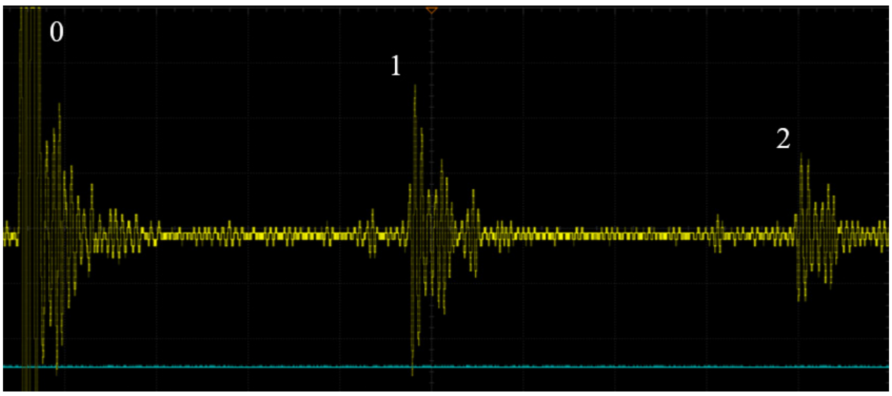
Experimental studies carried out according to the previous scheme (Figure 1) also allowed us to establish the high efficiency of excitation of waves rotating along the spherical surface excited by Rayleigh waves in steel balls. As it was found, in contrast to the case of excitation of a surface mode on a cylinder, no phase shift for the spherical surface rotating mode was detected. To investigate the scattering field of SRW excited on a spherical surface, the setup was modified (Figure 6*a*). In this case, we studied the features of the formation of the scattering field of such modes, the rotation trajectory of which has a significant difference from those studied earlier. The difference consists in obtaining and analyzing not only amplitude, but also amplitude-angle characteristics of $A_n(\varphi)$ in the plane of the substrate surface $z = 0$ waves, where the index $n$ coincides with the pulse number of the investigated rotating mode circling the sphere surface. The studies were carried out by shadow method, and the change of the angle of reception was achieved by moving the PET with an operating frequency of 2.5 MHz along a circular trajectory, directing its plane of wave incidence to the point of contact of the sphere with the plane of the substrate $x = x_0$. So the distance between the PET and the point $x_0$ was $s = 55$ mm. The angular dependence of the reference signal $A_{n0}(\varphi)$ obtained at $n = 0$ is also plotted. So the path traveled by the SRW when receiving the $n^{\text{th}}$ pulse of the wave will increase.




*a*




*b*




*c*

**Figure 6** – Schematic diagram of the experimental setup for studies of the scattering field of surface waves scattering by a steel sphere (*a*), amplitude-angle dependences of the amplitude of pulses of waves $A_n(\varphi)$ (*b*) and oscillograms of the surface rotating wave pulses on the spherical sample (*c*). *a*: 1 and 2 – emitting and receiving transducers; 3 – steel sphere; *b*: curves 1, 2, 3 and 4 correspond to the values of the number n of the surface rotating wave impulse sequentially traveling around the sphere surface; 5 – dependence obtained in the absence of Rayleigh wave rounding of the sample surface; *c*: signs 1 and 2 correspond to surface rotating wave pulses with numbers 1 and 2 registered by the receiving transducer, sign 0 corresponds to the reference signal obtained in the shadow mode of object sounding; sphere diameter 25.44 mm, operating frequency of transducers ν = 2.5 MHz

The studies have shown that the shape of the oscillograms of the fixed pulses when changing the angle of signal reception from zero to $\varphi = 20$–$30°$ and varying the number of the pulse number $n$, coinciding with the number of the wave rotating on the sphere surface, is similar to that for the SRW modes illustrated in Figure 2. At the same time, they differ in the absence of wave phase inversion for adjacent pulses, which takes place in the case of SRW excitation on cylindrical samples. These data indicate the possibility of ultrasonic diagnostics and control of such objects, using not only the speed, but also the amplitude of remotely excited.

As for the scattering field of $n$-fold waves circling the sphere surface after their exit to the substrate plane in the vicinity of $x \to x_0$, their expansion and amplitude decrease are observed as $n$ increases. As can be seen from Figure 6, a weakly pronounced minimum and two lateral maxima – $A_{\max 1}$ and $A_{\max 2}$, located in the vicinity of the angles $\varphi = \pm(10$–$15°)$, are found in the vicinity of $\varphi \to 0$. On the other hand, two additional field minima located in the vicinity of $\varphi = \pm(90$–$95°)$ were detected. At the same time, the difference in amplitude between these extrema is ≈ 17–22 dB, which is characteristic of the scattering fields of small aperture sources [1].

The following factors can affect the course of the indicated dependences of the scattering fields $A_n(\varphi)$. First, as $n$ grows, the distance from the source of the scattering field to the receiver will increase significantly due to the wave's additional round-trip distance $\Delta s = 2\pi rn$:

$$S_n = S_0 + 2\pi rn. \tag{4}$$

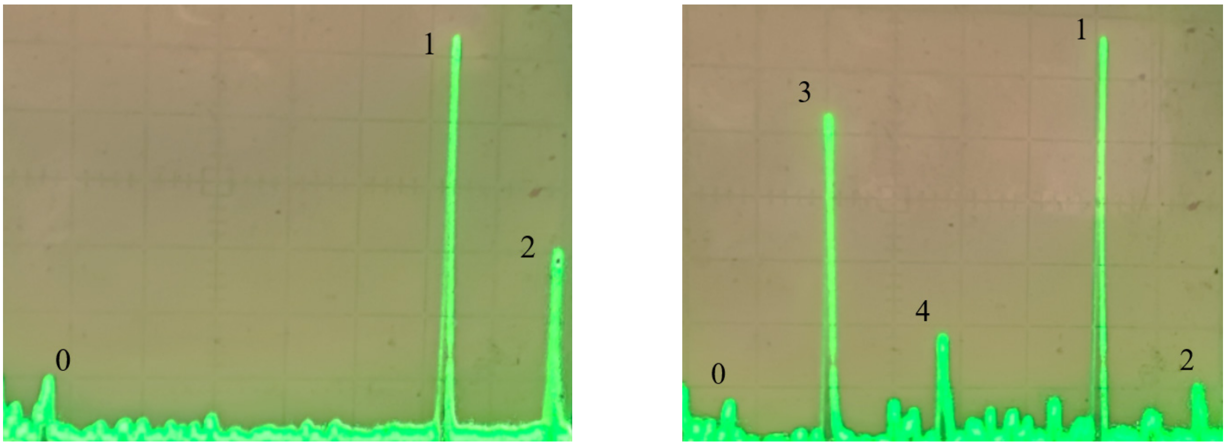
Secondly, it concerns the boundary conditions affecting the process of transferring part of the Rayleigh mode momentum energy to the spherical body, where, as it is supposed, as in the case considered above, SRW of different directions should be generated.

*About detection of surface defects*

Figures 7 and 8 show the results of ultrasonic inspection of a steel cylinder with a longitudinal crack with a depth of 0.8–0.9 mm and opening 0.03–0.05 mm, sample diameter 15.96 mm, ultrasonic wave frequency 5 MHz. Figure 7 shows the oscillograms of pulses obtained during the control by echo method with the use of an artificial (reference) reflector in the form of a prism, located so that the ALB is installed between the PET and the prism. The artificial reflector provides registration of SRW pulses rotating counterclockwise (Figure 1*a*). In the absence of a crack, only counterclockwise rotating SRW pulses are observed (2, Figure 7*a*), as well as the Rayleigh wave pulse reflected by the substrate-cylinder contact region (0, Figure 7*a*). The presence of the crack leads to partial reflection of the SRW from its surface, which provides pulse registration without an artificial reflector due to the change in the direction of the rotating mode (3 and 4, Figure 7*b*). The fraction of energy that passes through the crack is registered with the help of an artificial reflector, a decrease in the amplitudes of the ABI pulses that passed through the crack is observed (2, Figure 7*b*). The criterion for the presence of a defect in the echo method is the appearance of a series of SRW pulses reflected from the crack surface (3 and 4, Figure 7*b*), with a simultaneous decrease or disappearance of the series of pulses that passed through the crack (2, Figure 7*b*).

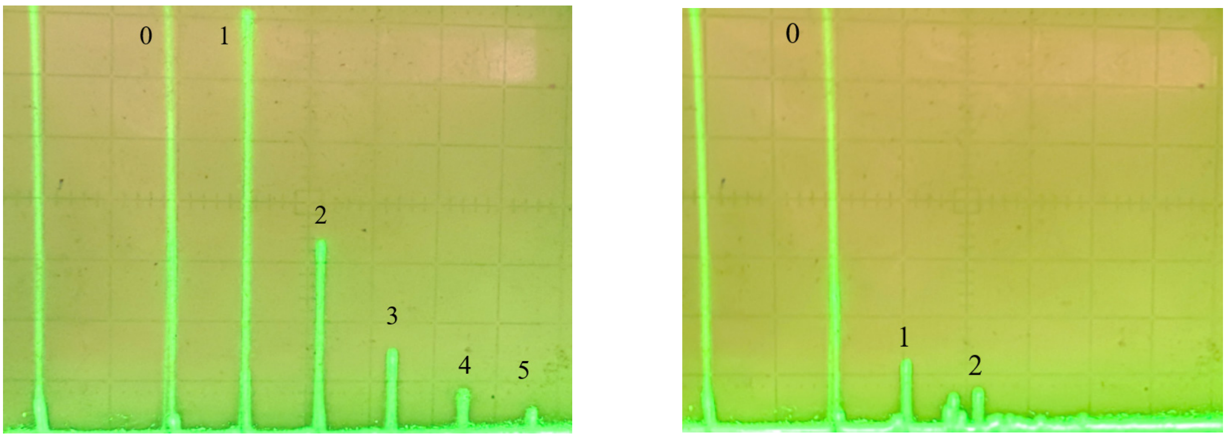
Figure 8 shows the oscillograms of the pulses obtained during shadowing (Figure 1*a*), with only counterclockwise rotating modes recorded. In the absence of a crack, there is a series of SRW pulses rotating counterclockwise (1–5, Figure 8*a*), as well as a reference pulse of Rayleigh wave propagating in the substrate and passing the area of contact "ALB-substrate" (0, Figure 8*a*). The presence of a crack leads to a decrease in the energy of the SRW mode that passed through the crack, as a result, a decrease or disappearance of signals on the oscillogram is observed (1 and 2, Figure 8*b*). The criterion for the presence of a defect in shadow inspection is the decrease and disappearance of the SRW pulses that passed through the crack (1 and 2, Figure 8*b*).

The possibility of using SRW for controlling the surface structure of solid bodies having cylindrical and spherical surfaces at different hardening methods (hardening, cementation, etc.) has been established. In this case, two objects of cylindrical or spherical shape are used in the control: one of which is controlled, the second is a reference used as a carrier of the controlled parameter (diameter, thickness or quality of the hardened layer, etc.). It should be noted that the SRW generated on both ALBs passes the same path and the receiving PET, in the shadow mode, registers their total interference pulse. If in the object the controlled parameter differs from the reference one, then a phase shift occurs between the SRW pulses of cylinders (spheres), which leads to the change of amplitude distribution in the series of registered SRW pulses.




*a* *b*

**Figure 7** – Oscillograms of pulses obtained during detection of a defect in the form of a crack by a surface rotating wave on a cylindrical steel sample in echo-mode in the absence (*a*) and presence (*b*) of the defect: 0 – Rayleigh wave pulse reflected by the area of contact "substrate-cylinder" and from the artificial reflector (1, 2), where 2 – pulse delayed by additional rounding of the sample perimeter; 3 and 4 – impulses of a surface rotating wave reflected from a crack without a crack (*a*) and in the presence of a crack (*b*); transducer operating frequency 5 MHz, sample diameter 15.96 mm, and crack opening 0.03–0.035 mm at its depth 0.8–0.9mm




*a* *b*

**Figure 8** – Oscillograms of pulses obtained during the detection of a defect in the form of a crack by a surface rotating wave on a cylindrical steel sample in the shadow mode in the absence (*a*) and presence (*b*) of the defect: 0 – reference pulse of Rayleigh wave; 1–5 – pulses of rotating mode without attenuation by the crack (*a*) and in the presence of it (*b*); transducer operating frequency 5 MHz, sample diameter 15.96 mm, crack opening 0.03–0.035 mm at its depth 0.8–0.9 mm

Studies of the possibility of controlling the defectiveness of cylindrical objects with cracks have been carried out, with simulated coatings of different thicknesses, made on a polymer base and covering half of the surface area of the samples with thicknesses from 22 to 430 μm. It was found that the presence of the coating leads to a decrease in the amplitude of the rotating mode pulses, and the amplitude for the given coatings does not change monotonically depending on the thickness. Increasing the thickness of polymer coatings on the ALB surface leads to a monotonous decrease in the rotating mode velocity. Presence of coating on controlled objects allows to carry out their control by SRW modes by the proposed remote method of sounding.

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## Conclusion

A remote method of sounding and control of cylindrical and spherical objects by means of surface rotating waves excited in them is proposed. The controlled objects are placed on a metal substrate, which serves as an acoustic delay line for transmission-reception of signals between transducers and the object of study, which is a body of acoustic load. Piezoelectric transducers with prism angle $\beta = 65°$ are used as sources and receivers of Rayleigh wave, shadow or echo method of object sounding is used.

It has been established that as a result of Rayleigh wave scattering in the area of contact between the substrate and the object, surface modes rotating in opposing directions are generated in the latter. When the optimal mode of sounding is realized, the amplitude of the counterclockwise rotating $A_{\mathrm{I}}$ mode exceeds the amplitude of the $A_{\mathrm{II}}$ wave moving in the oppositional direction by a factor of 5 or more.

It is shown that the main parameter affecting the acoustic path of the proposed measurement scheme is the angular wave number $p = 2\pi r/\lambda$. The quasi-linear growth of the wave attenuation coefficient from the sample diameter at frequencies $\nu = 1–5$ MHz has been experimentally established. The growth of the distance traveled by the wave is accompanied by a drop in the amplitude of the wave according to the law close to the exponential law, reaching the greatest attenuation with a decrease in the radius of the cylinder (sphere). The change in the surface rotating waves velocity in the specified range of variation of $p$ did not exceed 1.5–2 %, increasing with decreasing sample radius and wave frequency, which is due to the effect of wave dispersion.

Based on the analysis of the acoustic path and experimental data, an expression for the dependence of the amplitude of the surface rotating mode, which has made $n$ revolutions on the surface of a cylinder with radius $r$, on the distance traveled $L \sim rn$ is obtained. It is supposed that in most cases the most significant attenuation of the surface rotating waves amplitude is achieved as a result of its energy dissipation in the area of acoustic contact between acoustic load body and substrate.

The peculiarities of scattering fields of surface acoustic pulses by a metallic sphere when its surface is bypassed by a rotating mode depending on the pulse number $n$ and the angle of reception $\varphi$ have been revealed for the first time. It is established that the scattering fields of waves rounding the surface of the sphere after their exit to the substrate plane expand with increasing $n$. Moreover, in the vicinity of $\varphi \to 0$ there is a weakly expressed amplitude minimum and two lateral maxima. In addition, two additional field minima located in the vicinity of $\varphi = \pm(90–95°)$ were found.

Experimental modeling of the possibility of control of surface cracks and coatings by rotating surface waves using both shadow and echo methods realized with the use of surface wave reflectors has been carried out. In this case, the amplitude or velocity of the rotating mode propagation can serve as an informative parameter characterizing the state of the surface layer and its defectiveness.

The methodology is developed and the possibility of distant scheme of sounding and effective control of solid bodies having cylindrical and spherical surface for the presence of surface defects is established. Surface rotating waves modes also allow to control the surface structure at various methods of hardening (hardening, carburizing, laser thermal hardening, etc.).

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