STATE PRIMARY STANDARD OF UNITS OF ULTRASONIC DISPLACEMENT AMPLITUDE, VIBRATIONAL VELOCITY OF THE SOLID MEDIA SURFACE, AND ELECTROACOUSTIC CONVERSION COEFFICIENT GET 194-2022

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The article investigates the issues of metrological support of acoustic emission means of nondestructive testing and diagnostics designed to improve the accuracy and veracity of control results to ensure safe and accident-free equipment operation at hazardous production facilities and structures. The composition of the State Primary Standard of the units of the amplitude of ultrasonic displacement, the vibrational velocity of the solid media surface, and the electroacoustic conversion coefficient, GET 194-2022 is presented. The reference installation "Coefficient," developed according to the laser interferometric measurement method and included in GET 194-2022 for reproducing units of electroacoustic conversion coefficient, is described, along with its operation principle. The metrological characteristics of GET 194-2022 are presented. The scope of the standard application is indicated, including the scientific and technical support for the uniformity and required accuracy of acoustic measurements in solid media, thus increasing the veracity of the results, reducing the risk of technogenic accidents, metrological assurance of hygienic requirements when working with sources of "contact ultrasound" on surfaces in contact with the operator's hands.

Keywords: State primary standard, ultrasonic displacement, vibrational velocity, acoustic emission, coefficient of electroacoustic transformation, transducer, unit reproduction.

Introduction. Among various types of nondestructive testing, acoustic methods rank first in terms of the usage scale (after visual measuring) and in assessing the defect detection.[1] The acoustic emission (AE) method, detecting the most dangerous developing defects [1], ranks high among acoustic methods to ensure accident-free operation of equipment at hazardous production facilities and structures.[2]

Acoustic measurements in solid media are the basis of nondestructive testing and diagnostics by the AE method. Concurrently, in this measurement type, significant difficulties arise while interpreting the measurement results. This results from the multiplicity of the types of waves propagating in solid media, numerous media materials, the impossibility of measurements directly inside the materials of controlled objects, and other influencing factors.

Generally, nondestructive testing and diagnostics by the AE method in employ objects and structures classified as "hazardous" (nuclear power plants, oil, chemical, petrochemical facilities, pipeline transport, aerospace objects, special products, etc.), with the associated provisions of the safety law.[3] This further emphasizes the relevance of acoustic measurements in solids. According to the Rostekhnadzor in Russia, there are over 200,000 such facilities, with approximately 70% of the country's population residing nearby.[4]

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[1]Nondestructive Testing, Reference book, in 7 volumes, under the general editorship of V. V. Klyuev, Mashinostroenie, Moscow (2005).

[2]Nondestructive Testing, Reference book, in 7 volumes, under the general editorship of V. V. Klyuev, 7, in 2 books, book 1, V. I. Ivanov, I. E. Vlasov, Acoustic Emission Method; book 2, F. Ya. Balitsky, A. V. Barkov, N. A. Barkova, et al., Vibrodiagnostics, Mashinostroenie, Moscow (2005).

[3]Federal Law No. 116-FZ dated July 21, 1997 "On Industrial Safety of Hazardous Manufacturing Entities."

[4]Head of Federal Service for Ecological, Technological and Atomic Supervision, Konstantin Pulikovsky answers questions from Internet conference participants, Tekhnadzor, No. 10 (2007). URL: http://www.tnadzor.ru/publications/detail.php?ID=1775 (reference date: 08/11/2022).

The relevance of the stated issue is also evident by the immense efforts of the international standardization organizations to develop new standards and revise (with approval) outdated standards, maintain existing standards in the field of AE methods as well as nondestructive testing of various objects, materials, and their metrological support.[5,6] For example, in ASTM International,[7] under the jurisdiction of subcommittee E07.04 on AE methods for 2011–2016, 32 standards have been developed, with almost half of them (13 standards) developed in 2015–2016.

The above circumstances impose high requirements for the metrological support of non-destructive testing and diagnostic tools implementing the AE method.

Amplitude parameters of the acoustic field on solid media (controlled objects) surfaces, including displacement and vibrational velocity, provide important information regarding the AE control of various processes (intercrystalline corrosion, corrosion cracking, phase transformations, welding, leaks, and other processes) occurring in product materials, objects, and structures. Changes in the amplitude parameters are associated with the local rearrangements of material structures, along with material deformation and cracking on the surface of controlled objects. Using these parameters, the stress–strain state of the controlled object can be assessed, the developing defects can be identified, and the degree of situational hazard and the period to object failure (destruction) can be determined [2, 3].

The metrological support for AE control tools used for acoustic measurements (transducers and AE equipment) is significant in improving the accuracy and veracity of acoustic measurements in solid media. The amplitude–frequency characteristics [4], electroacoustic conversion coefficient, threshold sensitivity to the minimum detectable acoustic signal (approximate limit of $1 \cdot 10^{-16}$ m, close to the level of the thermal noise of a solid body [5, 6]) are among the most important characteristics of acoustic measurement tools.

Aim. To date, the metrological support for such measurement in the Russian Federation is insufficient.

This work aimed to eliminate this disproportion, ensure the uniformity of acoustic measurements in solid media, expand the functional and measuring capabilities of the State Primary Standard of Units of Ultrasonic Displacement Amplitude and Vibrational Velocity of Solid Media Surface, GET 194-2011.

The required level of metrological support for acoustic measurements in solid media has been achieved by introducing into metrological practice the State Primary Standard of Units of Ultrasonic Displacement Amplitude, Vibrational Velocity of Solid Media Surface, and electroacoustic conversion coefficient, GET 194-2022,[8] designed based on the new-generation elements and laser interferometry principles, as well as using the scientific and technical materials and the accumulated experience on this subject [7–9]. GET 194-2022 will ensure the unity of acoustic measurements in solid media. It leads the four-stage State verification scheme for the instruments measuring the amplitude of ultrasonic displacement, vibrational velocity of the solid media surface, and electroacoustic conversion coefficient.

The Far Eastern branch of the Russian Metrological Institute of Technical Physics and Radio Engineering has accumulated significant theoretical and experimental experience in the research and application of noncontact methods for recording ultrasonic vibrations (including the laser interferometric measurement method) in a wide-frequency band and with high sensitivity resolution [7, 10–12]. This laid the foundation for the metrological support of acoustic measurements in solid media to create a whole family of standard measuring instruments, including those with the highest accuracy. The highest accuracy (UVT 58-A-89) laser interferometric units (ULI-1, ULI-2M) and their modifications [11], ultrasonic rod measures of displacements for various acoustic loads, transducers–shapers of the acoustic field for various wave types (PFAP-P, PFAP-R [13], etc.), calibrations of receiving transducers and AE equipment, and other means were developed in the study.

Composition of GET 194-2022. GET 194-2022 comprises two reference units ("Amplitude" and "Coefficient"), a set of reference transducers, and temperature measurement units for ambient temperature control and auxiliary equipment.

The composition, measurement method, and block diagram of the reference installation "Amplitude" are elaborated in [14]. This article presents the reference installation "Coefficient" from the composition of GET 194-2022, designed to

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[5]ASTM E1106-12 "Standard Test Method for Primary Calibration of Acoustic Emission Sensor."

[6]ISO/TR 13115:2011 "Nondestructive Testing — Methods for Absolute Calibration of Acoustic Emission Transducers by the Reciprocity Technique."

[7]ASTM International: [website]. URL: www.astm.org/COMMIT/SUBCOMMIT/E070.html (accessed 08/30/2022).

[8]Rosstandart Order No. 380 dated February 16, 2022 "On Approval of the State Primary Standard of Units of Ultrasonic Displacement Amplitude, Vibrational Velocity of Solid Media Surface, and Electroacoustic Conversion Coefficient."

reproduce, store, and transmit a unit of electroacoustic conversion coefficient $[m \cdot V^{-1}]$ in the dynamic range from $5 \cdot 10^{-11}$ to $5 \cdot 10^{-10}$ $m \cdot V^{-1}$ and the frequency range of 0.05–3.0 MHz.

Reference installation "Coefficient" represents an acoustic-electronic-optical measurement complex. The unit structure consists of the main components (Fig. 1), i.e., an interferometric measuring unit and a measuring rack with radioelectronic devices. The functional block diagram of the reference installation "Coefficient" is presented in Fig. 2. The main installation elements are the broadband high-stability variable-voltage generator (calibrator), reference electroacoustic transducer; laser interferometer with photoelectronic converter, low-frequency signal generator with electromechanical converter, digital voltmeter, verification device (attenuator), high-precision attenuation pad, spectrum analyzer with remote repeater, and personal computer.

Operation principle of the reference installation "Coefficient." The electrical signal from the output of a highly stable broadband generator 1 (Fig. 2) is fed into the input of the reference transducer 2 at a frequency equal to the operating frequency of the transducer and into the input of the attenuator 8. The acoustic vibrations of the working surface of the transducer, comprising one of the mirrors of the laser interferometer 3 with a photoelectric converter, are converted into an electrical signal incoming to the contact "I" of the circuit switch. Concurrently, an electrical signal from the attenuation pad 7 output is supplied to the "II" contact of the circuit switch. We select the attenuation values on the attenuation pad and the attenuator, thereby achieving equal electrical signals from the outputs of blocks 3 and 7. Spectrum analyzer 6, connected through a repeater at the input (not shown in the diagram) and operating in the selective tuning mode to the generator frequency functions as an indicator of such equality.

Since the signal level attenuation through the path "attenuation pad–attenuator" is equal to that through "transducer–laser interferometer," the coefficient of electroacoustic conversion of the converter in units $[m \cdot V^{-1}]$ is calculated by dividing the values of the total attenuation in the attenuator and attenuation pad (in time) by the conversion factor of the laser interferometer in $[V \cdot m^{-1}]$. This operation is performed for each set of reference transducers operating at discrete frequencies within the frequency range of the reference. These transducers are the measures of the units of electroacoustic conversion coefficients with a dimension of $[m \cdot V^{-1}]$. The measurement performed using the attenuator and the attenuation

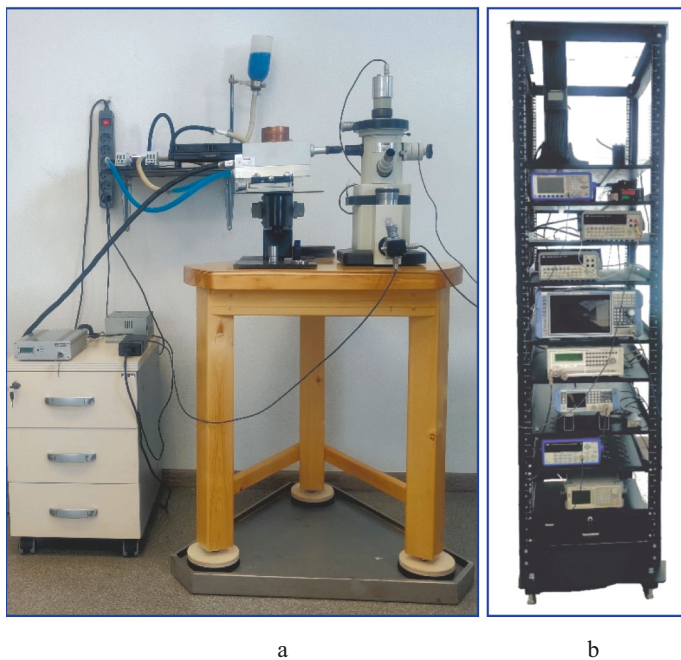a   b

Fig. 1. The reference installation "Coefficient": an interferometric measuring installation (a) and a measuring rack with radio-electronic devices (b).
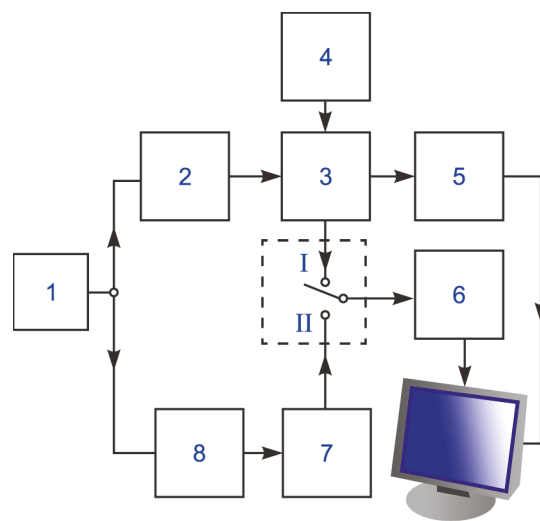

Fig. 2. Schematic of the reference installation "Coefficient": 1, wideband highly stable alternating voltage generator (calibrator); 2, reference electroacoustic transducer; 3, laser interferometer with a photoelectronic converter; 4, low-frequency signal generator with an electromechanical converter; 5, digital voltmeter; 6, spectrum analyzer with remote repeater; 7, high-precision attenuation pad; 8, attenuator; personal computer.

pad as a reference increases the measurement stability and accuracy in comparison with the use of AC voltmeters as a reference.

High-precision measurement of small ultrasonic vibrations with a laser interferometer is a lengthy process. The voltage at the load from the output of the photoelectronic converter must be measured when adding interfering beams in phase U_{max} and antiphase U_{min}. Concurrently, the voltage U_{out} from the high-frequency output of the photoelectronic converter must be measured at the frequency of oscillations of the surface A_{in} of the converter 2 at the "inflection point" at $U_{av} = (U_{max–}U_{min})/2$. This process takes considerable time (over 10 minutes). Within this time interval, the contrast of the interference pattern can noticeably change due to laser instability, minor changes in ambient temperature, air movement, operator breathing, etc. To reduce the time interval between measurements U_{max}, U_{min}, and U_{out} to several seconds, in GET 194-2022, the reference mirror of the interferometer moves smoothly by 1–2 μm in approximately 5 s using an electromechanical converter of a low-frequency generator 4 (Fig. 2). The interferometer operation algorithm is presented in Fig. 3, which shows the graphs of the harmonic signal U_d of infra-low-frequency (r-period) of the displacement ΔL of the reference mirror of the interferometer and the change in brightness U_b of the interference pattern incident on the photoelectronic converter, as well as the change in the electrical voltage at the output corresponding to the change in brightness. This voltage, varying from U_{min} to U_{max}, is continuously measured by digital voltmeter 5 (Fig. 2) and subsequently entered into a personal computer. The interval between the measurements readings of the voltmeter does not exceed tenths of a second. The computer software records the U_{min} and U_{max} values. During the displacement of the reference mirror of the interferometer, simultaneously at the generator frequency, the mirror formed by the reference electroacoustic transducer surface oscillates with amplitude A_{in}. This oscillation (M is the displacement axis) is converted into an output voltage U_{out} at the same frequency. The amplitude U_{out} gradually changes from zero (at U_{min} and U_{max}) to the maximum value (at $U_{av} = (U_{min} + U_{max})/2$). The maximum value of U_{out} is recorded on the spectrum analyzer screen and in the computer memory when the switch is in the "I" position. The signal from the generator, passing through the attenuator and the attenuation pad before entering the spectrum analyzer with the switch position "II," is equalized with the maximum value of U_{out} by the attenuator switches.

The obtained values of the parameters U_{max}, U_{min} and attenuation of the attenuator and the attenuation pad become the initial values for determining the electroacoustic conversion coefficient of the transducer in $[m \cdot V^{-1}]$ using the computer software.

To ensure the operation of GET 194-2022, prototypes of reference electroacoustic transducers are developed and manufactured, with the main characteristics of the working surface roughness Ra of 0.4 μm or under, the reflection coefficient of laser radiation with 0.63991-μm wavelength λ from the working surface of not less than 0.8, electroacoustic conversion
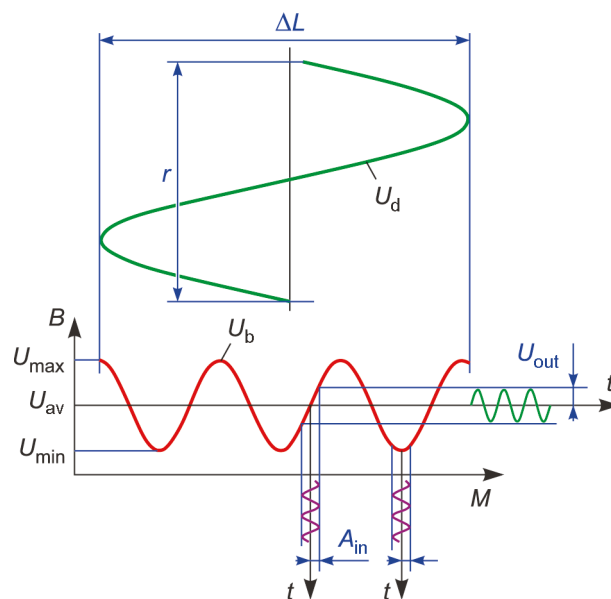

Fig. 3. Graphical representation of the interferometer operation algorithm.

coefficients in the operating frequency range of 0.05–3.0 MHz discretely in the interval from $5{\cdot}10^{-11}$ to $5{\cdot}10^{-10}$ m·V^{-1}, and the deviation from coaxiality of the working surface of the transducer and its cylindrical base surface under 0.01 mm.

Metrological characteristics of GET 194-2022. The reproduction frequency range of the units of the ultrasonic displacement amplitude and the vibrational velocity of the solid media surface is 0.3–3.0 MHz, with the reproduction frequency range of the electroacoustic conversion coefficient of 0.05–3.0 MHz.

GET 194-2022 enables the reproduction of the *unit of amplitude of the ultrasonic displacement* of the solid media surface with the root-mean-square deviation (RMSD) of the measurement result under or equal to $5{\cdot}10^{-3}$ with 49 independent measurements. The nonexcluded systematic error (NSE) does not exceed $0.9{\cdot}10^{-2}$ at a confidence level P of 0.99, the standard uncertainty is $u_A = 0.5{\cdot}10^{-2}$ according to type A and $u_B = 0.37{\cdot}10^{-2}$ according to type B, the total standard uncertainty is $u_C = 0.62{\cdot}10^{-2}$, and the expanded uncertainty $U_e = 1.24{\cdot}10^{-2}$ with coverage coefficient $k = 2$.

GET 194-2022 enables the reproduction of the *unit of vibrational velocity* of the surface of solid media with RMSD of $5{\cdot}10^{-3}$ or under with 49 independent measurements, NSE no more than $0.9{\cdot}10^{-2}$ ($P = 0.99$), $u_A = 0.5{\cdot}10^{-2}$, $u_B = 0.37{\cdot}10^{-2}$, $u_C = 0.62{\cdot}10^{-2}$, $U_e = 1.24{\cdot}10^{-2}$ ($k = 2$).

GET 194-2022 enables the reproduction of the *unit of electroacoustic conversion coefficient* with RMSD of no more than $2.0{\cdot}10^{-2}$ with 36 independent measurements, NSE no more than $2.5{\cdot}10^{-2}$ ($P = 0.99$), $u_A = 2.0{\cdot}10^{-2}$, $u_B = 1.0{\cdot}10^{-2}$, $u_C = 2.24{\cdot}10^{-2}$, and $U_e = 4.48{\cdot}10^{-2}$ ($k = 2$).

Conclusion. The introduction of GET 194-2022, leading the corresponding state verification scheme, will enable the following:

- ensure the uniformity and required accuracy when performing acoustic measurements in solid media;
- increase the reliability of the results of acoustic measurements in solid media during nondestructive testing, diagnostics, thereby increasing the safety of operation of facilities, structures of the fuel and energy complex, petroleum chemistry, gas facilities, nuclear power engineering, transport and reducing the risks of technogenic accidents;
- metrologically ensure the fulfillment of hygienic requirements when working with the sources of "contact ultrasound" for industrial, medical, and household purposes on nonworking surfaces in contact with the operator's hands.

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