REFERENCE COMPLEX FOR METROLOGICAL ENSURING OF ULTRASONIC MEASUREMENTS IN SOLID MEDIA

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In broad fields of physical research, non-destructive quality control of materials, and technical diagnostics acoustic measurement techniques are dominating. Propagation velocity and attenuation factor of longitudinal, shear and surface ultrasonic waves are the important informative parameters in NDT. The accuracy and reliability of measurements of these physical quantities, metrological verification of acoustic measurements in solid media are very actual questions. At the present stage of the development of ultrasonic measurements in solid media, the resource for increasing the accuracy and sensitivity with traditional measuring circuits has been exhausted.

Traditional, widespread methods in acoustic measurements are contact methods using, as a rule, piezoelectric transducers. In this case, the measuring circuit represents the radiating and reception transducers connected with the tested object by the medium providing acoustic contact. Thus, basic reason preventing the increase in accuracy of measurements is influence of the transitive layer, which significantly changes amplitude and phase characteristics of acoustic signals. In traditional circuits of measurements this influence is neither eliminated and not controlled; and, as estimations show, it considerably increases the error of acoustic measurements estimated by researchers.

Further growth of accuracy of measurements is possible only with the introduction of non-contact broadband methods of generation and reception of acoustic signals such as optical (laser) and capacitance techniques.

In recent years, optical methods of generating and receiving acoustic vibrations are more widely applied. Among the advantages of these methods are: the opportunity of generating acoustic wave packages of duration up to 10^{-12} s; non-contact and remoteness; and the opportunity to form practically any configuration and size of a light spot on a surface of studied object. When receiving ultrasonic vibrations, optical methods are practically noninertial, they do not demand acoustic contact with the studied object. These methods allow to narrow the area of measurements up to a few micrometers, they have high sensitivity, do not require calibration and provide high reproducibility of results.

Capacitance methods of generating and receiving ultrasonic vibrations in solids possess an essential advantage. Capacitance transducers are non-contact, have a range of frequencies to hundreds MHz, which easy in calculation, manufacturing and certification. The rational design of receivers allows achieving high sensitivity in reception of ultrasonic vibrations.

Since 1971, the Far Eastern Branch of VNIIFTRI has been working on the study of the non-contact methods of measurement of acoustic parameters of solid media and working out on their basis of means of metrological ensuring of acoustic methods of non-destructive control of materials are conducted.

Theoretical and experimental groundwork helped lay the foundation for metrological support of acoustic measurements in solid media in ultrasonic frequency range, to create reference installations, and to develop a system for transmitting sizes of physical units (velocity, attenuation of ultrasonic waves) from reference installations to working means of measurements.

The list of the designed reference installations, working standards, and worked out Metrology Instructions (MI) is given below.

1. IHA 39-A-86. Installation of the highest accuracy for storage and reproduction of a unit of velocity of longitudinal and shear ultrasonic wave propagation in solid media.

MI 2055-90. SSM. The State Verification System for means of measurements of the velocity of longitudinal ultrasonic wave propagation in solid media.

2. IHA 73-A-91. Installation of the highest accuracy for storage and reproduction of a unit of attenuation factor of longitudinal ultrasonic vibrations in solid media.

MI 2163-91. SSM. The State Verification System for means of measurements of the attenuation factor of longitudinal ultrasonic vibrations in solid media.

3. IHA 79-A-92. Installation of the highest accuracy for storage and reproduction of a unit of velocity of ultrasonic Rayleigh wave propagation in solid media.

MI 2227-92. SSM. The State Verification System for means of measurements of the velocity of ultrasonic Rayleigh wave propagation in solid media.

4. The working standard of 2-nd echelon (MAI-1) for measuring the attenuation factor and velocity of propagation of longitudinal and shear ultrasonic vibrations.

5. The working standard of 2-nd echelon (MWAC-1) for certification of converters of acoustic emission.

Let us consider the device, work and metrological characteristics of standards in more details. The transmission of the size of units of physical quantities is made by means of reference measures of propagation velocity or attenuation factor. Measures are the travelling transfer standard. Measures represent specially selected, prepared and tested samples of materials (steels, aluminium and copper alloys, quartz, optical glass) and provide storage of units and their reproduction by means of reference installation. The choice of materials of measures depends on their acoustic properties.

INSTALLATION OF THE HIGHEST ACCURACY IHA 39-A-86

1. Application

Installation is intended for storage and reproduction of a unit of velocity of longitudinal ultrasonic wave propagation in solid media and transmission of its size by means of working standards to applied working means of measurements.

2. Metrological characteristics

1) Reproduction range of unit of velocity of longitudinal ultrasonic wave - (4500÷6500) m/s

2) Frequency range - (0,5÷25) MHz

3) Mean-square error of result of measurements - not more than $1,2\cdot10^{-6}/d$

4) Residual systematic error of result of measurements - not more than $3,0\cdot10^{-5}$

5) Standard uncertainty (type A) - not more than $1,2\cdot10^{-6}/d$

6) Standard uncertainty (type B) - not more than $1,7\cdot10^{-5}$

(where d - numerical value of thickness of measures in meters).

3. Short description of work principle

The standard represents an electron-optical measuring complex on the basis of non-contact optical methods of excitation and registration of longitudinal ultrasonic vibrations which provides high level of metrological characteristics. By means of the pulsed Q-switched ruby laser on a measure surface it is excited short (duration of 30-40 nanoseconds) a longitudinal wave pulse. On an opposite surface of a measure by means of laser stabilized interferometer with a detection bandwidth of 80 MHz the sequence of the re-reflected pulses of a longitudinal wave is registered. In installation the pulse-echo method of measurement of velocity of longitudinal ultrasonic waves propagation is realized. By means of the selection and time binding block allocation of certain pair pulses of a longitudinal wave and a time binding to the centre of gravity of pulses (the scheme asynchronously develops the pulses normalized on amplitude in these points) is made. Measurement of time interval T between two ultrasonic pulses is made on the acoustic base equal or a multiple double thickness of a measure $2(N-1)d$, where N=2,3,4 is the integer characterizing number of a re-reflected ultrasonic “stop”-pulse. Velocity of longitudinal ultrasonic waves propagation C_L is given as:

$$C_L = \frac{2(N-1)d}{T}.$$

Fig. 1. Installation of the highest accuracy IHA 39-A-86

Extremely high metrological characteristics of installation are realized at use as measures of solid media with attenuation factor less than 1,5 dB/sm in a range of frequencies to 25 MHz in which a dispersion of velocity of longitudinal ultrasonic waves propagation does not exceed 10^{-4}.

INSTALLATION OF THE HIGHEST ACCURACY IHA 73-A-91

1. Application

Installation is intended for storage and reproduction of unit of attenuation factor of longitudinal ultrasonic vibrations in solid media (dB/m) and transmission of its size by means of working standards to applied working means of measurements.

2. Metrological characteristics

1) Reproduction range of unit of attenuation factor of ultrasonic vibrations - (10÷400) dB/m.

2) Frequency range - (1÷50) MHz.

3) Mean-square error of result of measurements - not more than 0,01.

4) Residual systematic error of result of measurements - not more than 0,01.

5) Standard uncertainty (type A) - not more than 0,01.

6) Standard uncertainty (type B) - not more than 0,01.

3. Short description of work principle

The principle of work of installation of the highest accuracy IHA 73-A-91 is based on measurement of easing of ultrasonic vibrations or width of acoustic spectral lines at non-contact excitation and reception of ultrasonic vibrations by a capacitance method.

3.1. Ways and means of excitation and reception of ultrasonic vibrations

For elimination of some systematic errors caused by presence of a layer of a liquid, providing acoustic contact between the sample and transducers, in the standard non-contact excitation and reception of ultrasonic vibrations is realized. As converters of ultrasonic vibrations capacitance transducers (CT) are used. The basic element of CT is the electrode with an electrochemical method oxide films put on its working surface. The oxide film gives protection of the electrode against mechanical and electric damages. The principle of CT work in a mode of radiation of ultrasonic vibrations is based on action of electrostatic forces on a surface of facings of the capacitor. One facing of the capacitor is electrode of CT, and another facing is a surface of the sample. Work of CT in a reception mode is based on pressure change on capacitor facings at distance change between them, caused by action ultrasonic waves.

Fig. 2. Installation of the highest accuracy IHA 73-A-91

3.2. Short description of measurement process

Measurement of attenuation factor by pulse-echo method

With the pulse-echo method attenuation A (in dB) of ultrasonic pulses re-reflected in the sample is traditionally measured and the attenuation factor α (dB/m) may be given as:

$$\alpha = \frac{A - \Delta A_{dif}}{2d},$$

where ΔA_{dif} is the diffraction correction in dB, d is the thickness of the sample in meters.

The size A is defined by automatic measurement of the relation of amplitudes by means of the developed measuring instrument of the relations which labels of time are adjusted on chosen pair of the re-reflected pulses. The error of definition A a measuring instrument of relations does not exceed 0,01 dB at A=15 dB. The calculation error of ΔA_{dif} does not exceed 0,002 dB. For maintenance of necessary accuracy of measurements ΔA_{dif} it was defined by a settlement way, proceeding from decisions of the wave equations for solids.

The pulse-echo method is applied at $\alpha \geq 100$ dB/m and $ka \geq 50$, where k is wave number and a is radius of electrode of CT.

Measurement of attenuation factor by resonance method

At α <100 dB/m and ka <50 error of measurement α by pulse-echo method can reach 1 % and more. For maintenance of demanded accuracy of measurements in these ranges the resonance method is realized in the standard. Method based on measurement of width of acoustic spectral lines ΔF at certain level (usually at level 0,707). Thus the attenuation factor α may be given as:

$$\alpha = \frac{20}{d\lg e}\lg[-\sin\Psi + \sqrt{1+\sin^2\Psi}],$$

where $\Psi = \pi d \Delta F / C$; ΔF is width of the acoustic spectral line on level 0,707; C is velocity of ultrasonic vibrations propagation.

INSTALLATION OF THE HIGHEST ACCURACY IHA 79-A-92

1. Application

Installation is intended for storage and reproduction of unit of velocity of propagation ultrasonic Rayleigh waves in solid media and transmission of its size by means of working standards to applied working means of measurements.

2. Metrological characteristics

1) Reproduction range of unit of velocity of ultrasonic Rayleigh wave propagation - (2000÷3500) m/s.

2) Frequency range - (0,3÷30) MHz

3) Mean-square error of result of measurements - no more than $3 \cdot 10^{-5}$

4) Residual systematic error of result of measurements - no more than $6 \cdot 10^{-5}$

5) Standard uncertainty (type A) - no more than $3 \cdot 10^{-5}$

6) Standard uncertainty (type B) - no more than $3{,}5 \cdot 10^{-5}$

3. Short description of work principle

3.1. Ways and means of excitation and reception of ultrasonic vibrations

In installation non-contact optical methods of generation and reception of ultrasonic vibrations in solids are used. Excitation of surface acoustic waves (SAW) is made in a frequency bandwidth to 30 MHz by means of the pulsed Q-switched ruby laser. The optical system of focusing of laser radiation allows forming a “point” optic-acoustic source (diameter ≈100 microns) on a surface of the sample, providing duration Rayleigh acoustic pulses of 100-150 nanoseconds. Registration of pulse SAW is carried out by two laser stabilized interferometers with the sizes of a zone of reception no more than 40 microns. Non-contact and “point” registration provide reproduction of amplitude and phase characteristics of SAW in a frequency range to 50 MHz and essential reduction of errors of measurements.

3.2. Short description of measurement process

In installation the pulse method of velocity measurement of Rayleigh waves propagation is realized. The short Rayleigh wave pulse generated by laser radiation propagate along a surface of the sample and is registered laser interferometers consistently in 2 points located a one line with a zone of excitation. Velocity of Rayleigh waves C_R is defined by time measurement of an Rayleigh wave pulse propagation T_R on the known fixed base l between two points of reception.

Value C_R is given as:

$$C_R = l / T_R .$$

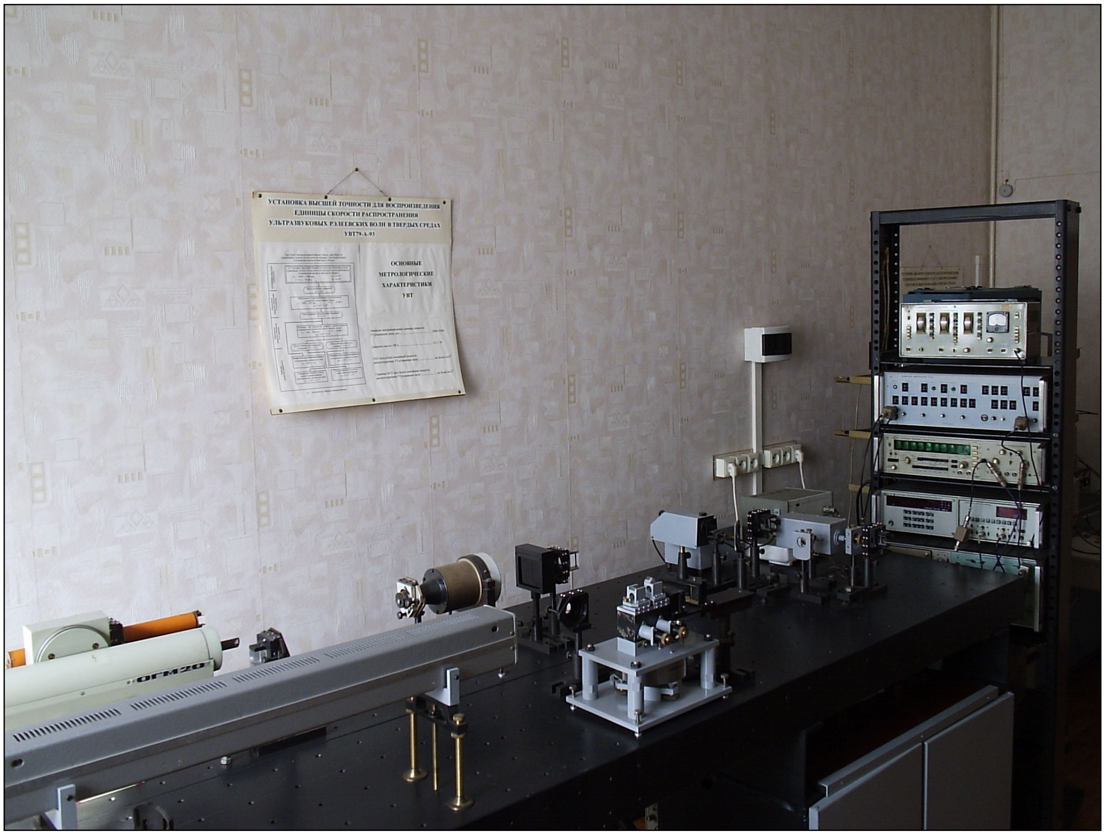

Fig. 3. Installation of the highest accuracy IHA 79-A-92

For measurement T_R in installation the method of an exact time binding and a method of combination of pulses are used. In the first case the special device automatically forms normalized on amplitude and duration electric pulses of a time binding to the set point of arriving input pulses. “Start”-“stop” pulses move on a measuring instrument of time intervals with resolution 1 nanoseconds. The second method is used in case of small amplitudes of acoustic signals or their difficult time form and consists in an establishment of a corresponding time interval T_R of start of a remembering oscilloscope development between the moments at which on the oscilloscope screen there is a combination registered in 2 points of a surface of profiles of an acoustic pulses.

THE WORKING STANDARD OF 2-ND ECHELON (MAI-1)

1. Application

Installation of MAI-1 is intended for measurements and transmission to measuring apparatuses of lower category of units of attenuation factor α and velocity of longitudinal ultrasonic vibrations propagation C_L in solid media. Installation is also intended for measurement of group velocity of shear waves propagation C_S .

2. Metrological characteristics

1) Frequency range of longitudinal ultrasonic vibrations - (1÷100) MHz

2) Measuring range of attenuation factor of longitudinal ultrasonic vibrations - (0,2÷2000) dB/m

3) Measurement Error α - not more than 10 %.

4) Measuring range of velocity of longitudinal ultrasonic vibrations propagation C_L - (2000÷15000) m/s

5) Error of measurement C_L - not more than 0,05 %.

6) Frequency range of shear ultrasonic waves - (0,5÷5,0) MHz

7) Measuring range of velocity of shear ultrasonic waves propagation C_S - (1000÷7000) m/s

8) Error of measurement C_S - not more than 0,5 %.

3. Short description of work principle

In installation MAI-1 the pulse-echo and resonance methods of measurement of attenuation factor and velocity of longitudinal ultrasonic vibrations propagation and the pulse method of measurement of velocity of shear ultrasonic waves propagation are realized.

3.1. Ways and means of excitation and reception of ultrasonic vibrations

For an exception of some systematic errors caused by acoustic contact between transducers of ultrasonic vibrations and the sample, and increases of accuracy of measurements of parameters α and C_L in installation MAI-1 are applied non-contact capacitance transducers (CT) of ultrasonic vibrations. In a mode of radiation work of CT on action of electric forces on capacitor facings and in a reception mode on pressure change on facings at distance change between them is based. One of capacitor facings is electrode of CT and another facing is the sample. The CT generates and registers ultrasonic vibrations in all range of frequencies from 1 to 100 MHz without transducer readjustment.

Occurrence of a shear component is caused by the fact that the sizes of the ultrasonic wave radiator are limited.

3.2. Short description of measurement process

At measurement of parameters α and an C_L installation MAI-1 works as a pulse-echo method as follows. In the plane-parallel sample the ultrasonic pulses are generated. By means of measurement blocks of relations of amplitudes and installation time intervals are defined the amplitude relation A_{nm} (in dB) of pair of the re-reflected ultrasonic pulses with numbers *n* and *m* and a time interval t_{nm} between them. Values α also C_L may be given as:

$$\alpha = \frac{A_{nm} - \Delta A_{dif}}{2d(m - n)}, \text{ dB/m}$$

$$C_L = \frac{2d(m-n)}{t_{nm}} + \Delta C_{dif}, \text{ m/s}$$

where ΔA_{dif} and ΔC_{dif} are the diffraction corrections calculated for solids; *d* is the thickness of the sample.

At definition of parameters α and a C_L resonance method measurements of width of spectral lines ΔF in the plane-parallel sample and an interval of frequencies Δf_{nm} between spectral lines with numbers *n* and *m* are made. Values α also C_L may be given as:

$$\alpha = \frac{10}{d\ln 10}\lg\left[\frac{2\eta}{1-\eta}\sin^2\Psi + 1 - \sqrt{\left(\frac{2\eta\sin^2\Psi}{1-\eta}\right)^2 - 1}\right], \text{ dB/m}$$

$$C_L = 2\Delta f d = \frac{2d(f_m - f_n)}{m-n}, \text{ m/s}$$

where $\Psi = \pi d(\Delta F - \Delta F_{corr})/C_L$; ΔF_{corr} is the correction including the loss of acoustic vibration energy into the environment; η is the measuring level of the width of acoustic spectral line.

At $\alpha \le 100$ dB/m the attenuation factor is given by

$$\alpha = \frac{20}{\ln 10} \frac{\pi(\Delta F - \Delta F_{corr})}{C_L}.$$

The group velocity of shear waves propagation C_S is calculated by the following formula:

$$C_S = \frac{C_L d}{C_L t_S + d} + (\Delta C_S)_{POP},$$

where $(\Delta C_S)_{POP}$ is the correction considering the sizes of an electrode. Time interval t_S between the first incoming pulse of a longitudinal wave and a shear component of signal is measured.

On the basis of installation MAI-1 the automated system for complex measurement and certification for acoustic parameters of materials is created.

THE WORKING STANDARD OF 2-ND ECHELON (MWAC-1)

1. Application

Installation is intended for measurement of factor of transformation at various values of a tangent of a component of a wave vector, for certification of the ultrasonic transducers applied in ultrasonic flaw detection and vibration measurements, calibrations of transducers, the control of manufacturing techniques of transducers.

2. Metrological characteristics

1) Measuring range of transformation factors K_{nn} - ($5 \cdot 10^5 \div 2 \cdot 10^{10}$) V/m

2) Frequency range of ultrasonic vibrations - (0,1÷5,0) MHz

3) Error of measurements - not more than 20 %

4) Error of displacement measurements by interferometer - not more 5 %

5) Measurement range of a tangent component of wave vector $k_=$ in frequency f - $(0 \div 2 \cdot 10^{-3}) f$, m^{-1}

6) Sizes of a working zone on a measure surface - 15×15 мм^2

3. Short description of work principle

The principle of action of installation is based on signal measurement on an exit of the certified transducer of ultrasonic vibrations (TUV) at a known field of displacement on its acoustic input.

3.1. Ways and means of excitation and reception of ultrasonic vibrations

Excitation of ultrasonic vibrations in acoustic measures is carried out by means of piezoelectric transducers with a various transmission angle.

Measurement (certification) of displacement on a surface of measures is carried out by means of the reference capacitance transducer which principle of work is based on signal occurrence on facings of the condenser formed by an electrode and a surface of the sample, at distance change between them. Reference capacitance transducer is certified by two-beam laser interferometer, a part of installation.

3.2. Short description of measurement process

Certified TUV is established on a working surface of a measure. Rediators generate ultrasonic vibrations in a measure. Tangent component of wave vector of ultrasonic vibrations can vary. At a known field of displacement l_M on a working surface of a measure signal measurement U_n on exit of TUV is made. The transformation factor may be given as:

$$K_{nn}(\omega, k_=) = \frac{U_n(\omega, k_=)}{k l_M},$$

where ω - circular frequency of ultrasonic vibrations; $k_= = \omega \sin\alpha / C$; α - a hade of ultrasonic vibrations on a working surface; C - velocity of longitudinal ultrasonic vibrations propagation in a measure material; k - amplification factor.

At certification precision TUV carrying out of measurements K_{nn} directly by means of laser interferometer is supposed. Thus TUV is established on the glass measure included in one of shoulders interferometer, and simultaneous changes l_M and U_n are made.

Continuation of works is planned in a direction of expansion of a range of frequencies to 25 MHz, considering the level of modern flaw detectors and decrease in an error of certification to 10 %.

CONCLUSION

The results of working out of non-contact broadband optical and capacitance methods of excitation and registration of ultrasonic vibrations and their application in the field of metrological ensuring of acoustic measurements in solid media and ultrasonic nondestructive testing are reflected in the report. The developed methods provide extremely high measurement accuracy of propagation velocity and attenuation factor for all basic modes of acoustic waves - longitudinal, shear and Rayleigh.

The conducted researches have formed a scientific and technical and metrological basis of creation of the state system of ensuring of traceability and demanded accuracy of measurements in the field of the acoustic nondestructive evaluation. Installations of the highest accuracy (the metrological status national standards is equivalent), working standards and precision working measuring instruments of acoustic parameters of solid media are created. There has been developed Metrology Instructions regulating a transmission order of the sizes of corresponding physical quantities on the basis of the state verification schemes, a number of state standards, tables of the recommended help data.

As the further prospects of development of works in this area it is possible to specify maintenance of increase in accuracy of measurements and expansion of a frequency range, perfection of existing standards, creation and certification of reference standards for measurements of velocity of shear waves and physical-mechanical properties of solid media, working out of tables of the standard help data on velocity and attenuation of acoustic waves, interstate standardization in the field of acoustic measurements.

Now the Far Eastern Branch of VNIIFTRI is developing the state special standard for storage, reproduction and transmission of sizes of velocity of propagation and attenuation of longitudinal, shear and surface ultrasonic waves in solids. At the same time, there is being conducted the study of a dynamic method of measuring physical-mechanical characteristics of the solid media which are directly connected with the velocities of ultrasonic wave propagation in solid media. The results of this work will be aimed at strengthening the capacity of the designed state special standard and certifying it as the original means for measuring physical-mechanical characteristics of solid media.