Methodology for assessing the uncertainty of measurements of mechanical stresses by the ultrasonic method with the help of an optical-acoustic separate-combined transducer

A V Fedorov, V A Bychenok, I V Berkutov, I E Alifanova and A E Khoshev

1 ITMO University, Kronverksky Prospekt, 49, St. Petersburg, 197101, Russia
2 Scientific Establishment Engineering and Design Center for Support of the Operation of Space technology, Matrosa Zheleznyaka street, 57 lit. A, St. Petersburg, 197343, Russia
3 Scientific and Technical Center «Etalon», Matrosa Zheleznyaka street, 57 lit. A, St. Petersburg, 197343, Russia

E-mail: sherbairina@mail.ru

Abstract. The work is devoted to the ultrasonic method of controlling mechanical stresses using ultrasonic head waves. The factors that contribute to the result of measurements of mechanical stresses include: the propagation velocity of the head ultrasonic wave, the temperature of the environment and the object of control, the coefficients of acoustoelastic and thermoacoustic coupling, parameters of the optical-acoustic transducer. The contribution of each of these factors to the results of measurements of mechanical stresses is assessed. A technique for assessing the uncertainty of measurements of mechanical stresses by the ultrasonic method using head waves has been developed.

1. Introduction
Measurement of mechanical stresses is relevant in the production, exploitation and recycling of crucial and expensive products of special mechanical engineering in the case of reliability, reducing production costs, improving manufacturability, as well as in planning and evaluating the effectiveness of compensating measures to reduce the mechanical stresses. Information about the actual stress-strain state is necessary for further design of modern products, since at present, for many problems, it is not possible to reliably establish the direction of mechanical stresses by calculation.

One of the most promising methods for monitoring mechanical stresses are methods of acoustic strain measurement. Acoustic strain measurement is based on the phenomenon of acoustoelasticity – the linear dependence of various modes of ultrasonic waves on the acting mechanical stresses in the material of the body. In this way, in acoustic strain measurement, indirect measurements of MN, and the assessment of the accuracy of the measurement result is not a trivial check.

The principles of the theory of errors have been used for a long time for the accuracy of the measurements. However, the error models, confidence values and the formation of confidence intervals in different countries differ markedly from each other, which makes it difficult to compare the measurements. A new concept for assessing the effectiveness of introducing the concept of “standard, total and expanded uncertainty” of a measurement result was proposed on the initiative of...
a number of international metrological organizations to achieve comparability of measurement results. The "Guide for the expression of uncertainty in measurement" [1] has been developed for the application of such an accuracy of measurements of means.

2. Development of a method for assessing the uncertainty of mechanical stresses measurements

In this paper we consider the method of acoustic strain measurement, in which the information parameter for monitoring the mechanical stresses is the propagation velocity of the ultrasonic head wave. The speed of the ultrasonic head wave is the highest, which makes it possible to register it steadily among other types of ultrasonic waves and noises. The definition and registration of the relative change in the value of the propagation velocity of the ultrasonic head wave with a correction for the change in the temperature of the controlled object is used to determine the mechanical stresses. The change in the propagation velocity of the ultrasonic head wave is directly proportional to the change in the values of the mechanical stresses that arise in the material when efforts are applied to it.

The propagation velocity of the ultrasonic head wave is measured using an optical-acoustic separate-combined transducer (OASCT), the diagram of which is shown in figure 1 [2].

![Figure 1: Design diagram of the OASCT](image)

The calculation of mechanical stresses is made according to the formula

\[ \sigma = K_v \frac{K_T (T - T_0) + \nu - \nu_0}{\nu_0}, \]  

(1)

where:

- \( \nu_0 \) is the propagation speed of the ultrasonic head wave in the material of the controlled object in the unstressed state (\( \sigma = 0 \)), measured at temperature \( T_0 \),
- \( \nu \) is the propagation speed of the ultrasonic head wave in the material of the controlled object in the stressed state (\( \sigma \neq 0 \)), measured at temperature \( T \),
- \( K_v \) is the acoustoelastic coupling coefficient (ACC) – correlation between acoustic parameters and mechanical stresses [3],
- \( K_T \) is the thermoacoustic coupling coefficient (TCC) – correlation between acoustic parameters and temperature of environment, control object and OASCT.

In this way, mechanical stresses are not measured directly, and the results of measurements of the propagation velocity of the ultrasonic head wave and the results of the determinations of the ACC and TCC are the sources of uncertainty in measuring mechanical stresses. Equation (1) acts as a model equation.

Figure 2 shows the Ishikawa diagram, which allows you to represent the factors that form the uncertainty in the measurement of mechanical stresses and establishes a cause-and-effect relationship between them.

The propagation velocity of the ultrasonic head wave is expressed as a path \( L \), equal to the base of OASCT, traversed by the ultrasonic head wave during the time \( t \) minus the delay \( \Delta t \) – the time of passage of the ultrasonic wave in the OASCT prism

\[ \nu = \frac{L}{t - \Delta t}. \]  

(2)
Figure 2. Ishikawa diagram of contributions to the mechanical stresses measurement uncertainty.

ACC is determined during uniaxial tensile tests of a proportional sample made of the same material as the test object. Under stepwise loading of a specimen by a tensile force until the occurrence of the mechanical stresses in it \( \sigma = 0 - 0.9 \sigma_T \) a calibration (regression) dependence of the propagation velocity of the ultrasonic head wave on the value of the mechanical stresses is constructed. In this case, ACC acts as a regression coefficient and is determined by the formula

\[
K_\nu = \frac{P}{a \cdot b} \cdot \frac{v_0}{v - v_0}, \tag{3}
\]

where:

\( P \) is the force applied to the sample, \( a, b \) are linear dimensions of the cross-section of the sample. When assessing the expanded uncertainty of the ACC measurement, it is necessary to consider the correlation between \( P \) and \( v \).

TCC is determined during tests in a heat chamber. With a stepwise change in the temperature of the sample and the OASCT, the propagation velocity of the head ultrasonic wave in the sample material is measured and a calibration (regression) dependence of the propagation velocity of the head ultrasonic wave on temperature is plotted. In this case, the TCC acts as a regression coefficient and is determined by the formula

\[
K_T = \frac{v - v_0}{T - T_0}, \tag{4}
\]

When assessing the expanded uncertainty of the TCC measurement, it is necessary to consider the correlation between \( v \) and \( T \).

In this way the sources of mechanical stresses measurement uncertainty have been identified. Figure 3 shows an extended Ishikawa diagram that allows the representation of the factors that form the uncertainty in the measurement of mechanical stresses and establishes a cause-and-effect relationship between them. Its structure includes causal diagrams describing the sources of uncertainty for the propagation velocity of the ultrasonic head wave, ACC and the TCC.

All input quantities are divided into two categories in accordance with the method of their evaluation: category A – components evaluated by processing multiple measurements; category B – components evaluated in a different way (according to characteristics taken from the passport for the device, measurement procedures, from previous experiments, from reference books, etc.)

As a result of measurements of the input quantities, there is a non-excluded bias, which is assigned a normal or uniform distribution law and the corresponding coverage factor for a confidence level of 95%.
Figure 3. Expanded Ishikawa diagram of contributions to the mechanical stresses’ measurement uncertainty.

3. The results of the estimation of the measurement uncertainty of the mechanical stresses

Table 1 shows a list of input quantities, their name, designation, category of the measured quantity, coverage factor and sensitivity factor.

Table 1. List of input quantities.

| Sources of uncertainty | Designation | Measured value category | Distribution law | Coverage factor $\alpha$ $(p = 95\%)$ | Sensitivity factor |
|------------------------|-------------|-------------------------|------------------|----------------------------------------|-------------------|
| Contribution to the uncertainty of measurements of the propagation velocity of the head ultrasonic wave $v$ | Time of propagation of the ultrasonic head wave in the controlled object OASCT base | $t$ | A | normal | $2$ | $-1,16 \cdot 10^9 \frac{m}{s^2}$ |
| | Time of propagation of the ultrasonic head wave in the unstrained state of the test object | $L$ | B | uniform | $\sqrt{3}$ | $1,97 \cdot 10^5 \frac{1}{s^2}$ |
| | OASCT delay time | $\Delta t$ | B | uniform | $\sqrt{3}$ | $-1,16 \cdot 10^9 \frac{m}{s^2}$ |
| Contribution to measurement uncertainty of ACC $K$ | Tensile force | $P$ | B | uniform | $\sqrt{3}$ | $-9,74 \cdot 10^5 \frac{1}{m^2}$ |
| | Linear cross-sectional dimension of the sample | $a$ | B | uniform | $\sqrt{3}$ | $2,92 \cdot 10^{12} \frac{N}{m^3}$ |
| | Linear cross-sectional dimension of the sample | $b$ | B | uniform | $\sqrt{3}$ | $2,92 \cdot 10^{12} \frac{N}{m^3}$ |
| | Propagation speed of the ultrasonic head wave in the stressed state of the controlled object | $v$ | A | normal | $2$ | $-3,31 \cdot 10^6 \frac{N \cdot s}{m^3}$ |
Table 1 continuation.

| Propagation speed of the ultrasonic head wave in the unstressed state of the controlled object | \( v_0 \) | A | normal | 2 | \(-3.89 \cdot 10^9 \text{N} \cdot \text{s} \cdot \text{m}^{-2}\) |
|---|---|---|---|---|---|

Contribution to measurement uncertainty of TCC \( K_T \)

| Temperature of the OASCT and the controlled object in the unstressed state | \( T_0 \) | B | uniform | \( \sqrt{3} \) | \( 0,1 \text{\ K} \) |
|---|---|---|---|---|---|
| Temperature of the OASCT and the controlled object in the stressed state | \( T \) | A | uniform | \( \sqrt{3} \) | \(-0,1 \text{\ K} \) |
| Propagation speed of the ultrasonic head wave in the stressed state of the controlled object | \( v \) | B | normal | 2 | \( 0,67 \text{\ m} \cdot \text{K}^{-2} \) |
| Propagation speed of the ultrasonic head wave in the unstressed state of the controlled object | \( v_0 \) | A | normal | 2 | \(-0,67 \text{\ m} \cdot \text{K}^{-2} \) |

Table 2 shows the values of the propagation velocity of the ultrasonic waves, the coefficients of the ACC and the TCC and the standard uncertainties of their measurements.

Table 2. Values of input quantities and standard uncertainties of their measurements.

| Input name and designation | Input quantity value | Standard uncertainty of the input quantity |
|---|---|---|
| Propagation speed of the ultrasonic head wave \( v \) | 5900 m/s | 0,76 m/s |
| ACC \( K_v \) | \(-580 \cdot 10^8 \text{Pa} \) | \(1,1 \cdot 10^8 \text{Pa} \) |
| TCC \( K_T \) | \(6,69 \text{\ m} \cdot \text{K}^{-2} \) | \(0,04 \text{\ m} \cdot \text{K}^{-2} \) |

The total standard uncertainty of mechanical stresses measurements is determined by the formula

\[
u(\sigma) = \sqrt{c_{v_0}^2 \cdot u_{v_0}^2 + c_{v}^2 \cdot u_v^2 + c_{K_v}^2 \cdot u_{K_v}^2 + c_{K_T}^2 \cdot u_{K_T}^2 + 2 \cdot r_{T,v} \cdot c_v \cdot c_T \cdot u_v \cdot u_T}, \tag{5}\]

where \( u_i \) and \( c_i \) are standard uncertainty and sensitivity factor of the \( i \) input quantity, \( r_{T,v} \) is the coefficient of correlation between the propagation velocity of the ultrasonic wave in the stressed state \( v \) and the temperature of the OASCT and the controlled object \( T \).

The sensitivity coefficients \( c_i \) show how the estimate of the output quantity \( y \) will change with a change in the estimates of the input quantities \( x_i \), they are found as partial derivatives of the output quantity for each of the input quantities

\[
c_i = \left. \frac{\partial y}{\partial x_i} \right|_{x_1, x_2, \ldots, x_m}, \tag{6}\]

The expanded uncertainty of mechanical stresses measurements is determined by the formula

\[
U_\sigma = k \cdot u(\sigma). \tag{7}\]

Where \( k \) is the coverage coefficient, defined as the Student's coefficient for the confidence level of 0.95 and the effective number of degrees of freedom, determined by the Welch-Satterswaite equation (in our case \( k = 1.65 \)).
Figure 4 shows graphs of the relative contribution of the input quantities to the measurement uncertainty of the output quantities $-\nu_{in,i}/\nu_{out,i}$.

Figure 4. The relative contribution of the input quantities to the measurement uncertainty of the output quantities: a – contribution to the measurement of the ultrasonic head wave propagation speed, b – contribution to the measurement of the ACC, c – contribution to the measurement of the TCC, d – contribution to the measurement of the mechanical stresses.

As a result of calculating the expanded uncertainty of mechanical stresses measurements, it was found that its value depends on the value of the measured mechanical stresses, as shown in figure 5. The expanded uncertainty value of mechanical stresses $U_\sigma$ was from 9 to 22 MPa when measuring mechanical stresses in the range of values from 0 to 1200 MPa.

Figure 5. Dependence of the expanded uncertainty on the value of the measured mechanical stresses.
4. Conclusion
A method was developed for assessing the uncertainty of mechanical stresses measurements by the ultrasonic method using OASCT based on [1]. The results of measurements of the propagation velocity of the ultrasonic head wave, the temperature of the controlled object and the OASCT can be seen from the graphs shown in figure 4. The coefficients of the ACC and TCC make a significant contribution to the uncertainty of the mechanical stresses’ measurements. In turn, the results of measuring the OASCT parameters and the travel time of the ultrasonic head wave based on the OASCT make a significant contribution to the measurement uncertainty of the propagation velocity of the ultrasonic head wave.

The dependence of the expanded measurement uncertainty on the value of the measured mechanical stresses was obtained. This dependence shows that mechanical stresses’ measurements in the range of less than 100 MPa have an uncertainty of more than 10% of the measured value. The measurement uncertainty will not exceed 4% (at a confidence level of 95%), when measuring mechanical stresses with the numbers higher than 200 MPa.

The proposed approach of assessing the measurement uncertainty of mechanical stresses can be useful in developing requirements for the used measuring instruments, calibration samples and control objects, as well as in the development of methods for monitoring mechanical stresses by the ultrasonic method using OASCT.

References
[1] GOST 34100.3-2017/ISO/IEC Guide 98-3:2008 Uncertainty of measurement. Part 3. Guide to the expression of uncertainty in measurement
[2] Bychenok V A, Berkutov I V, Mayorov A L, Ilyin A V, Kirienko V V, Prohorovich V E and Chekmareva M A Residual stress control in the near seam zone of the welding joint V mire nerazrushayushcheho kontrolya 21(4) 50–3
[3] GOST R 55043-2012 Non-destructive testing. Evaluation of elastic-acoustic coefficients. General requirements