Complex of National Standards for NDT of Mechanical Stresses and Application of Acoustoelasticity Methods in Industry and Transport

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Abstract

The report shows the results of developing of Russian national standards concerning to use of acoustoelasticity effect in the problems of NDT of stresses acting in industrials metals and alloys. Shear waves is the main instrument in the process of nondestructive evaluation of mechanical stresses by the help of acoustoelastic phenomenon. In the case of occurrence of uniaxial stress along a certain direction in solid, the velocity of shear waves polarized along and across of this direction will vary in different ways. An acoustic value characterizing this difference may be used for evaluation of the stress by mutually perpendicularly polarized shear waves propagated across the direction of stress acting. I hope that the developed standards will be very useful addition to other NDT standards as regulatory and technical documents establishing the basic requirements for ultrasonic pulse-echo method application for measuring of uniaxial or plane stresses in different industrials objects.

Keywords: Engineering materials, stress state, acoustoelastic effect, ultrasonic pulse-echo method, Russian national standards

1. Introduction

Stresses arising in an engineering material under the influence of temperature changes and its own weight; redistribution of working loads leads to reduction of durability of separate elements and of the construction as a whole. Owing to complexity of products and the wide range of loads, to which components are exposed in process of manufacturing and exploitation, it’s not always possible to calculate exactly effective stresses. Therefore problem of an experimental estimate of the real stressed state of machines and engineering structures is rather urgent in different industries.

Some problems of relevant prevision of dangerous stressed states of large-sized engineering constructions may be successfully solved on a base of investigations of nonlinear acoustic effects in engineering materials, for example, the acoustoelastic effect. Taking into account the nonlinear terms in the wave equation, one must find the dependence between the velocity of shear or longitudinal wave and the values of the mechanical stresses or strains in the medium. This dependence, i. e., the acoustoelastic effect, may be the physical foundation of the nondestructive manner of the evaluation of stressed states of solids [1, 2].

In the same time, acoustical NDT methods are well established in the finding of defects and damage of a material, but are not widely used to study changes in it’s stress state which varies during the production, processing of different types and in process of exploitation. These changes can be estimated using acoustic methods. The ultrasonic pulse-echo methods of NDT find great use in practice. It is possible to solve this problem without destruction of an engineering material by exciting waves of the amplitude essentially smaller than the effective stresses and evaluating their propagation speed changes in comparison with the unstressed material with a relative error of at least 0.01 %.

Relative cheapness and safety of an acoustical method in comparison with x-ray, a wider choice of materials and their stressed states in comparison with tensometry or magnetic methods render it attractive enough for achievement of such purposes. Methodological basis for use of the acoustoelastic effect to evaluate the plane stresses of engineering materials by ultrasonic echo-method was developed by author during more than 30 years [3].
In order to investigate anisotropic materials by nondestructive manner shear waves of ultrasonic frequency can be used rather effectively. Two "pure" modes with mutually perpendicular polarization directions are known to exist in an anisotropic material for each direction of shear wave propagation. Symmetry axes directions of micro structured material, which are not so evident at first sight, can be revealed by rotating the shear wave transducer. When shear oscillations are exited on the detail's surface at some angle with respect to the directions mentioned, the acoustical double refraction similar to that in optics can be observed. A value characterizing this effect in rolled material is a parameter of acoustic anisotropy - the relative difference of velocities of mutually perpendicularly polarized shear waves

\[ a_0 = \frac{t_{02} - t_{01}}{t_{av}} = \frac{V_{01} - V_{02}}{V_{av}}. \]  

(1)

Here \( t_{01} \) and \( t_{02} \) - time delays in the material of pulses of shear waves polarized along and across the direction of rolling, \( V_1 \) and \( V_2 \) - the corresponding velocities of shear waves propagating along the normal to the detail’s surface.

So, the velocity isn't a directly measured ultrasonic wave parameter. Such a parameter could be propagation time, and the thickness of testing material also varies with stress changing. So there must be three (not two) acoustoelastic equations determining two principal stresses. To solve this problem we use longitudinal wave propagated in the same direction as shear waves (across the plane of stress acting). Longitudinal waves are used together with shear waves as a specific “thickness-meter” to provide simultaneous monitoring of the “acoustical path” for ultrasonic pulses.

2. The evaluation of stresses or residual stresses in different objects

Numerous constructive elements include details with one size significantly less then the other two. Frequently such details experience biaxial stress under loading, or it is possible to consider the stressed state as locally biaxial stress in the area of the acoustical testing by ultrasonic pulse-echo method. Some simple relations between the duration and carrying frequency of ultrasonic pulse, elastic wave velocity and material thickness are proposed for acoustoelastic method effective application. So, the metallic material thickness must be 7-8 mm to provide in-plane principal stresses evaluation using three ultrasonic bulk waves and may be about 4-5 mm using shear waves only (without providing the same accuracy).

Following the procedure stated in introduction one can design and check in practice simple and reliable combined equations for biaxial stress evaluation on the base of precise time-of-flight measurements of shear and longitudinal ultrasonic waves [3]:

\[ \sigma_1 = K_1 \Delta_1 - K_2 \Delta_2, \]

\[ \sigma_2 = K_1 \Delta_2 - K_2 \Delta_1. \]  

(2)

Here \( K_1, K_2 \) - coefficients of elastic-acoustic connection [3], which depend only on linear and nonlinear properties of the material, have dimension of stresses (of modules of elasticity) and can be calculated theoretically or by the acoustic-mechanic testing of material samples.

Dimensionless quantities

\[ \Delta_1 = \left( \frac{t_3}{t_1} \frac{t_{01}}{t_{03}} - 1 \right), \quad \Delta_2 = \left( \frac{t_3}{t_2} \frac{t_{02}}{t_{03}} - 1 \right) \]

contain only relative values of
acoustic parameters. \( t_{0i}, t_i \) \((i = 1, 2, 3)\) are time delays of pulses of elastic waves composing the unique orthogonal basis providing two shear and one longitudinal waves propagation normally to the plane of stress action without turning of the plane of polarization. The parameters \( \Delta_1, \Delta_2 \) do not depend on any change of the acoustical path during material deformation.

In the case of uniaxial stress, knowledge of propagation time of only two types of waves is sufficient for stress evaluation. So, the formula for evaluation of stress acting in the direction 1 of shear wave polarization may be constructed on a base of acoustical birefringence phenomenon in a form:

\[
\sigma_1 = (K_1 + K_2) \left( \frac{t_1 t_{02}}{t_2 t_{01}} - 1 \right).
\]

By neglecting the terms of the second order with respect to relative values of time-of-flight variations one can receive a well known formula for determination of uniaxial stress acting in the direction 1 of shear wave polarization on basis of acoustical birefringence phenomenon [4]:

\[
\sigma_1 = D(a - a_0).
\]

So, the value of uniaxial stress appearing in the plane perpendicular to shear waves propagation direction, may be evaluated directly using the elastic-acoustic coefficient \( D = K_1 + K_2 \) and the values of acoustical anisotropy parameters of the material after and before the stress occurrence:

\[
a = \frac{t_2 - t_1}{t_2}, \quad a_0 = \frac{t_{20} - t_{10}}{t_{20}}.
\]

Here \( a_0 \) is the value of material intrinsic anisotropy (1).

The first national standard of Russian Federation (RF) which establishes general requirements for NDT of stresses in elements of engineering objects [5] entered into action in October 2007. The document recommends the abovementioned procedure for evaluation of mechanical stresses in plane details of different machines and constructions after their montage or exploitation. The measuring acoustic parameters must be made as described in detail in [1], using experimental setup or special device for precise determination of time intervals between first and one of next echo-pulses. Experimental arrangement must provide propagation in the material shear waves during no less than 50 microseconds and longitudinal shear waves during at least 30 ms. The error of time interval measuring by the using ultrasonic arrangement must not exceed 0.01 ms.

2. The evaluation of axial and circumferential stresses in steel pipes

The reliability of acoustoelastic manner for biaxial stress evaluation in linear or technological pipelines of large (820–1420 mm) diameter was experimentally justified in numerous investigations of GAZPROM objects. For example, a terminated steel pipe cut out from linear pipeline was closed by two bottoms and exposed to inner pressure of water of 70 atm. (previously). Pressure of 25 and 50 atm. were applied to closed pipe with simultaneous nondestructive stress evaluation by acoustoelastic method.

Theoretical solution of the problem is known as a “Lame problem” and was found in 19th century. As “radial” stresses are essentially smaller than “circumferential” and “axial” stresses, the stressed state of a small part of a thin envelope of the pipe is performed as biaxial stress. So, the stresses are large in proportion to relation between diameter and thickness of the pipe, and circumferential stress is twice larger than axial stress.
Precise measurements of time-of-flight of shear and longitudinal waves propagated across the plane of stress acting were carried out before and during the loading. A special compact device for nondestructive evaluation of mechanical stresses produced by “ENCOTES” Ltd was used for the experiment. Values of stresses acting along ($\sigma_1$) and across ($\sigma_2$) the pipe axis were calculated automatically by the computational module of the device, in accordance with the algorithms (2).

The results of our investigations show that the observed data are quite close to Lame predictions. The difference between the stresses evaluated by ultrasound and by theoretical calculations is equal to 11 MPa for axial stress $\sigma_1$, 25 MPa for circumferential stress $\sigma_2$ and does not exceed 5% of the steel yield point equal to 500 MPa. So, it is very good accuracy for non-destructive evaluation of plane stress in pipes.

Led by the author and in collaboration with Technical Committee (TC) 132 “Technical Diagnostics” the development team creates and introduces into action a national standard [6]. The document regulates the basic provisions of ultrasonic techniques for measuring stresses in steel pipes of large diameter which used in the construction of gas and oil pipelines. It is based on results of laboratory and field tests realized by employees of “ENCOTES” Ltd on GAZPROM facilities with the participation of the author of the report.

### 3. Experimental evaluation of dynamic stress in rods and bars

The essence of the acoustoelastic phenomenon is the dependence between elastic wave velocity and mechanical stress (strain) value in solids. The probability of acoustoelastic effect using in the cases of quasi static (in comparison to elastic wave frequency) stressed state evaluation was studied experimentally. Longitudinal oscillations of rod samples were exited and harmonic stresses of about 500 Hz frequency range and of the 20-120 MPa amplitude range were provided.

The experimental setup was constructed from ordinary and original blocks, including specially designed piezoelectric transducers for exciting and receiving pulses of shear waves with smooth envelope and the main (carrier) frequency of 5 MHz. The influence of dynamic stress on high-frequency pulsed signals propagation along the direction perpendicular to the rod axes was experimentally investigated.

It was shown experimentally that acoustoelastic phenomenon may be used for the quantitative estimation of average (among the ultrasonic beam volume) peak values of dynamic stresses. Moreover, the quantitative characteristics of the effect differ only slightly from the ordinary acoustoelasticity parameters which are known for steel and aluminum (the materials of rods). Therefore, a new method of non-destructive evaluation of amplitude of vibration was proposed on the base of the researches. Method may be used for the measuring of the sound and vibration characteristics not only on the surface, but also inside the material’s volume.

So, the general requirements for evaluating of dynamic stress, frequency of changes of which is much smaller than the carrier frequency of the probing acoustic pulse, by ultrasonic pulse-echo method, were established in national standard [7]. I hope that this regulatory and technical document will be useful addition to other standards concerning to practical application of acoustoelasticity phenomenon in industrial metals and alloys.

### 4. The measurements of nonlinear elastic properties of solids

Unlike many other methods of an estimation of the stress states of engineering materials where
dependences of informative parameters on stresses (deformations) are phenomenological, that is are only by practical experience, here dependencies between the speeds of elastic waves and stresses can be found mathematically, in approach of the five-constant theory of elasticity. In 1953 for the first time dependences of speeds of bulk waves on uniaxial stress and all-round compression were revealed “on a feather tip” [1]. For a case of elastic waves propagation along the normal to the plane of stress acting it is possible to present the formulas of Hughes and Kelly in a form:

\[
\frac{V_1^2}{V_{01}^2} - 1 = 2 \left( \frac{V_1}{V_{01}} - 1 \right) = \frac{1}{3K_0} \left( \lambda + 2\mu + m + \frac{\lambda n}{\mu} \right) \sigma = 2k_1 \sigma,
\]

\[
\frac{V_2^2}{V_{02}^2} - 1 = 2 \left( \frac{V_2}{V_{02}} - 1 \right) = \frac{1}{3K_0} \left( 2\lambda - m + \frac{\lambda n}{2} \right) \sigma = 2k_2 \sigma,
\]

\[
\frac{V_3^2}{V_{03}^2} - 1 = 2 \left( \frac{V_3}{V_{03}} - 1 \right) = \frac{1}{3K_0} \left[ \frac{2\lambda}{\mu} \left( \lambda + 2\mu + m \right) - 2l \right] \sigma = 2k_3 \sigma.
\]

Here \(V_1, V_2\) - speeds of the shear waves polarized along and across to a direction of action of stress, \(V_3\) - speed of a longitudinal wave; \(\lambda, \mu, K_0 = \lambda + \frac{2}{3} \mu\) – modules of linear elasticity; \(m, n, l\) – modules of nonlinear elasticity of Murnaghan. Corresponding combinations of these constants are designated \(k_1, k_2, k_3\) and named “coefficients of acoustic-elastic connection” [3,5,6]. Those coefficients represent the tangencies of the angles between axes \(\sigma\) and line of dependence \(\Delta V/V(\sigma)\) for corresponding type of bulk elastic wave. \(k_1, k_2, k_3\) depend only on linear and nonlinear properties of the material (no any phenomenological presumptions!).

So, it is necessary to excite in a material all three bulk waves which can propagate on a normal to a plane of action of stresses – two mutually perpendicularly polarized shear waves and a longitudinal wave. Thus, the combined equations for biaxial stress evaluation on the base of precise time-of-flight measurements of shear and longitudinal ultrasonic waves may be written in a form [3]:

\[
\frac{L}{t_i} \frac{t_{0i}}{L_0} - 1 = k_i \sigma_1 + k_2 \sigma_2,
\]

\[
\frac{L}{t_2} \frac{t_{02}}{L_0} - 1 = k_2 \sigma_1 + k_3 \sigma_2,
\]

\[
\frac{L}{t_3} \frac{t_{03}}{L_0} - 1 = k_3 \sigma_1 + k_3 \sigma_2.
\]

Here \(L_0, L\) - a distance of wave propagation before and after the occurrence of stresses, proportional to a thickness of a material; \(t_{0i}, t_i\) \((i=1,2,3)\) - times for which this distances were passed (it is supposed that elastic-acoustic properties of a material are identical in all directions). In case of uniaxial stress (for example \(\sigma_2 = 0\)) the equations (5) and (6) coincide.

Having excluded variation of a material thickness \(\frac{h}{h_0} = \frac{L}{L_0}\) from the combined equations (6) and neglecting terms of the second order in relation to values \(\Delta_i = \left( \frac{t_i}{t_i} \frac{t_{0i}}{t_{0i}} - 1 \right)\) \((i=1,2)\), one can receive the simple enough algorithm (2) for determination of biaxial stresses by results of precise
time-of-flight measurements of shear and longitudinal ultrasonic waves. The coefficients of elastic-acoustic connection $K_1$, $K_2$ in formulas (2) are coupled with values $k_1, k_2, k_3$ by the relations: $K_1 = \frac{k_1 - k_3}{(k_1 - k_3)^2 - (k_2 - k_3)^2}$, $K_2 = \frac{k_2 - k_3}{(k_1 - k_3)^2 - (k_2 - k_3)^2}$. 

It may be known in advance that the stressed state of a detail is uniaxial. Then, bearing our assumptions in mind, knowledge of propagation time of only two types of waves is sufficient for stress evaluation. Considering the greatest sensitivity to stress of the wave polarized along a direction of its action, the formula for stress evaluation may be writing down in a form:

$$\sigma_i = \frac{1}{k_i - k_i} \left( \frac{t_i}{t_0} - 1 \right), \quad i=2 \text{ or } 3. \quad (4)$$

If $i=2$ (only shear waves are used for ultrasonic measurements) the elastic-acoustic coefficient $D = \frac{1}{k_1 - k_2} = K_1 + K_2$ is appearing in formulas (3,4) for uniaxial stress nondestructive evaluation. In isotropic hyper elastic medium $a_0 = 0$, the coefficient $D = 8\mu^2 / 4\mu + n$, where $\mu$ - shear modulus, $n$ – Murnaghan modulus of nonlinear elasticity.

National standard RF concerning to experimental estimation of the coefficients of elastic-acoustic connection in weakly and strongly anisotropic engineering materials [9] was entry into force at January 1, 2014. The determination of values $k_1, k_2, k_3$ is recommended by using expressions (6), where $\sigma_2 = 0$ and $\sigma_1$ may represent tension or compression.

When the procedure of $k_1, k_2, k_3$ is provided in isotropic or weakly anisotropic material in accordance to regulatory document [9], the values of third order elasticity modulus $m, n, l$ (or any other three constants of nonlinear elasticity which are in linear relations with the Murnaghan’s modules) may be find with application of formulas (5).

So, modulus $n$ is evaluated by use first and second relations in (5) according to formula $\frac{4\mu + n}{8\mu^2} = k_1 - k_2$. The error of it’s evaluation is small in relation to corresponding errors for nonlinear elastic constants $l$ and $m$. The standard for quantitative estimation of the parameters of quadratic nonlinearity of solids [10], must be helpful not only for practical realization of the acoustoelastic effect, but also for using in practice another nonlinear effects in solids.

4. Conclusions

1. The acoustoelasticity phenomenon may be use as the physical foundation of the nondestructive method of the evaluation of stressed states of solids. The data of direct measurements of mechanical stresses in industrial objects may help us to refine the computation of the stressed-strained state of the engineering structures by the finite-element method. The using of nondestructive pulse-echo methods of stress and residual stress relevant measurements allows to optimize the engineering constructions and to increase the rate of safety during their production and exploitation. It leads to essential economy of engineering materials and increasing of their quality range.
2. Ultrasonic pulse-echo methods of inner dynamic stresses in engineering materials must be developed and some fundament for their practical using must be constructed. It will be a subject of great importance for testing of large material’s volumes and in the cases of non-uniform distribution of loads inside the volume. The realization of methods of inner dynamic stress evaluation allows to estimate the strength of civil constructions under vibration and to choose the relevant manners of people and objects protection.

3. The number of standards of Russian Federation which establishes general requirements for NDT of stresses in elements of industrial objects, including linear and technological pipelines, were entered into action from 2007 to 2014 years. It is based on methodological foundation developed by author during more than 30 years and on results of laboratory and field tests realized by researches of Mechanical Engineering Research Institute and Institute of Applied Physics of RAS, “ENCOTES” Ltd and GAZPROM with the participation of the author. In collaboration with Technical Committee (TC) 132 “Technical Diagnostics” the development team creates a complex of national standards which regulate the basic provisions of ultrasonic techniques for measuring stresses in key details of engineering structures used in industry and transport.

References