Usage of the acoustic method for monitoring of the gaz pipelines stress

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Abstract. Nowadays, Russian pipeline system is a unique and expanding facility. It is a chain of complex of technical facilities that carries gas under high pressure in difficult geological, geographical and climatic (arctic) conditions, both in the Russian Federation and beyond its borders. Ensuring safe operation is an important task.

1. Introduction

The construction materials that are used in the pipeline production, in many cases have significant anisotropy: rolled steel sheets, rods, etc [1, 2]. In particular, steels, used in the manufacture of "large" diameter pipes, are related to such materials. High-strength steels of class X70, manufactured by using the method of controlled rolling [3], are used during the production of the linear part of trunk gas pipelines. The base of these parts is mild low-alloyed steels. A distinctive feature of this class of steels is a significant structural heterogeneity. Pipelines are exposed to high stresses, as a result of which, the probability of their destruction and number of defects, such as stress corrosion cracking (SCC), increases. These examples indicate continuing pipeline system deterioration. Premature failure of pipelines, lead to significant costs, associated with interruptions in the transportation of hydrocarbons, subsequent repair and elimination of the environmental consequences of the accident. Promising way of their reduction is the creation of a system of control and prevention emergencies without interrupting the operation of the system. Now modern methods of stress state material diagnostics, that use non-destructive testing methods, are becoming more important for monitoring stresses in pipelines. Due to this, there is an increased attention to methods and instruments of non-destructive control of the pipeline material stress state. This is why the development the ways of stress diagnostics, based on non-destructive control methods during both manufacture and operations, is relevant scientific and technical problem.

Acoustic methods can be used to control the mechanical stresses arising in the gas pipeline material. The presence of anisotropy leads to the complication of the acoustoelasticity matrix theory equations, traditionally used in determining the stress state of a material, and to an increase the number of errors in determining the stresses in a material of a controlled pipe. As measured parameters, the velocities (time of propagation) of elastic waves are used.

2. Research methodology

Control of mechanical stresses in the material by the acoustic method is based on the relations of acoustoelasticity [4–6]. The equations of the velocity (propagation time) of elastic volume waves with different polarization with acting stresses have the following forms:
\[
\begin{align*}
\frac{V_1 - V_{01}}{V_{01}} &= \beta_1 \sigma_1 + \beta_2 \sigma_2, \\
\frac{V_2 - V_{02}}{V_{02}} &= \beta_3 \sigma_1 + \beta_4 \sigma_2, \\
\frac{V_3 - V_{03}}{V_{03}} &= \beta_5 (\sigma_1 + \sigma_2).
\end{align*}
\]

\( V_1 \) – speed of transverse elastic wave, propagating normally to the surface of the pipeline and polarized in the longitudinal direction;

\( V_2 \) – velocity of transverse elastic wave, propagating normally to the surface of the pipeline and polarized in the annular direction;

\( V_3 \) – speed of the longitudinal wave, propagating normally to the surface of the pipeline;

\( V_{01}, V_{02}, V_{03} \) – propagation velocities of elastic waves of the corresponding types in a non-stressed material;

\( \beta_{51,23,4,5} \) – acoustoelastic velocity coefficients.

During the construction of acoustoelasticity engineering correlation, the ratio, based on time intervals [7] was used. On the base of the acoustoelasticity basic equations, in case of a plane stress with the main stresses \( \sigma_1, \sigma_2 \), in a plane, located perpendicularly to the direction of elastic waves propagation, the equations, that relate the stresses to the propagation times (delays) of elastic waves of two types: longitudinal and transverse, polarized along principal stresses [7] are obtained.

Pipeline material is made of steel with adjustable rolling that is considered to be an orthotropic material with anisotropy axes, directed in the longitudinal and circumferential directions (axes of the Cartesian coordinates \( x \) and \( y \)). The wave vector, used for volume waves, coincide in direction with \( z \) axis. The main stresses (longitudinal (axial) \( \sigma_1 \) and circumferential \( \sigma_2 \)) lie in the plane \( z = 0 \) directed along the \( x \) and \( y \) axes respectively.

The large trunk pipelines material (more than 700 mm diameter) stress is assumed to be flat for each measurement zone.

Propagation times of elastic waves in the stressed state are denoted by \( t_1, t_2, t_3 \), and in unstressed state by \( t_{01}, t_{02}, t_{03} \). The values of the pipe wall thickness in the measurement zone are denoted by \( h \) and \( h_0 \).

The equations (1) – (3) will have the following form:

\[
\begin{align*}
\frac{h}{t_{01}} &= 1 + \beta_1 \sigma_1 + \beta_2 \sigma_2, \\
\frac{h}{t_{02}} &= 1 + \beta_3 \sigma_1 + \beta_4 \sigma_2, \\
\frac{h}{t_{03}} &= 1 + \beta_5 (\sigma_1 + \sigma_2).
\end{align*}
\]

(4) (5) (6)

Elementary transformations make it possible to eliminate the unknown value \( \frac{h}{h_0} \), and, by rejection the additives of the second order of smallness, write down the equations of acoustoelasticity in the following form:

\[
\begin{align*}
\delta d_1 &= \alpha_1 \sigma_1 + \alpha_2 \sigma_2, \\
\delta d_2 &= \alpha_3 \sigma_1 + \alpha_4 \sigma_2, \\
\delta d_1 &= \frac{d_1 - d_{01}}{d_{01}}, d_1 = \frac{t_1}{t_4} d_{01} = \frac{t_{01}}{t_{03}}, \\
\delta d_2 &= \frac{d_2 - d_{02}}{d_{02}}, d_2 = \frac{t_2}{t_4} d_{02} = \frac{t_{02}}{t_{03}}.
\end{align*}
\]

(7) (8)

\( \alpha_1, \alpha_2, \alpha_3, \alpha_4 \) – acoustoelastic coefficients of relative delays, associated with acoustoelasticity coefficient:

\[
\begin{align*}
\alpha_1 &= \beta_5 - \beta_1, \alpha_2 &= \beta_5 - \beta_2, \\
\alpha_3 &= \beta_5 - \beta_3, \alpha_4 &= \beta_5 - \beta_4.
\end{align*}
\]

(9) (10)

From equations (18) – (19) it is easy to obtain the design relations for determining the plane stress state:

\[
\begin{align*}
\sigma_1 &= k_1 \delta d_1 + k_2 \delta d_2, \\
\sigma_2 &= k_3 \delta d_1 + k_4 \delta d_2.
\end{align*}
\]

(11) (12)
To determine the acoustoelastic coefficients of the biaxial stress state in anisotropic materials, such as rolled products, use standard samples which are cut along and across the rolled product. This method seems to us to be most convenient for obtaining acoustoelastic coefficients of anisotropic material.

3. Results of research and discussion

For the calibration and determination of acoustoelastic coefficients, two groups of samples were cut out of the pipe made of X70 steel (in accordance with GOST 1497): longitudinal (along the pipe axis) and circumferential (across the pipe).

Acoustic measurements were performed using the ICC “ASTRON”. A converter with three active elements [8–10] was used: two transversely polarized piezo plates with polarization vectors directed along and across the anisotropy axes of the orthotropic material, and a longitudinal piezo plate. The measurements were made repeatedly in the "loading - unloading" mode.

The averaged results of acoustic measurements on samples are shown in Figures 1, 2.

For all obtained dependences, the correlation coefficient turned out to be practically equal to 1, which indicates the existence of a linear dependence of the parameters $\delta d_1, \delta d_2$ on the uniaxial stress.

The regression processing of the data allows to determine the acoustoelastic coefficients $\alpha_1, \alpha_2, \alpha_3, \alpha_4$:

$\alpha_1 \approx 16,6 \times 10^{-6} \text{MPa}^{-1}$,
$\alpha_2 \approx 3,6 \times 10^{-6} \text{MPa}^{-1}$,
$\alpha_3 \approx 2,2 \times 10^{-6} \text{MPa}$,
$\alpha_4 \approx 9,3 \times 10^{-6} \text{MPa}^{-1}$.

The results of the calculation of tensometric coefficients by equation gave the following values:

$k_1 = 0,63 \times 10^5 \text{MPa}$,
$k_2 = -0,25 \times 10^5 \text{MPa}$,
$k_3 = -0,15 \times 10^5 \text{MPa}$,
$k_4 = 1,13 \times 10^5 \text{MPa}$.

Testing the possibility of using equations (11), (12) for calculating the stresses in the pipeline material made of steel X70 was made with hydraulic pressing of a pipeline segment with a diameter in amount of 1420 mm and wall thickness of 19.5 mm with welded heads.

The longitudinal $\sigma_1$ and circumferential $\sigma_2$ stresses are calculated using the well-known equation depending on pressure and pipe geometry:

$$\sigma_1 = \frac{PD}{4h}$$

(14)
\[ \sigma_2 = \frac{pd}{zh} \]  

\[ P \] – pressure in the pipe, \( D \) – internal diameter, \( h \) – wall thickness.

Hydropressing was made in the pressure with range of \( P \) from 0 to 7.5 MPa.

The results of measurements and processing of the results are stated in table 1 with \( \sigma_1^a, \sigma_2^a \) denoted experimentally obtained stresses, \( \Delta \sigma_1, \Delta \sigma_2 \) – absolute tolerance of their determination.

**Table 1. Results of check experiment**

| Parameter | Value |
|-----------|-------|
| \( P \), MPa | 0 | 1.0 | 2.5 | 4.0 | 5.0 | 6.0 | 7.5 |
| \( \sigma_1 \), MPa | 0 | 18 | 44 | 71 | 89 | 106 | 133 |
| \( \sigma_2 \), MPa | 0 | 36 | 88 | 142 | 178 | 212 | 266 |
| \( \delta d_1 \times 10^4 \) | 0 | 4.0 | 9.7 | 16.5 | 21.1 | 25.3 | 31.1 |
| \( \delta d_2 \times 10^4 \) | 0 | 3.9 | 10.0 | 15.6 | 19.5 | 23.1 | 28.7 |
| \( \sigma_1^a \), MPa | 0 | 15 | 36 | 65 | 84 | 102 | 124 |
| \( \sigma_2^a \), MPa | 0 | 38 | 98 | 152 | 189 | 223 | 278 |
| \( \Delta \sigma_1 \), MPa | 0 | -3 | -8 | -6 | -5 | -4 | -9 |
| \( \Delta \sigma_2 \), MPa | 0 | 2 | 10 | 10 | 11 | 11 | 12 |

The results, stated in Table 1, indicate a sufficiently high accuracy in the determination of stresses in the investigated section of the pipeline.

Estimation of the pipeline material anisotropy influence on the tolerance in the determination of stresses shows that the deviation in measuring the stresses in the pipeline reaches 200 MPa [7, 11]. Accounting of anisotropy (corresponding coefficients of acoustoelasticity) allows to reduce the measurement tolerance to 20 MPa.

**4. Conclusions**

The proposed method can be used in determining the mechanical stresses in the material of gas pipelines made of anisotropic steel.

To improve the accuracy in determining the residual stresses, it is necessary to take into account the pipeline material anisotropy by conducting calibration experiments on samples (made from controlled pipe material) in order to obtain acoustoelastic coefficients.

The tolerance in the determination of stresses can reach 20 MPa that is quite acceptable for the practical use.

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**References**

[1] Efron L. I. 2012 *Metallurgy in the "big" metallurgy. Pipe steels* (Moscow: Metallurgizdat).
[2] Danchenko V N, Kolikov A P, Romantsev B A, Samusev S V 2002 *Technology of pipe production* (Moscow: Internet Engineering).
[3] API 5L (PSL 2). Pipes steel electrowelded straight-seam
[4] Guz A N, Makhort F G, Gushcha O I 1977 *Introduction to acoustoelasticity* (Kiev: Naukova Dumka)
[5] Bobrenko V M, Vangeli M S, Kutsenko A N 1991 *Acoustic tensometry* (Chisinau: Stinitsa)
[6] Klyuev V V et al 2004 *Unbrakable control Volume 4, Book.1. Directory. In 7 volume. Acoustic tensometry* (Moscow: Mashinostroenie).
[7] Nikitina N E 2005 *Acousto-elasticity. Experience of practical application* (Nizhny Novgorod: TALAM)
[8] Prilutsky M A, Uglov A L, Khlybov A A Ultrasonic shear wave sensor / Pat. №2365911 Russian Federation, IPC G01N 29/22. Application No. 2007126281/28 07.10.2007; publ. 08.27.09 Bul. 24

[9] Uglov A L, Erofeev V I, Smirnov A N 2009 Acoustic control of equipment for the manufacture and operation (Moscow: Science)

[10] Aleshin N P, Uglov A L, Khlybov A A, Prilutsky M A 2008 Zavodskaya Laboratoriya. Diagnostika Materialov 3 14–19

[11] Khlybov A A 2018 Russian Journal of Nondestructive Testing 54 3–10