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WAY OF DETERMINING THE SPATIAL DISTRIBUTION OF STRESSES ALONG THE MAIN PIPELINE SECTION USING ULTRASONIC METHOD

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СПОСІБ ВИЗНАЧЕННЯ ПРОСТОРОВОГО РОЗПОДІЛУ НАПРУЖЕНЬ УЗДОВЖ ДІЛЯНКИ МАГІСТРАЛЬНОГО ТРУБОПРОВОДУ УЛЬТРАЗВУКОВИМ МЕТОДОМ

Purpose. Determination of the stress state and visualization of spatial stress distribution along the main pipeline section under operating conditions, which will make it possible to advise on the way for pipeline repair and recovery with provision of the structural integrity.

Methodology. Mathematical model for determining the main pipeline stress-strain state, which relates the stress value at a control point to speed variation of ultrasonic waves propagating in mutually perpendicular directions, was described on the basis of the acoustoelasticity laws and acoustic theory. Stress spatial distribution was modeled on a pipeline section using the computer algebra system.

Findings. The choice of approach to the spatial representation of the pipeline stress state was justified; basic steps and mathematical relationships to determine the stress state of the pipeline section were described. The results obtained were confirmed in practice. Their interpolation and visualization as continuous surface allows simulating the stress state between the control points on the pipeline surface.

Originality. The way of determining the data of the stress-strain state of main pipelines, their processing, visualization and adequate interpretation of the situation in terms of repairs was developed.

Practical value. The algorithm of pipeline wall stress determining along three mutually perpendicular directions is presented. The method of visualization of the spatial stress distribution both along the normal pipeline crossing and the main pipeline section was proposed, which allows non-destructive testing results to be used under operating conditions. This is especially important for dangerous sections of gas pipelines and pipeline systems, whose failure can result in environmental pollution and accidents with drastic consequences.

Keywords: *pipeline, stress, ultrasound, non-destructive testing, acoustoelasticity, modeling, interpolation*

Introduction. Ukraine's gas transportation system is closely related to the gas transportation systems of neighboring European countries and plays a significant role for the European energy security. They share a common goal – Siberia gas transportation to Europe. It is a diversification source providing over 30 % of the gas needs of the state, and the object of special responsibility. During the long-term operation of the main pipelines, which are an integral part of the gas transportation system of Ukraine, various deformation processes arise, leading to their technical state change and emergency situations. Safe and reliable operation of gas transportation system facilities is not possible without a diagnostic monitoring of the technical state of pipelines, including the stress-strain state of the main pipeline sections [1].

Statement of the general problem. Timely evaluation of stress-strain state allows foreseeing a significant number of pipeline breaks and failures, as well as developing a set of preventive measures and reducing the operational risk to the acceptable level. Therefore, the task of creating system devices and techniques to become an integral part of technological systems for processing, determining and visualization of data of the stress-strain state of pipeline sections under repair and adequate interpretation of an emergency situation is relevant. This is especially important for potentially dangerous sections of pipelines and pipeline systems in general that need to be repaired and are operated in extreme conditions caused by different kinds of overstress, whose failure can result in significant property damage and environmental pollution, as well as in accidents with drastic consequences.

Analysis of the recent research and publications. The stress-strain state of the main pipeline sections can be evaluated during their operation by monitoring the stress within its walls. Ultrasonic method is one of the methods for determining the stress intensity within the wall of a

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pipeline under operation. Based on common physical reasons, the speed or time of ultrasonic wave propagation can be stated to be the physical parameter corresponding to the actual stress intensity of the test metal.

Many test centers are involved in the problem of determining stresses in objects in operation for the purpose of their actual technical state assessment. The dependence of the speed of ultrasonic wave propagation on the stress state in metal samples was evaluated by domestic (Huz A., Hushcha O., Paton B. [2]) and foreign (D. Eagle and K. Winkler) scientists. Famous domestic and foreign ultrasonic measuring instruments (such as “Stresskan”) applied to control the stress state of pipelines in the field environment failed to be implemented on a large scale basis due to the low accuracy level (40 % error) [3]. The specialists of Ivano-Frankivsk National Technical University of Oil and Gas and Research Institute “Kvant” jointly developed the ultrasonic mechanical stress meter, designed to measure the plane stress state of elements of welded metal structures without their destruction, as well as to investigate the physical and mechanical properties of structural materials [3]. The methods of ultrasonic testing of the stress-strain state of pipelines, developed by Ivano-Frankivsk National Technical University of Oil and Gas scientists, are known [4, 6]. The specified research studies indicate methods developed to determine the total stress value within the walls of pipelines depending on the time or speed of transverse ultrasonic wave propagation and on the group speed of zero and first modes of plate wave propagation [5]. However, the effectiveness of different methods and stress control equipment used directly under operating conditions still remains low.

The authors [7] developed the mathematical model for calculating the stress state of the main gas pipeline based on the results of its center line discrete points position in space, usually defined by a geodesic pig. The geometric characteristic of a curve (curvature) is the second derivative of the radius vector and, based on the structural mechanics, is proportional to the bending moment in case of elastic and general strain. Thus, with these geometric values, one may conclude the additional stress or strain influencing the pipeline section. However, the availability of a huge number of papers indicates some difficulties, primarily related to inaccuracies of point positions measurement, the so-called “noise”.

Unsolved aspects of the problem. Digging the underground pipeline section out for repair is followed by a disbalance, sometimes by a pipeline section protruded off the repair pit due to a stress state formed during a continuous operation. In practice, especially during the underground pipeline sections repair, not only the total stress value within pipeline walls, but also the values of main stress vectors, allowing determining the location and direction of stress application, both around and along the pipe, and establishing their causes for timely responding by repair and recovery teams, should be taken into consideration. The easier way to do this is to visualize the stress distribution within the pipeline section to be checked. It is also possible to determine the optimal length of the pipeline repair section to be dug out, which significantly affects the repair performance.

Objectives of the article. The way out of this situation is to develop a way to research the actual distribution of stresses within the repair section of the main pipeline, allowing correctly presenting its spatial description under operating conditions by visualizing the obtained data.

Presentation of the main research. In some cases solving the problems, such as digging the pipeline out, is associated with significant costs, since this requires additional equipment and pipeline surface preparation for its technical state monitoring. Therefore, the possibility of the main pipeline trenching and pipeline surface control points selection, which significantly improves the repair performance, is of interest.

The developed mathematical model for stress calculation by means of longitudinal ultrasonic waves propagating in a distorted environment is described in [8], resulting in the analytical dependence relating the stress values within the environment of ultrasonic longitudinal waves propagation at a control point in three mutually perpendicular directions to their speed variation was estimated

$$\left.\frac{\Delta V}{V_0}\right|_{\perp XZ} = A_X\sigma_X + A_Z\sigma_Z;$$

$$\left.\frac{\Delta V_w}{V_0^*}\right|_{\angle XY} = 1.4142\left(A_{X1}\sigma_X + A_{Z1}\sigma_Z\right); \quad (1)$$

$$\left.\frac{\Delta V_w}{V_0^*}\right|_{\angle YZ} = 1.4142\left(A_{Y2}\sigma_Y + A_{Z2}\sigma_Z\right),$$

where ΔV_w is measured variation of speed of longitudinal ultrasonic wave propagation in the environment with an applied load in the directions of X, Y, Z axes, (Fig. 1); V_0^*, V_0 is speed of longitudinal ultrasonic wave propagation in a stress-free environment in these directions; $A_X, A_Z, A_{X1}, A_{Z1}, A_{Y2}, A_{Z2}$ are acoustoelasticity coefficients determined experimentally in a normal XZ plane relative to the load direction and at α angle to XY and YZ planes.

Reference (1) takes into account the first equation describing the propagation of ultrasonic wave relative to the XZ plane, next two equations describing the propagation of ultrasonic wave at the same angles to XY and YZ planes using the proposed system of primary converters, which are part of the ultrasound device [8]. The sensors are inclined at an angle ensuring the longitudinal ultrasonic wave propagation in the pipeline wall at an angle of 45° to the

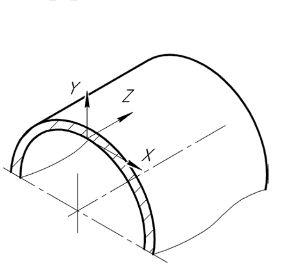

Fig. 1. Pipe surface element:
X, Y, Z – system axes at the point of measurement

interface of two environments. The system of primary transducers comprises five piezoelectric sensors installed at certain angles. Two pairs of sensors are installed in mutually perpendicular planes, one sensor used as a transmitter, and the second as a receiver of ultrasonic waves per each plane. One piezoelectric transducer is a dual element, located in the central part of the sensing system and is installed perpendicular to the test surface.

Thus, with the help of the sensing system, the speed of ultrasonic wave propagation in three planes is determined, which allows determining the stress intensity acting in three mutually perpendicular directions.

To get a complete picture of stress distribution both in and along the normal cross section, more than one measurement is required. For this purpose the number of control points both around and along the pipe has to be increased. Increasing the number of points shall be justified, since each additional measurement increases the monitoring time.

To monitor the stress-strain state of a repair section of the underground linear part of gas pipeline "Soiuz" of Bohorodchany linear production department of the main gas pipelines, trunk pipeline operators "Prykarpattranshas" used the developed primary transducer, ultrasonic flaw detector UD4-T and PC. The small size and weight of the devices, ease of operation and the independent power supply possibility allowed applying them under operating conditions.

The upper generating line of the main pipeline was monitored at eight points around the pipe, which was previously dug out by trenching in three locations along the pipeline repair section, see Fig. 2. Control point interval around the pipe was θ = 45°, the distance between the trenches was 20 meters. At these points the variation of speed of ultrasonic wave propagation was determined by the pipe cross section. The stress values in monitored sections are listed in Table 1.

These values represent a discrete set of values. For qualitative analysis of the situation, these results are to be visualized by interpolation, and represented as a continuous surface, allowing simulating the stress state between the control points of the pipeline surface. It should be noted that the calculation procedure described is analogically applied for the calculation of stresses σ_x, σ_y, σ_z.

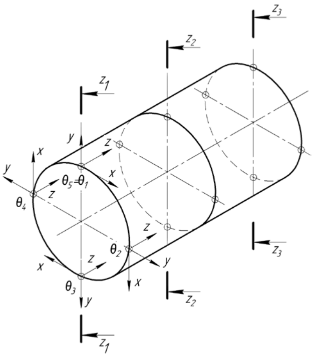

Fig. 2. Measuring grid:

z_1, z_2, z_3 – position of the pipe cross sections along the monitored pipeline section to be measured; θ_1, θ_2, θ_3, θ_4, θ_4 – *angular position of the measurement points*

Table 1

Stress within monitored sections, MPa

Control points	Stress type	Cross section		
		1	2	3
1	σ_x	86.3	130.2	126.5
	σ_y	11.2	13.6	10.3
	σ_z	43.7	66.3	64.4
2	σ_x	98.2	152.9	143.5
	σ_y	8.3	9.8	8.7
	σ_z	47.9	76.2	70.2
3	σ_x	106.4	180.2	170.3
	σ_y	11.3	10.4	9.1
	σ_z	54.2	88.9	84.5
4	σ_x	169.3	205.8	193.1
	σ_z	13.2	13.9	12.2
	σ_z	85.7	103.2	96.3
5	σ_x	143.8	172.7	160.7
	σ_y	10.1	11.8	11.2
	σ_z	75.3	89.3	78.2
6	σ_x	100.7	156.2	139.6
	σ_y	9.8	8.6	8.1
	σ_z	51.2	78.3	68.4
7	σ_x	126.8	157.8	153.2
	σ_y	10.1	9.6	11.3
	σ_z	60.4	86.3	74.8
8	σ_x	107.3	146.3	145.3
	σ_y	10.3	11.2	9.6
	σ_z	52.3	68.2	60.7

The small number of control points allows choosing a continuous interpolation for creating the pipeline stress state model, which provides the necessary degree of smoothness without additional information (differential characteristics) at the points of measurement.

Stress values are presented in the form of surface, whose independent parameters are the coordinates of pipeline control points.

Interpolation function is represented as the sum of functions-summands [9]. In general, the interpolation function *s* looks like the following

$$s(u,v)=\sum_{i=1}^{n} a_i \cdot B_i(u,v,u_i,v_i),$$

where *u, v* are independent function coordinates; a_i stands for the basic function B_i coefficients; u_i and v_i are grid points coordinates; *n* is the number of points of measurement.

The basic function is presented by a fractional rational function, whose suitability for the use in continuous interpolation has been investigated [10]

$$z=1/(1+kx^2+my^2),$$

where *k* and *m* are control parameters.

The position *z* of measurement cross sections and the angular position θ of the point of measurement were taken as independent parameters. To facilitate mathematical calculations and operate fewer intermediate data, control points 1, 3, 5, 7 in three cross sections have been processed. So θ_1 corresponds to the point of measurement 1, θ_2 – point 3, θ_3 – point 5, θ_4 – point 7 respectively. With the assumption that $\theta_1 = \theta_5$. Due to regular grid measurements, grid points parameters are conveniently assigned with serial numbers, see Fig. 2.

In case of irregular grid measurements, real or relative values of these parameters are recommended.

In general, the interpolation function takes the form

$$\sigma(z,t) = \sum_{i=1}^{n} \frac{a_i}{1 + k_i \cdot \left(z - z_i\right)^2 + m_i \cdot \left(\theta - \theta_i\right)^2}.$$

To simplify and take into account the frequency of grid measurements, let us assume $k = m$

$$\sigma(z,t) = \sum_{i=1}^{n} \frac{a_i}{1 + k_i \cdot \left[\left(z - z_i\right)^2 + \left(\theta - \theta_i\right)^2\right]}.$$

Previous research studies show that the smaller the value of control parameters is, the fewer oscillations the interpolation function provides [10]. The calculations assume $k = 0.01$.

Knowing the coordinates of grid points (cross section position, angle and stress values at the point of measurement), we construct the interpolation function for each measurement point. We use the equations to create a linear system relative to a_i coefficients. When the system is solved, we determine the coefficients a_i for functions-summands.

The calculations were carried out using the automated computer algebra system Mathcad, which also provided visualization of the results. By the same algorithm we obtain the functions for σ_x, σ_y and σ_z. Interpolation results are presented in Figs. 3–5.

Upon analyzing the results obtained for pre-selected control points, one can see that real stress values for intermediate points not processed in three cross-sections of the pipeline section differ from the simulated within 5–10 %.

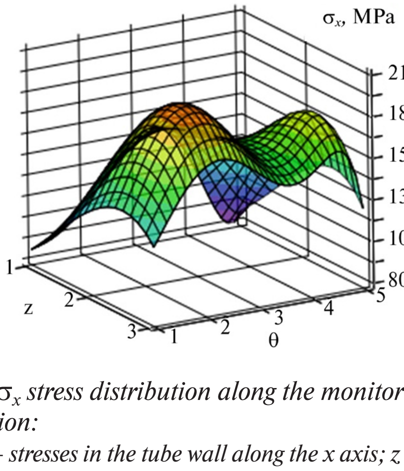

Fig. 3. σ_x *stress distribution along the monitored pipeline section:*

σ_x – stresses in the tube wall along the x axis; z – cross sections to be measured; θ – angular positions of measurement points per each section

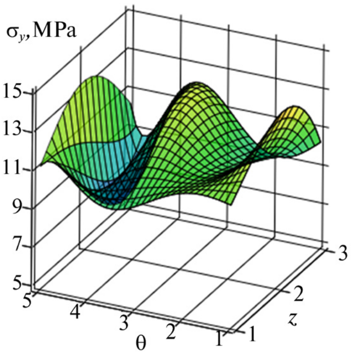

Fig. 4. σ_y *stress distribution along the monitored pipeline section:*

σ_y – stresses in the tube wall along the y axis; z – cross sections to be measured; θ – angular positions of measurement points per each section

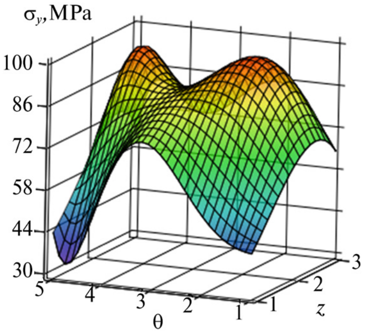

Fig. 5. σ_z *stress distribution along the monitored pipeline section:*

σ_z – stresses in the tube wall along the z axis; z – cross sections to be measured; θ – angular positions of measurement points per each section

Conclusions. Obviously, the presentation of results in a graphical form is not only more demonstrative, but also gives an insight into the state of stress along the pipeline not only at control points, but also between them. Knowing the actual spatial stress distribution allows drawing conclusions and assessing the safety of repairs and full or partial pipeline repair section digging out indicating the boundaries, without violating the integrity of the structure, thus ensuring the efficiency of operations. Therefore, the obtained monitoring results allow developing recommendations and optimizing the repair and recovery works.

References.

1. Poberezhnyi, L., Stanetskyi, A. and Rudko, V., 2011. Corrosive monitoring of transit gas pipelines. *Visnyk TNTU*, 16(3), pp. 20–26.

2. Paton, B. E., Troitskii, V. A. and Bondarenko, A. Y., 2008. Method for low-frequency ultrasonic control of extended objects by directed waves. *Tekhnycheskaia dyahnostyka y nerazrushaiushchyi control*, 2, pp. 20–30.

3. Shlapak, L. S., 2014. Ultrasonic measuring mechanical stress. *Truboprovidnyi transport*, 3(87), pp. 10–13.

4. Liutak, I. Z. and Kisil, I. S., 2010. *Ultrasonic control parameters of the technical state of pipelines*. Ivano-Frankivsk: IFNTUNH.

5. Liutak, I. Z., Liutak, Z. P. and Striletskyi, Yu. I., 2015. Improvement of the method of control of walls of pipelines by ultrasonic method with the use of information software. *Metody ta prylady kontroliu yakosti*, 2, pp. 27–37.

6. Mandra, A.A., Lyutak, I.Z. and Lyutak, Z.P., 2014. Modeling of ultrasonic guided waves propagation in a waveguide with cross-section of finite size. *Journal Of Hydrocarbon Power Engineering*, 1(1), pp. 58–65.

7. Oryniak, I.V., Bohdan, A.V. and Lokhman, I.V., 2014. Defining the geometry of the center line of the main gas pipeline. *Truboprovidnyi transport*, 3(87), pp. 24–27.

8. Semegen, M.M., Liutak, Z.P. and Kostiv, B.V., 2012. Improvement of the acoustic control method to determine the redistribution of stresses on the pipeline section. *Visnyk Khmelnytskoho Natsionalnoho Universytetu*, 4(191), pp. 22–26.

9. Sydorenko, Yu.V. and Satskova, A.V., 2003. Computer realization of various ways of parametrizating Gaussian interpolation function. *Applied geometry and engineering graphics*, 72, pp. 174–178.

10. Taras, I.P. and Pavlyk, I.V., 2010. Visualization of physical objects and processes by creating interpolation geometric patterns. *Rozvidka ta rozrobka naftovykh i hazovykh rodovyshch*, 2(35), pp. 83–88.

Мета. Визначення напруженого стану й візуалізація просторового розподілу напружень уздовж ділянки магістрального трубопроводу в експлуатаційних умовах, що створить можливість давати рекомендації відносно проведення ремонтно-відновлюваних робіт, забезпечивши при цьому цілісність конструкції трубопроводу.

Методика. На основі законів акустопружності й теорії акустики описана математична модель визначення напружено-деформованого стану магістрального трубопроводу, що пов'язує величину напружень в околі однієї точки контролю зі зміною швидкості ультразвукових хвиль, які поширюються у взаємно перпендикулярних напрямках. За допомогою автоматизованої системи комп'ютерної алгебри змодельовано просторовий розподіл напружень на ділянці трубопроводу.

Результати. Обгрунтовано вибір підходу для просторового опису напруженого стану трубопроводу, показані основні етапи й математичні залежності для визначення даних стану. Отримані результати підтверджені на практиці. Їх інтерполяція й візуалізація у вигляді неперервних поверхонь дає можливість змоделювати напружений стан між точками контролю на поверхні трубопроводу.

Наукова новизна. Розроблено спосіб для визначення даних напружено-деформованого стану магістральних трубопроводів, їх обробки, візуалізації та адекватної інтерпретації ситуації в умовах проведення ремонтних робіт.

Практична значимість. Представлено алгоритм визначення напружень у стінці трубопроводу у трьох взаємно перпендикулярних напрямках ультразвуковим методом. Запропоновано спосіб візуалізації просторового розподілу напружень як по периметру нормального перерізу труби, так і вздовж ділянки магістрального трубопроводу, що дає можливість використовувати результати неруйнівного контролю безпосередньо в експлуатаційних умовах. Це особливо важливо для газопроводів і трубопровідних систем у цілому на їх небезпечних ділянках, відмова яких може привести до забруднення навколишнього середовища, а також до аварій з важкими наслідками.

Ключові слова: *трубопровід, напруження, ультразвук, неруйнівний контроль, акустопружність, моделювання, інтерполяція*

Цель. Определение напряженного состояния и визуализация пространственного распределения напряжений вдоль участка магистрального трубопровода в эксплуатационных условиях, что позволит давать рекомендации относительно проведения ремонтно-восстановительных работ, обеспечив при этом целостность конструкции трубопровода.

Методика. На основе законов акустоупругости и теории акустики описана математическая модель определения напряжённо-деформированного состояния магистрального трубопровода, которая связывает величину напряжений в окрестности одной точки контроля с изменением скорости ультразвуковых волн, распространяющихся во взаимно перпендикулярных направлениях. С помощью автоматизированной системы компьютерной алгебры смоделировано пространственное распределение напряжений на участке трубопровода.

Результаты. Обоснован выбор подхода для пространственного представления напряжённого состояния трубопровода, показаны основные этапы и математические зависимости для определения данного состояния. Полученные результаты подтверждены на практике. Их интерполяция и визуализация в виде непрерывных поверхностей позволит смоделировать напряжённое состояние между точками контроля на поверхности трубопровода.

Научная новизна. Разработан способ для определения значений напряжённо-деформированного состояния магистральных трубопроводов, их обработки, визуализации и адекватной интерпретации ситуации в условиях проведения ремонтных работ.

Практическая значимость. Представлен алгоритм определения напряжений в стенке трубопровода в трёх взаимно перпендикулярных направлениях ультразвуковым методом. Предложен способ визуализации пространственного распределения напряжений как по периметру нормального сечения трубы, так и вдоль участка магистрального трубопровода, что позволяет использовать результаты неразрушающего контроля непосредственно в эксплуатационных условиях. Это особенно важно для газопроводов и трубопроводных систем в целом на их опасных участках, отказ которых может привести к загрязнению окружающей среды, а также к авариям с тяжёлыми последствиями.

Ключевые слова: *трубопровод, напряжения, ультразвук, неразрушающий контроль, акустоупругость, моделирование, интерполяция*

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