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Remote monitoring of gas pipelines on the basis of magnetic elastic sensors of mechanical voltage

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Abstract

A method of controlling the stress state of gas pipelines with a four-pole magnetoanisotropic converter has been suggested. The Arduino hardware and software platform has been used to enhance the capabilities of the INI-1C basic mechanical stress measuring device. The system of remote monitoring for periodic measurements of pipeline voltages, accumulation and analysis of the received data has been described in order to provide objective information for making technological decisions.

Keywords: *Arduino, bluetooth, magnetoelastic effect, main pipelines, stress-deformation mill.*

Ukraine is a strategically important territory for the transit of gas and oil to European consumers [1]. However, due to difficult economic conditions, construction of new main pipelines is almost underway. More than 80 % of main pipelines have reached their estimated lifetime (30 years). The issue of energy security of Ukraine and the fulfillment of transport obligations towards the countries of Europe requires the reliable operation of national pipeline transport, uninterrupted and high-quality gas transportation to consumers in different regions and for export. Safe operation of objects of gas transmission systems is impossible without systematic carrying out of diagnostic control and investigation of stress-strain state of pipelines.

For the operational control of the magnitude and sign of stresses in the elements of welded metal structures without their destruction during the manufacture, repair and control of their condition during operation, an ultrasonic device was developed [2]. The implementation of fundamentally new approaches and computerized processing of ultrasonic waves significantly simplifies the process of diagnosis and improves the reliability of the assessment of stress-strain state of the pipeline on complex sections of the route, technological pipelines of compressor stations, crane units, as well as facilitates the search of stress concentration zones.

The urgency of the problem of technical diagnostics of hazardous production facilities is becoming increasingly apparent. There is a tendency to move from periodic control to continuous monitoring. The main reasons for manufacturers to turn to monitoring are:

lack of or difficult access to the object during operation;

high speeds of growth of operational defects and, as a consequence, – a long durability of the structure until its complete destruction;

the consequences of the structure destruction can lead to great material losses and are a significant risk for the maintenance personnel.

Technological piping of compressor stations (CS) is operated in rather difficult conditions – under the influence of dynamic stresses, re-static loads, corrosion and erosion wear. In cases where the loads acting on the pipeline exceed the design, forced production of the resource occurs, which eventually leads to an emergency.

To improve the control over the technical condition, a system of automated control of the stress-strain state was developed and created for continuous monitoring of the change of the controlled parameters and monitoring.

The purpose of the creation of an information-measuring system for the control of the stress-strain state of the gas pumping unit process piping of the compressor station is to ensure the reliable and safe operation of the equipment on the basis of the analysis of information on the state of the system obtained from the sensors. The obtained data are analyzed in real time. Assessment of the technical condition of the piping in general and each control section in particular allows you to control technological process and carry out repair work on the actual technical condition of the piping.

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Table 1 – Results of measurements and calculations of gas pumping unit process piping GPU-3, of the compressor station "Tarutyno"

Cross-section	Measurement results						Calculated stresses		
	P, MPa	D_{in}, mm	δ, mm	T, °C	σ_L^1, MPa	σ_L^2, MPa	σ_R, MPa	σ_i^{max}, MPa	σ_{ys}, MPa
1	4.03	987.40	16.30	18	-51	47	134.27	166	460
2	4.03	987.38	16.31	18	12	-4	134.18	136	460
3	4.03	987.04	16.48	18	-118	-102	132.75	217	460
4	4.03	958.34	30.83	17	–	161	68.89	140	340
5	4.03	962.04	28.98	18	116	68	73.58	102	340
6	4.03	965.36	27.32	17	-157	–	78.32	208	340
7	5.88	507.02	11.49	18	-87	-163	142.71	265	390
8	5.88	694.28	12.86	48	-144	-83	174.60	276	460
9	5.88	693.44	13.28	49	-167	-89	168.87	291	460
10	5.88	672.68	23.66	49	–	35	91.94	80	340
11	5.88	672.78	23.61	49	–	89	92.15	91	340
13	5.88	491.48	19.26	49	130	74	82.52	114	340
14	5.88	499.08	15.46	49	-191	2	104.40	260	340
15	5.88	681.70	19.15	50	35	75	115.12	102	340
16	5.88	681.58	19.21	50	-4	-191	114.74	267	340
17	5.88	507.00	11.50	18	-83	-197	142.58	295	390
18	5.88	507.88	11.56	18	18	-220	142.08	316	390
19	5.88	484.68	23.66	47	–	-98	66.24	143	340

Estimation of the stresses of the "Tarutyno" compressor station

The feasibility of controlling the stresses of gas pipelines of the gas pumping unit of the compresssor station "Tarutyn” at least twice a year during the maximum load of the compressor station was substantiated on the basis of the experience of previous studies [3].

In separate sections the scheme of placement of points for control of deflected mode of pipelines of gas pumping unit process piping (GPU-1, GPU-2 and GPU-3) of the compressor station "Tarutyno" is changed.

The scheme of points placement for control of deflected mode of pipelines of gas-compressor unit piping allows having more complete information on character of the intense constructive inclusion of gas-compressor unit in work and modes of operation.

The methodology of deflected mode control of gas piping of gas pumping unit of compressor station “Tarutyno” remains unchanged compared to previous studies. The method of processing the results of field studies, their graphical representation remains unchanged, which will allow a comparative analysis of the results obtained over time from the same positions and approaches to the analysis.

A series of monitoring the stress state of pipelines by electromagnetic method was carried out twice a year (data for 2014).

Ring stresses were determined analytically by the formula:

$$\sigma_R = \frac{nPD_{in}}{2\delta},$$

where n is the overload coefficient equal to for gas pipelines 1.1; P is internal pressure in the pipeline; D_{in} is inner diameter of the pipeline; δ is pipe wall thickness experimentally determined at control points.

The measured values of the total stresses σ_Σ and the calculated values of the ring stresses σ_R were used to determine the longitudinal stresses σ_L defined at the measurement points. The calculation of the maximum value of the stress intensity σ_i^{max} was carried out according to the energy theory of strength

$$\sigma_i^{max} = \sqrt{\sigma_R^2 + \sigma_L^2 - \sigma_R \sigma_L} .$$

Stresses σ_i^{max} were determined and compared with permissible yield stresses for tubing material σ_{ys}.

The strength condition thus has the form:

$$\sigma_i^{max} \le \sigma_{ys} .$$

The results of the measurements and calculations of gas pumping unit process piping GPU-3, of the compressor station "Tarutyno" are shown in Table 1.

The analysis of the results obtained from the series of measurements and calculations of the stress state of the pipelines of the compressor station piping testifies to the following:

1. The ring stresses in the control cross-sections of the pipelines of the gas pumping unit process piping in which the measurements were made are smaller than σ_{ys}, that is, the condition $\sigma_R < \sigma_{ys}$ is fulfilled.

2. Maximum loads σ_i^{max} are also smaller than σ_{ys} in all control points, taking into account the operation mode of the gas pumping unit and the thermal regime of the pipelines and do not go beyond the voltage changes during the measurement period in previous years.

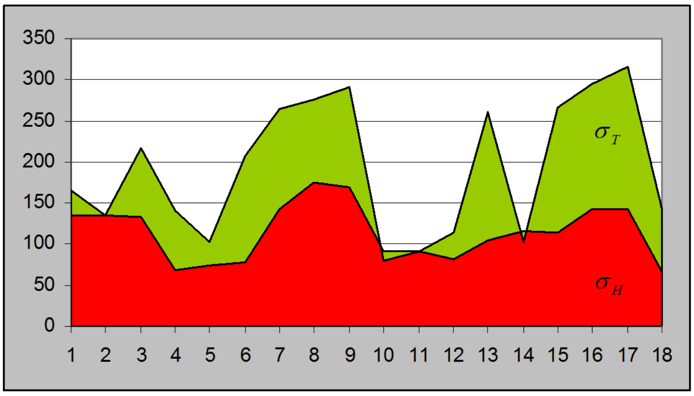


Figure 1 – Diagram of ring σ_H and maximum σ_T stresses at control points of pipelines

3. The greatest stresses occur in the pipelines:

GPU-1 – in cross-sections 1, 2, 6, 7, 8, 9, 10, 14, 15, 16, 17 (σ_i^{max} = 212 – 282 MPa);

GPA-2 – in cross-sections 1, 7, 8, 9, 13, 18 (σ_i^{max} = 215 – 268 MPa);

GPA-3 – in cross-sections 1, 2, 3, 7, 8, 9, 13, 16, 17 (σ_i^{max} = 208 – 316 MPa).

It is suggested to install a system for remote monitoring of the stress-strain state at the points with maximum voltage. The practical significance of the obtained results is to use the developed flexible system for determining the voltages of the main pipelines, which is intended for conducting periodic measurements of the voltages, accumulation and analysis of the obtained data in order to provide objective information for making technological decisions.

An autonomous stationary multichannel system for determining the stress state of pipelines using a discrete information storage device allows for permanent determination of voltages with periodic information removal. This level of system allows full automation of the determination of the stressed state of the pipeline, which allows to monitor dangerous areas in real time without any restrictions, being at a considerable distance from the location of the transducers.

Four-pole magnetoanisotropic converter is recognized as the most suitable for use on the main pipelines. It does not require special surface preparation [4]. Measurement of electrical parameters, used to determine the voltages, was performed with the help of INI-1C device.

Magnetoanisotropic method of mechanical stresses measuring

Control of metal stress-strain state in industrial conditions is carried out by technical means, which are based on different physical methods (acoustic, electromagnetic, magnetic, etc.) [5].

The principle of work of magnetoelastic sensors is based on the use of the magnetoelastic effect, a physical phenomenon that consists in changing the magnetic properties of ferromagnetic materials under the impact of mechanical forces.

The benefits of magnetoelastic sensors are most clearly demonstrated when measuring the parameters of objects which are being operated in tough environment (rolling mills, mine hoists, drilling rigs, steel ropes of suspension bridges, etc.).

The transformer magnetoelastic converters meet the requirements of high operational reliability for the measurement of mechanical voltage in the main pipelines.

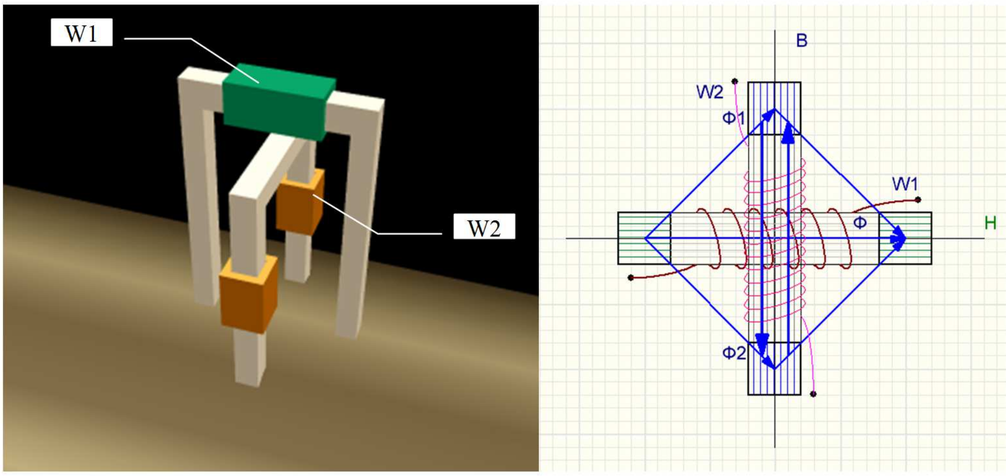
The principle of action of magnetoelastic transducers is based on the change of the magnetic permeability μ of ferromagnetic under the impact of mechanical stress σ (magnetoelastic effect), which arises in them due to the influence on the ferromagnetic bodies of mechanical forces P (tensile, contracting, twisting). Thus, in a magnetoelastic converter, we obtain the following chain of transformations: P → σ → μ → RM → Z [6].

Measurements are made in the surface layer from 0.5 to 1.5 mm thick. The error of measuring voltages is estimated at 12–15 %. At the current level of development, the magnetic method is used to detect and qualitatively assess the stress state. It is based on calibration curves, correlation ratios and coefficients linking the residual stresses and the values of the magnetic characteristics of the material.

The principle of action of magnetoelastic and magnetoanisotropic converters is based on the magnetoelastic effect. The converters are two mutually perpendicular U-shaped magnetic conductors, one of which houses the excitation winding and the other the measuring windings (Fig. 2). The converters use the anisotropy of magnetic properties that occurs in the ferromagnet when loaded by an external force.

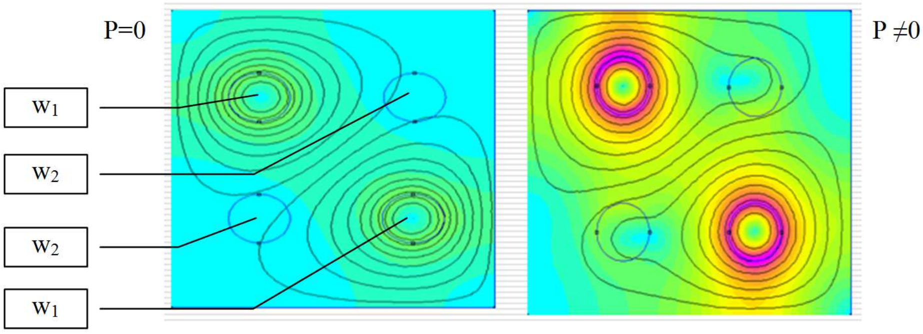
In the absence of measurable force, the sensor material is isotropic, the magnetic field lines do not intersect the plane of the secondary winding w_2 and e. p. c. is not given (Fig. 3 *a*). Under the action of mechanical stress that arises from the application of external forces to a sensitive element, its material becomes anisotropic.

The measured force P, creating a mechanical voltage in the magnetic circuit, reduces the magnetic conductivity in the vertical direction and increases in the horizontal. The magnetic induction vector thus rotates,



a) *b)*

Figure 2 – Transformer magnetoelectric converter (a) and circuit diagram (b)



a) *b)*

a) in the absence of mechanical effort, b) in the application of external forces

Figure 3 – Power lines of the magnetoelastic converter

the power lines are distorted (Fig. 3 *b*), trying to travel most of the way in the lightest direction, and the EMF E2 = f (P) is given in the secondary winding. The magnitude of the electromotive force is determined by the angle of rotation of the magnetic induction vector, which in turn depends on the measured force.

The effect of deformation of the field causes slight changes in inductance, but leads to a significant change in the flow of the two windings.

The output signal of transformer magnetoelastic converters depends on the relative position of its magnetic circuit relative to the direction of mechanical voltage. Changing the sign of the mechanical voltage causes the change of the EPC sign of the converter. Transformer magnetoelastic converter allows to determine both the magnitude (Fig. 4 *a*) and the direction (Fig. 4 *b*) of the mechanical voltage.

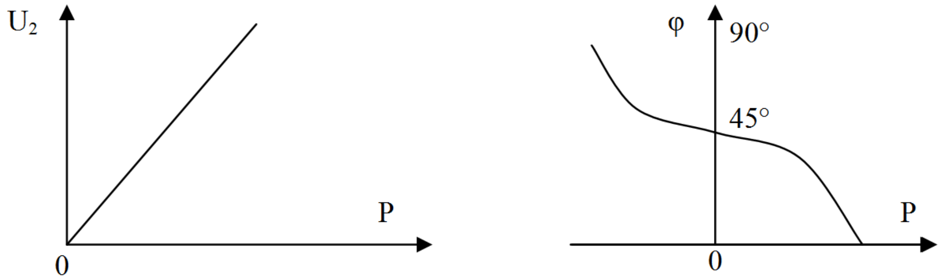
Under the action of the measured force applied to the sensing element, a voltage proportional to the measured force appears in the output winding of the sensor. As the force direction changes, the phase of the output voltage changes.

Mechanical voltage sensors using transformer magnetoelastic converters, differ in simplicity of construction, high output power, accuracy of measurements, stability of characteristics, low inertia, high reliability [7].

In paper [8] a monitoring system aimed at preventing accidents at main gas pipelines, oil pipelines, ammonia pipelines and preventing environmental pollution is described. The monitoring system includes: complex of equipment, techniques, software and is intended for the following tasks: measurement of mechanical stresses in the pipeline on a potentially dangerous area, transmission of the received data to the server of the operator, graphical display of the current stress distribution in the cross sections of the pipeline, graphical display of changes in the pipeline time points.

The IFNTUOG is conducting research to develop a system of continuous control of the modes of operation of the main pipeline to control the stress-strain state by magnetic and anisotropic method. The authors have developed a laboratory sample to remotely transmit system status information.

The purpose of this work is the development of an information and measuring system to monitor the stressed state of pipelines, which ensures the reception and transmission of data in a continuous mode, upon request and availability of data, implements the reception and forwarding of SMS by event and remote control, as well as can perform permanent data backup to a memory card. The block diagram of the information and measuring system is presented in Fig. 5.



a) *b)*

Figure 4 – Functional dependencies of the magnetoelastic anisotropic force converter phase (*a*) and output voltage (*b*)

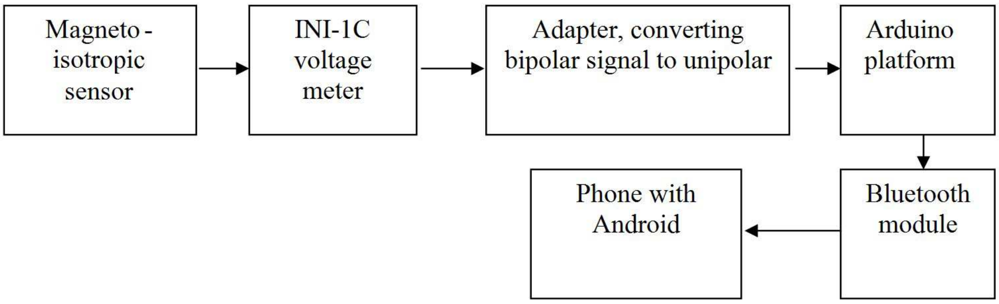
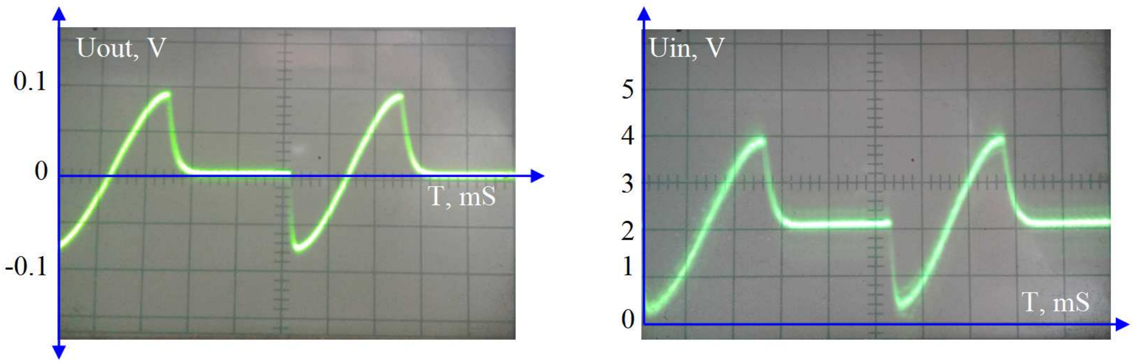


Figure 5 – The block diagram of the information and measuring system



a) *b)*

Figure 6 – Oscillograph chart of the output signal of the INI-1C meter (*a*) and the signal at the input of the ADC (*b*)

As a basic measuring device electromagnetic voltage meter INI-1C was used. The design of the device provides the outputs of the signal generator and the information signal, proportional to the mechanical stress on the back panel. The task of joining the INI-1C output signal with an Arduino analog input was that a 10-pole analog-to-digital converter (ADC) requires a unipolar signal in the operating range 0–5 V, while the output signal from the INI-1C meter is bipolar with a ± 100 amplitude mV (Fig. 6).

Hardware and software

To work with the INI-1C base unit, the authors developed an adapter that converts a bipolar signal into a unipolar signal with a normalized voltage to operate the Arduino analog-to-digital converter within 0.1–3.7 V. The circuit diagram and its modeling in CircuitMaker are shown in Fig. 7.

Figure 8 shows the developed board of this module. An amplified signal of 0–3 V amplitude is fed to the input of the Arduino analog-to-digital converter (channel A0). The algorithm uses the principle of signal scanning, that is the signal is first digitized and stored in a memory array, and then a synchronization search is performed, followed by information being displayed.

In the first version of the information and measuring system, the obtained digitized data was transferred to Excel (Fig. 9).

With this set of data, you can determine the spectrum of the signal by decomposing it to a Fourier series.

For the operational control, another option was chosen – by time impulses from the comparator of the output signal (Fig. 10), the information was presented in the usual conditional units accepted for the device (INI-1C, since it was possible to compare the data of both previous measurements and current) (Fig. 11).

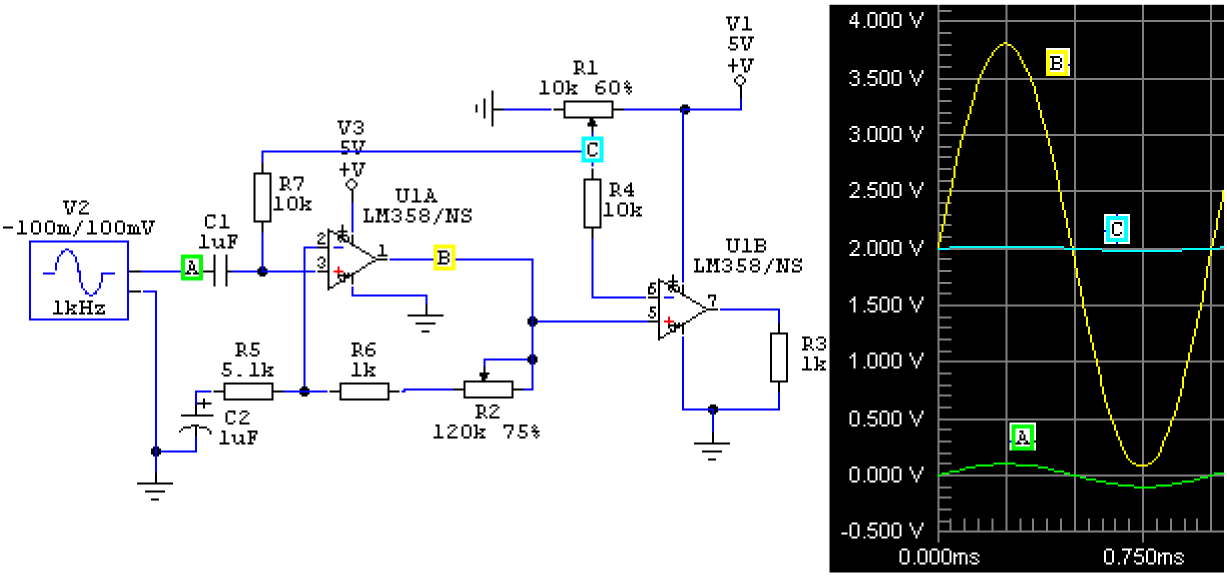


Figure 7 – Simulation of the operation of a bipolar signal converter into a single-pole CircuitMaker software package

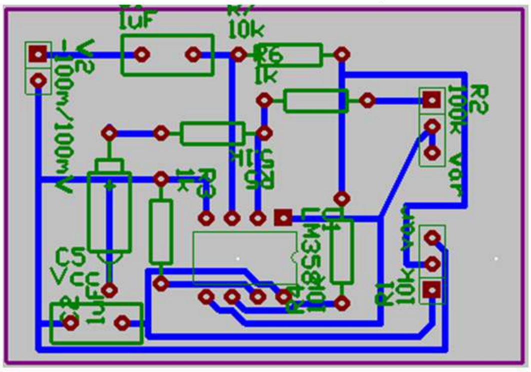
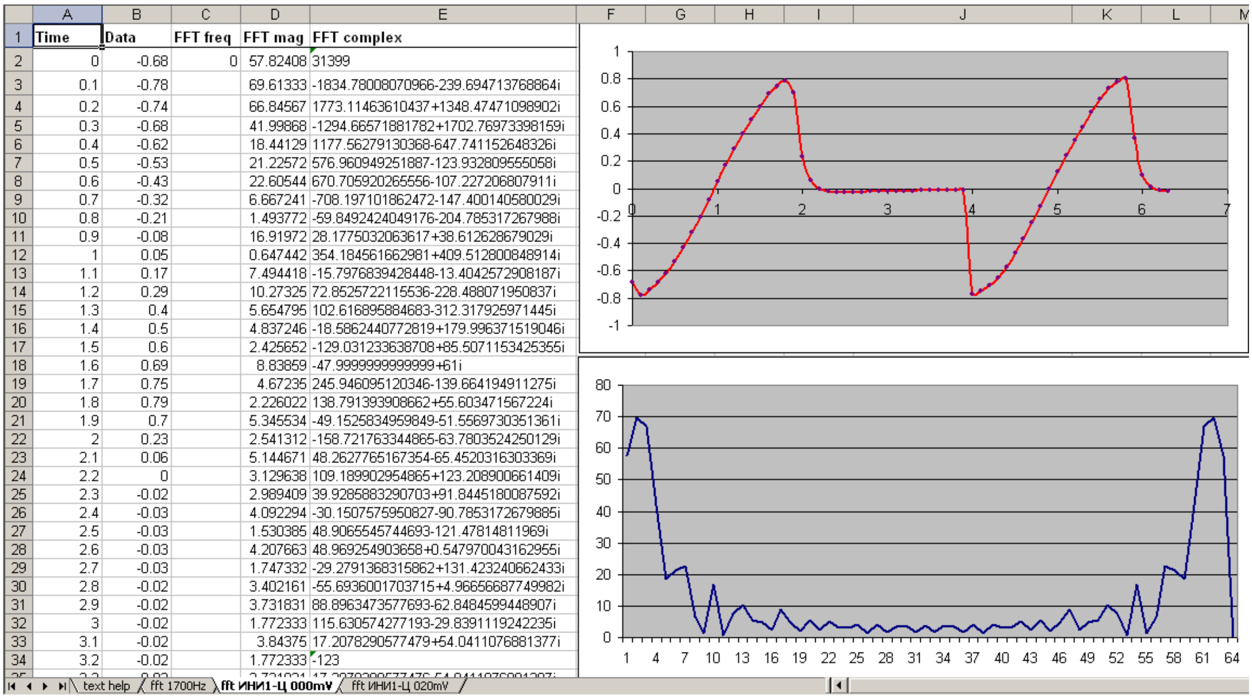


Figure 8 – Arduino Adapter Module



	A	B	C	D	E
1	Time	Data	FFT freq	FFT mag	FFT complex
2	0	-0.68	0	57.82408	31399
3	0.1	-0.78		69.61333	-1834.78008070966-239.694713768864i
4	0.2	-0.74		66.84567	1773.11463610437+1348.47471098902i
5	0.3	-0.68		41.99868	-1294.66571881782+1702.76973398159i
6	0.4	-0.62		18.44129	1177.56279130368-647.741152648326i
7	0.5	-0.53		21.22572	576.960949251887-123.932809555058i
8	0.6	-0.43		22.60544	670.705920265556-107.227206807911i
9	0.7	-0.32		6.667241	-708.197101862472-147.400140580029i
10	0.8	-0.21		1.493772	-59.8492424049176-204.785317267988i
11	0.9	-0.08		16.91972	28.1775032063617+38.612628679029i
12	1	0.05		0.647442	354.184561662981+409.512800848914i
13	1.1	0.17		7.494418	-15.7976839428448-13.4042572908187i
14	1.2	0.29		10.27325	72.8525722115536-228.488071950837i
15	1.3	0.4		5.654795	102.616895884683-312.317925971445i
16	1.4	0.5		4.837246	-18.5862440772819+179.996371519046i
17	1.5	0.6		2.425652	-129.031233638708+85.5071153425355i
18	1.6	0.69		8.83859	-47.9999999999999+61i
19	1.7	0.75		4.67235	245.946095120346-139.664194911275i
20	1.8	0.79		2.226022	138.791393908662+55.603471567224i
21	1.9	0.7		5.345534	-49.1525834959849-51.5569730351361i
22	2	0.23		2.541312	-158.721763344865-63.7803524250129i
23	2.1	0.06		5.144671	48.2627765167354-65.4520316303369i
24	2.2	0		3.129638	109.189902954865+123.208900661409i
25	2.3	-0.02		2.989409	39.9285883290703+91.8445180087592i
26	2.4	-0.03		4.092294	-30.1507575950827-90.7853172679885i
27	2.5	-0.03		1.530385	48.9065545744693-121.47814811969i
28	2.6	-0.03		4.207663	48.969254903658+0.547970043162955i
29	2.7	-0.03		1.747332	-29.2791368315862+131.423240662433i
30	2.8	-0.02		3.402161	-55.6936001703715+4.96656687749982i
31	2.9	-0.02		3.731831	88.8963473577693-62.8484599448907i
32	3	-0.02		1.772333	115.630574277193-29.8391119242235i
33	3.1	-0.02		3.84375	17.2078290577479+54.0411076881377i
34	3.2	-0.02		1.772333	-123

Figure 9 – Digitized signal from a magnetoanisotropic sensor.
The data from the Arduino card is transferred for further processing in Excel

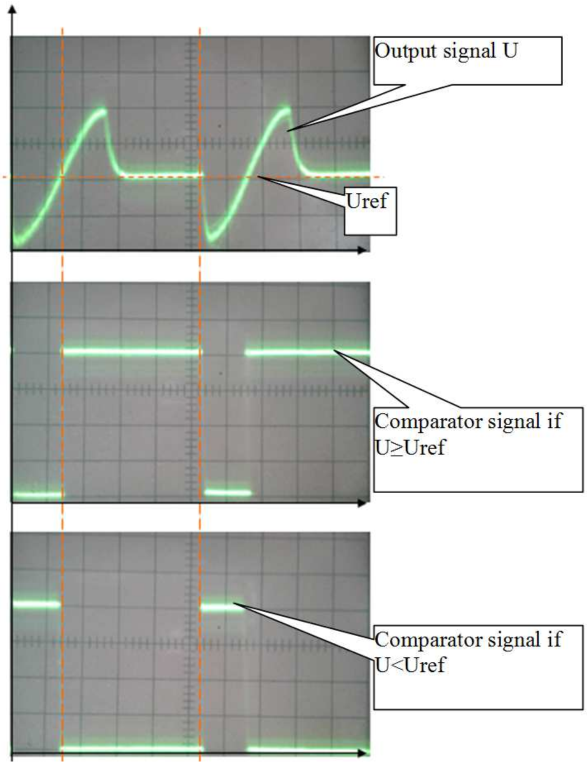


Figure 10 – Comparator and output signal pulses

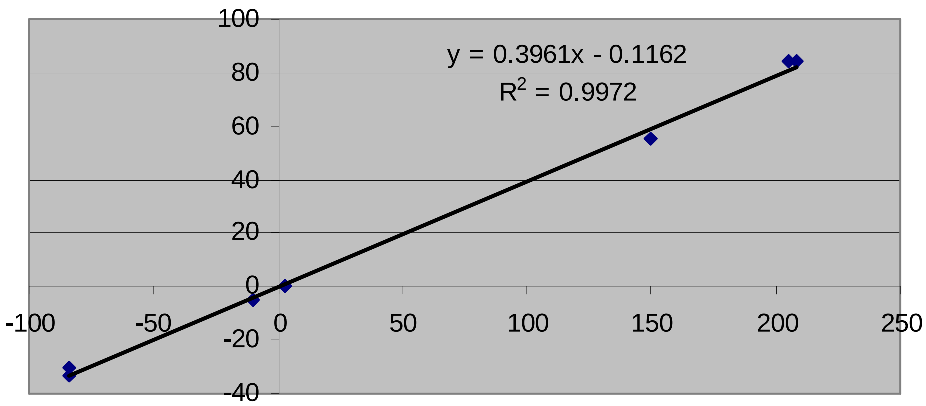
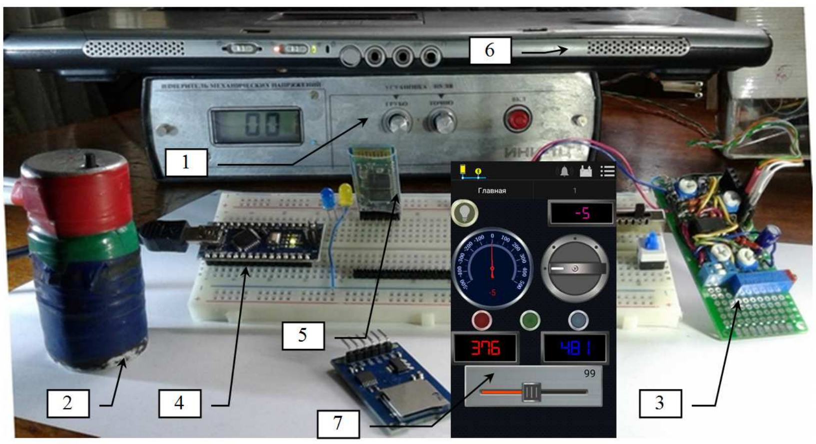


Figure 11 – Calibration of the Arduino Module in accordance with the INI-1C readings



1 – INI-1C mechanical stress meter, 2 – magneto-anisotropic sensor, 3 – analog adapter, 4 – Arduino Nano module, 5 – Bluetooth HC-05 module, 6 – laptop, 7 – screenshot from a mobile phone screen

Figure 12 – Mechanical Stress Information and Measurement System on Arduino Platform

Noncontact measurement signal transmission from Arduino to an Android phone was developed using Bluetooth connection [9]. Arduino module programming [10], as well as its own algorithms, was implemented in the Arduino IDE v.1.8.7 integrated environment. Figure 12 shows the laboratory layout of the developed information and measurement system.

Conclusions

Mechanical Stress Information and Measurement System for pipelines encompasses a number of modules that so far have made up a whole complex of hardware solutions: an analog module for converting a bipolar signal of the base unit of a universal mechanical stress meter into a digital one, a digital module on an Arduino platform the Bluetooth channel, the converter mounting unit on the pipeline. The software calculates the dependence of the signal change on the mechanical effort using a sampling of multiple measurement statistics points and is displayed on the monitor or smartphone screen.

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УДК 621.9.08

Дистанційний моніторинг газопроводів на основі магнітопружних датчиків механічних напружень

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Запропоновано метод контролю напруженого стану газопроводів із чотириполюсним магнітоанізотропним перетворювачем. Для розширення можливостей базового вимірювального приладу механічних напружень ИНИ-1Ц використано апаратно-програмну платформу Arduino. Описано систему дистанційного моніторингу для періодичних вимірювань напружень магістральних трубопроводів, накопичення та аналізу одержаних даних з метою надання об'єктивної інформації для прийняття технологічних рішень.

Ключові слова: *Arduino, магістральні трубопроводи, магнітопружний ефект, механічні напруження, моніторинг.*