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On the assessment of the potential for extracting information on defects in the main pipeline by the method of radar analysis of natural oscillation frequency

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Abstract. The paper deals with the issue of diagnostics of main pipelines by the vibration method, exploring the influence of the formation of cracks in the walls of the pipeline on the change in the frequency characteristics of the pipeline. By analyzing the difference in the natural oscillation frequency of a pipe with a crack and without it, it is possible to assess the location of the defect with a certain accuracy. The issue of the possibility of reading the natural oscillations of the main pipeline from the surface of the soil located above the pipeline is also being studied.

1. Introduction

In the modern world, enough methods for diagnostics and non-destructive testing of pipelines have been developed, which have both pros and cons. In the work, when analyzing existing technologies, the methods used to identify defects in main pipelines were considered. Fixed or sliding set pressure reduction method consists of two approaches. The first approach is to compare the pressure, calculated from the hydraulic slope of the oil pipeline at its given throughput, with the pressure determined at regular intervals by pressure sensors. The calculation is carried out analytically for each measuring point, taking into account the change in pressure and pumping flow rate at the pumping station. The second approach is to measure and compare local pressure drops in the pipeline. At certain intervals, all pressure values at the measuring points on the pipeline section are recorded and compared with those previously recorded. If the pressure gradient exceeds a preset value (at constant flow rate), an alarm is triggered. The disadvantage of this method is the large amount of error, in addition, this method will not be able to determine the variable work of the tie-in [1, 2, 5].

The cost comparison method is based on the constancy of the instantaneous cost of the oil product in the initial and final sections of the pipeline in the absence of leakage and in a steady pumping mode. At the inlet and outlet of each section of the pipeline, turbine or volumetric flow meters are installed, remotely connected to a computer located in the central control room. The information from the flow meters is fed into the computer, which, taking into account the temperature correction, continuously compares the flow rates at the beginning and end of each section of the pipeline. The disadvantage of this method is the false alarms of the system caused by the violation of the stationary nature of oil transportation [3, 4].

The acoustic emission method is based on the registration of acoustic emission (AE) signals about microcracks in the pipeline wall and fluid leakages by highly sensitive piezoelectric sensors located on the controlled section of the pipeline. Using piezosensors, the difference in the arrival times of the AE



sound signals to the transducers is determined. Taking into account the propagation speed of the AE signals and the distance between the sensors on the pipeline, the location of the defect is analytically determined. The disadvantages of this method are the attenuation of acoustic sound in the pipeline and the impossibility of using this method immediately, since it is necessary to sort the noise range [6, 10].

The thermal method is based on changes in surface temperature above the pipeline route. Temperature drops range from fractions of a degree to tens of degrees. To implement this method, special thermal imaging devices are used, which are used in special mobile laboratories [7]. The disadvantage of this method is the small girth of the area when measuring. Also, the lack of sensitivity does not allow taking measurements underground.

The eddy current method is based on the use of eddy current flaw detectors designed to detect inhomogeneities in the form of cracks, cavities in the surface and subsurface layers of metals by creating eddy currents and their registration [8]. The disadvantage is that the contact method requires access to the pipeline and cannot be used for trench pipelines.

The ultrasonic method is based on the registration of acoustic noise arising from the outflow of fluid through a through - hole in the wall of a pipeline under pressure. The main mechanism for generating AE signals is turbulent pulsations resulting from the collapse of gas bubbles, caused by a strong local decrease in pressure in the fluid at the sites of the leakage - in other words, we register the formation of cavitation by the method of acoustic emission [9, 10]. The disadvantages of this method are the limited technological capabilities of the equipment.

The scraper diagnostic method is carried out using a magnetic flaw detector, which is designed for in-line diagnostics of pipelines. The defect detector has two belts of multi-element magnetic field transducers on Hall elements [11]. The disadvantages of this method are that the method is not contactless, that is, it is possible to detect a defect only when the probe is launched through the pipeline. As a rule, the frequency of probe diagnostics is about 3-5 years, therefore this method is imperfect and cannot register defective conditions promptly. In addition, the cost and maintenance of such a probe is extremely high.

All of the above methods are either contact, requiring the installation of special recording equipment at many sections of the pipeline, or are non-contact, but poorly suited for diagnosing pipelines underground. The article discusses the possibility of detecting pipeline damage by indirect methods based on the inhomogeneity of pipeline displacements both on the surface and underground, as well as on local changes in the natural oscillation frequency of (NOF) of the pipeline.

2. Methods and materials

Natural oscillation frequency for pipelines is usually based on the theory of fixed rods oscillations theory [12], however, if the ratio of the pipeline wall thickness to its radius is less than or equal to 0.05, then the problem should be considered for closed cylindrical shells in the form of a straight pipeline with a large diameter. This theory was worked out by V.P. Ilyin [13] on the basis of the geometrically nonlinear theory of shells intended for the analysis of thin-walled tubes. It takes into account the influence of radial and tangential forces of inertia, as well as external and internal pressure on the pipe walls. The solution to the problems is to calculate the natural frequencies of vibrations of a closed cylindrical shell, loaded with internal or external pressure when fixing the end sections of the pipe:

$$\begin{aligned}
\omega_{mn}^2 &= \frac{Egh_*^2\lambda_n^4 + m^4(m-1)(m^2-1 \pm p_*)}{\gamma r^2\lambda_n^2 h_* + m^4 + m^2}, \\
h_* &= \frac{h}{r\sqrt{12(1-\nu^2)}}, \\
p_* &= \frac{rp}{Ehh_*^2}, \\
\lambda_n &= \frac{n\pi r}{L\sqrt{h_*}},
\end{aligned} \tag{1}$$

where m, n are wave numbers in the circumferential and longitudinal directions, E is the modulus of elasticity, γ is the specific gravity, g is the acceleration of gravity, ν is the Poisson's ratio.

It should be noted that for parameter p_* , positive corresponds to the internal pressure in the pipe, negative - to the external one.

Formula (1) allows to determine the frequencies of the oscillations modes of the straight pipe section by substituting coefficient $m, n = 1, 2, 3$. The formula also allows to set the degree of influence of inertia forces and pressure on the mode frequency. So $\lambda_n^2 h_*$ and m^2 are determined by tangential components, m^4 - by radial ones.

The analysis of cylindrical shells with a fluid flow is a more complex computational task that requires taking into account the effect of the additional fluid mass and flow rate.

The solution is in determining the natural frequencies of a closed cylindrical shell with a fluid flow and fixed end sections. It is presented in the form of the formula:

$$\omega_{mn}^2 = \frac{\lambda_n^4 + m^4(m^2-1)(m^2-1 \pm p_*) + M_{nm}^* U^2 h_* \lambda_n^2}{rh\rho_{oil}(\lambda_n^2 h_* + m^4 + m^2) - M_{nm}^* r^2}, \tag{2}$$

where M_{mn}^* - added mass of fluid in the pipe.

$$\begin{aligned}
M_{mn}^* &= -\rho_{oil}\Phi_{mn}m^4, \\
\Phi_{mn} &= \frac{I_m(\lambda_0)}{\lambda_0 I_m'(\lambda_0)}, \\
\lambda_0 &= \frac{n\pi r}{L},
\end{aligned} \tag{3}$$

$I_m(\lambda_0)$ – modified Bessel function of m order.

The previously presented classical equations for calculating the vibrational modes of pipelines are used only for the analysis of objects without inhomogeneities such as welds, defects in the form of cracks and stubs. Due to inhomogeneities in the geometry and mass of the pipeline, it is required to divide the object into sections and solve integral equations in these sections. Such problems are solved by the finite element method, which consists in dividing the object under study into a set of elements at the nodes of which equations are solved that determine the characteristics of the fluid flow in the pipeline and the effect on its walls. Also, the method allows to determine the of natural oscillation frequency of the object, taking into account the violation of the integrity.

To solve this problem, a three-dimensional model of the pipeline filled with oil was created (figure 1).

Pipeline parameters: section length – 10 m; section radius - 0.5 m; wall thickness - 10 mm; weld seam: thickness - 30mm; width – 20 mm; defect - a transverse crack in the form of the ellipse, with

dimensions of 10×50 mm. The properties of materials for the computational model are shown in table 1. To calculate the of natural oscillation frequencies, a pipeline model with fixed end sections was used, and to estimate the value of the displacement of the pipeline walls and the soil surface under the influence of oil flow, a soil layer 1.5 m thick was added to the model under the study. It is typical for underground oil pipelines.

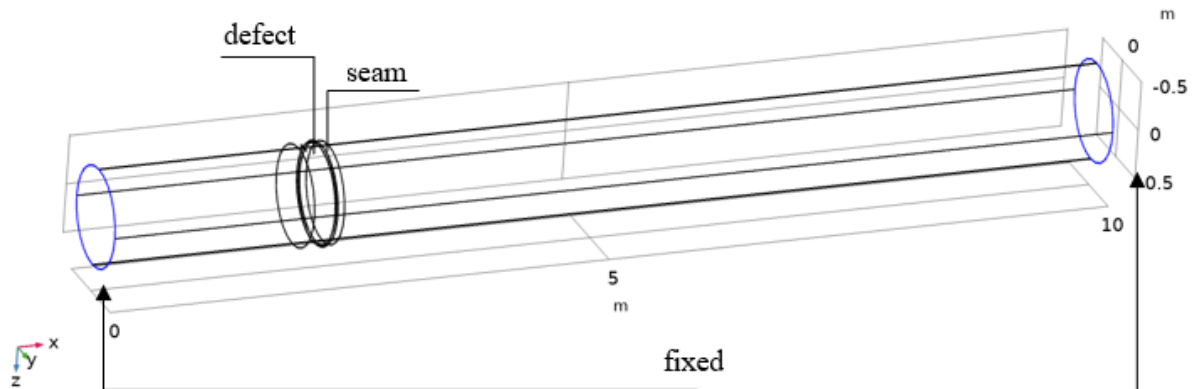


Figure 1. Pipeline model.

Table 1. Physical properties of materials.

Solids			
Material name	Density ρ , kg. / m ³	Young E, Pa modulus	Poison's ratio ν
Steel	7850	200E9	0.3
Soil	2500	400E6	0.35
Fluid			
Material name	Density ρ , kg/m ³	Dynamic viscosity μ , Pa·c	
Oil	800	1E-2	

In the course of modeling, the flow of oil flowing between its ends was simulated in the pipeline. The flow rate is 3.33 m / s and creates a pressure in the pipeline of 80 atm. Two studies were carried out: determination of the dependence of the natural oscillation frequency of the pipe on its integrity and the presence of inhomogeneities; analysis of the effect of fluid flow in a pipe on the displacement of its walls and adjacent soil, to assess the possibility of reading vibration on the surface of the soil or pipe.

To solve the problems posed at the mesh nodes of the model (figure 2), the Navier-Stokes equations and the continuity equation for a liquid are solved, showing the field of flow velocities:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \operatorname{div} \mathbf{u} = \operatorname{div}[-p\mathbf{I} + \mathbf{K}] + \mathbf{F}, \quad (4)$$

$$\rho \operatorname{div} \mathbf{u} = 0$$

where $\mathbf{u}$ is the velocity field; p is the fluid pressure; ρ is the density; $\mathbf{F}$ - external forces affecting the fluid; $\mathbf{K} = (\mu + \mu_T) (\operatorname{grad} \mathbf{u} + (\operatorname{grad} \mathbf{u})^T)$ - the dynamic viscosity parameter; $\mathbf{I}$ - identity matrix

The pressure and velocity field in the pipe affect the deformation of the pipe walls, which is transmitted to the adjacent soil for which the equations are solved in the model indicating the nature of the displacement of the particles of the medium under the influence of the applied forces.

$$\rho \frac{\partial^2 \mathbf{u}_{solid}}{\partial t^2} = \text{div}[\mathbf{FS}]^T + \mathbf{F}_V, \quad (5)$$

$$\mathbf{F} = \mathbf{I} + \text{grad} \mathbf{u}_{solid},$$

where $\mathbf{u}_{solid}$ is the displacement field; $\mathbf{F}$ - external force applied to the volume; $\mathbf{S}$ - the material stress; T - the temperature in Kelvin; $\mathbf{F}$ - deformation gradient; $\mathbf{I}$ - the identity matrix.

The following equations are used to study the model for the type of natural frequencies:

$$-\rho \omega^2 \mathbf{u}_{solid} = \text{div}[\mathbf{FS}]^T, \quad (6)$$

$$\mathbf{F} = \mathbf{I} + \text{grad} \mathbf{u}_{solid},$$

$$-i\omega = \lambda,$$

where $f = -\lambda/(2\pi i)$; λ - the wave length; quality factor $Q = \frac{\text{Im}(\lambda)}{2\text{Re}(\lambda)}$; attenuation factor $\delta = \text{Re}(\lambda)$

3. Results

The model was calculated in a cylindrical coordinate system to determine the effect of fluid flow on the mechanics of solids in the form of pipe walls and soil. Figure 2 shows the distribution of velocities inside the tube and the influence of inhomogeneities on this parameter in the form of a weld seam and a defect in the form of a crack, taking into account the flow movement from coordinate $z = 0$ to $z = 5$. With a general decrease in the oil flow rate near the walls, in the area of the weld, a zone of increased speed is observed, however, in the area of the defect, this effect is not observed due to the small size of the hole relative to the pipe, in conjunction with the flow parameters and fluid properties.

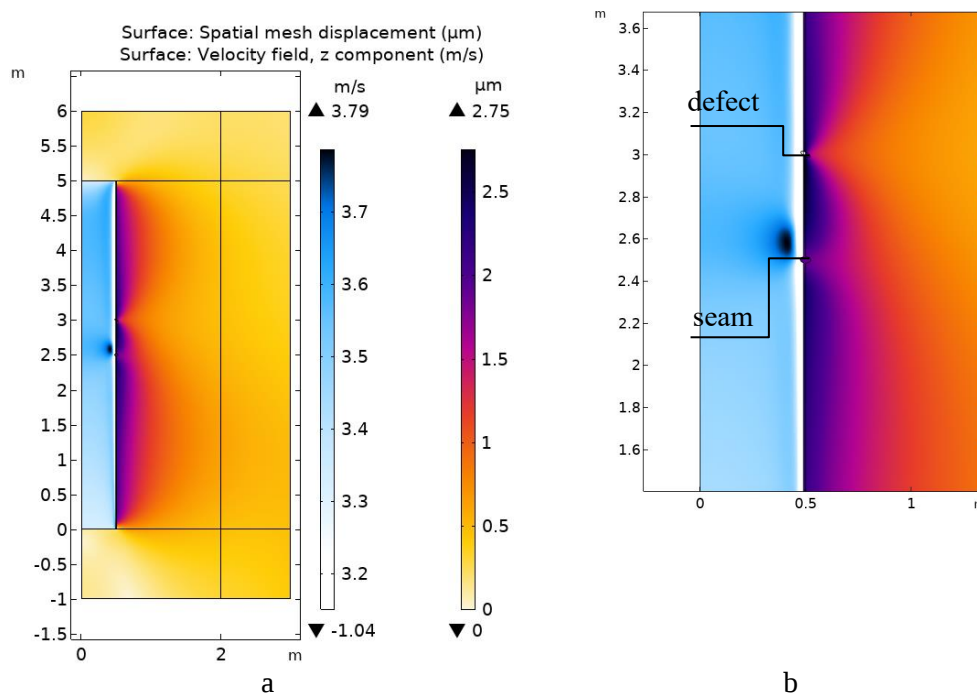


Figure 2. Distribution of flow velocity inside the pipe and displacement of pipe and soil.

When analyzing the displacement of the pipe and soil, a change in the flow rate was revealed in the area of pipe inhomogeneities, however, the displacement of the solid decreases stronger in the area of

the defect, which also stands out on the surface of the soil (figure 3). The largest displacement was obtained on the pipe surface, $D_R = 2.75 \mu\text{m}$, which decreases $D_R = 0.6 \mu\text{m}$ on the ground surface (1.5 m from the pipe). It can be recorded with laser locators. The axial component of the displacement D_Z , indicating the displacement of the pipe directed along the axis of the pipeline, on the soil surface does not reflect the presence of the defect, therefore, it can be neglected.

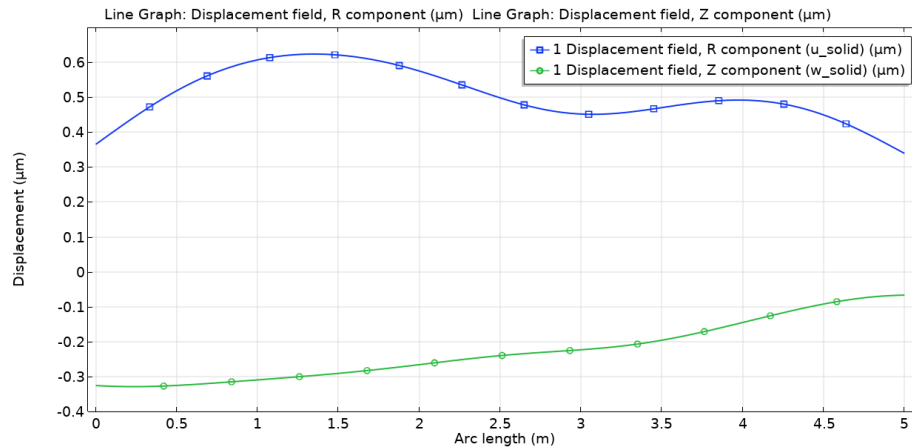
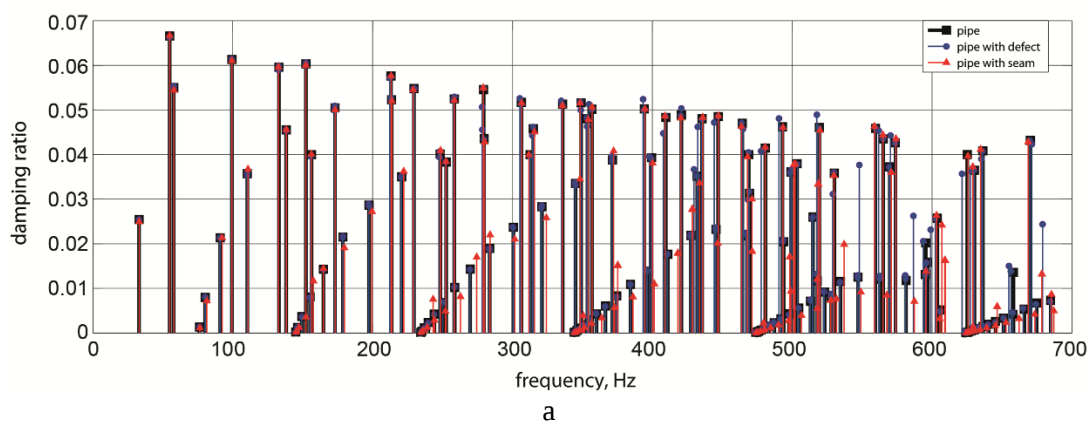


Figure 3. Components of soil displacement on the surface: Z - component D_Z , R - component D_R .

In the process of modeling, frequency analysis of the pipe deformation coefficient was carried out (figure 1) for 3 cases: a pipe without a defect; defective pipe; a pipe with a welded seam. The NOF modes were calculated for range 1–700 Hz. Comparative assessments indicate a shift of several modes when introducing inhomogeneity into the computational model (figure 4 a). So, for the cases of a pipe with a welded seam, the greatest frequency shift occurs by 2 - 4 Hz and does not exceed 1 Hz for a defect (figure 4 b). There is also the emergence of new modes that are unique for inhomogeneity at frequencies from 400 Hz for a defect and at frequencies from 260 Hz for a model with a seam (figure 4 c). This is due to the greater change in the total mass of the pipe and the bulk density in the case of adding a weld than in the presence of a defect in the form of a hole. The small geometrical dimensions of the defect and the seam in comparison with the dimensions of the pipe cause the appearance of new FSCs in a higher frequency range.



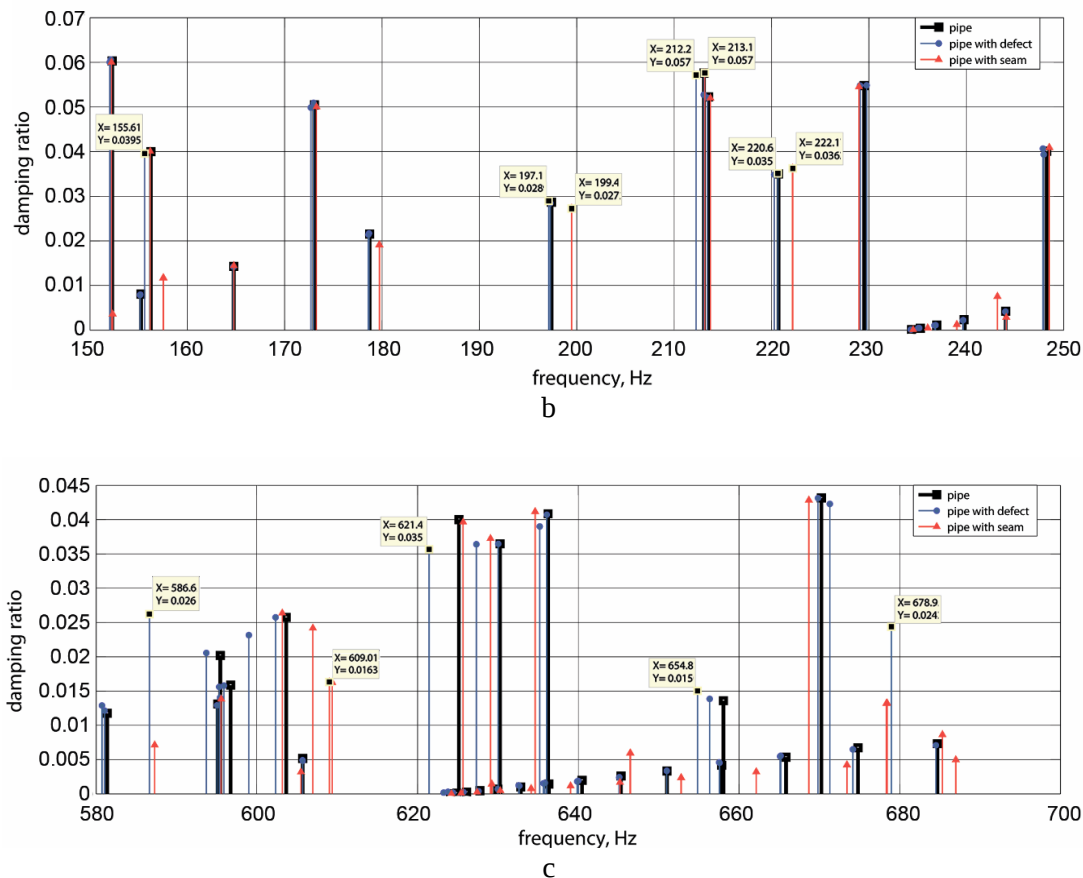


Figure 4. Comparative characteristics of NOF of pipes.

4. Conclusion

Theoretical assessments of the effect of the fluid flow inside the pipe on its walls and soil showed a 2.5 μm displacement on the pipe surface and 0.6 μm on the surface of the soil layer with thickness of 1.5 m. It makes possible to register this displacement with a laser locator. A study of the NOF of a pipe with the introduction of various inhomogeneities showed a shift in the frequency of vibrational modes down the spectrum in the presence of a defect in the hole water and up the spectrum in the presence of the weld seam. Also, in the presence of inhomogeneities, the appearance of new NOFs in the range of 400 - 700 Hz was recorded in the spectrum. This phenomenon can be used to identify the type of inhomogeneities in the frequency study of pipe oscillations.

Acknowledgments

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