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FREE OSCILLATION IN STRAIGHT PIPELINE SECTIONS WITH LENGTH AND THICKNESS HETEROGENEITY CONSIDERING EXTERNAL RESISTANCE

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Abstract- This study examines the free oscillations of a straight section of a pipeline that exhibits non-uniformity in both length and thickness, while accounting for external environmental resistance. It is believed that the characteristics of the pipe differ along its length and thickness and that it is located on a non-uniform base. The differential equation used to solve the problem is a partial differential equation with variable coefficients of the fourth order, compiled to study the problems of vibrations of two-dimensional structural elements based on the classical Euler equation for the stability of rods. Also, the differential equation in which the oscillation of pipelines is studied, the inhomogeneity that varies in length and thickness in a resisting medium, is a modified form of the Sophie-Germain equation for plates with a homogeneous isotropic material. The degree of complexity of solving the resulting differential equation is very high, first we simplify the equation using the transformation being solved. Since we have a differential equation in which partial derivatives with variable coefficients that vary relative to the deflection of the pipeline, we use the method of separation into variables and the orthogonal Bubnov-Gale kin method to determine the characteristic frequency. In addition, the equation of motion in the form of a power function was found for the solution, the boundary condition and the reaction of the resistance of the medium were selected, the bending function was established, the orthogonality of the Bubnov-Gale kin method was checked, and the problem was completely solved. The specific values of the characteristic parameters are given, and the calculation results are shown in graphs and shown in the tables.

Keywords: Vibration, Heterogeneity, Material, Pipeline, Base, Density, Elastic Modulus, External Resistance.

1. INTRODUCTION

The modern advancement of the oil and gas industry, coupled with the growing demand for long-distance transportation of these resources, is driving the expansion of the main pipeline network. An example is the construction of main underwater oil and gas pipelines that run through the Black Sea, the Baltic Sea and the Mediterranean Sea.

These pipelines, which extend along the seabed of the Baltic and Black Seas for 1200 km and 900 km, respectively, employ thin-walled pipes with a diameter of 1220 mm or greater. The design of such pipeline necessitates comprehensive static and dynamic calculations to ensure reliable operation. Existing calculation models (Kirxov-Klebsch), primarily based on beam theory and regulatory standards, typically account for various reliability factors. However, they do not always accurately reflect the real operating conditions. Therefore, it is crucial to utilize calculation models that incorporate all specific features of the pipeline's design and operation. This includes not only external and internal pressure considerations but also variations in the substrate and the material composition of the pipe, which cannot be sufficiently addressed by a basic beam model with a non-deformable cross-sectional profile.

Thus, this study aims to enhance the dynamic analysis of thin-walled pipes, both onshore and offshore, to improve their reliability and stability under actual operating conditions. The heterogeneity of the pipe material may arise from factors such as thermal and mechanical processing, manufacturing technology variations, inconsistencies in material composition, and several other influencing factors.

When designing and constructing pipelines for marine and terrestrial environments, it must be borne in mind that the structure is constantly under stress due to various forces and influences. In this regard, strict control is carried out before operation, the welds are checked by X-ray, and the insulating coating is ultrasound. The effects of an earthquake on the seabed are not considered too terrible for pipelines, as earthquake waves quickly fade on the seabed.

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The devices are designed and used to protect pipelines, as well as all engineering structures existing on the surface of the earth (in a terrestrial environment). The study examines the issue of transverse oscillations in a straight section of a continuously heterogeneous pipeline supported by a non-uniform viscoelastic foundation. The equations of motion governing the deflection exhibit variable coefficients and are solved using a combined analytical and numerical approach. The results of the calculations indicate a substantial impact of the material heterogeneity of both the pipeline and the foundation on the values of circular frequency.

In the design and construction of pipelines, the structural engineer must meticulously evaluate the actual physical and mechanical properties of the pipe material, considering factors such as material heterogeneity, manufacturing processes, welding stresses, and others [3-5]. It is crucial to recognize that issues related to strength, durability, stability, and the analysis of frequency-amplitude characteristics considerably complicate problem solving, particularly when accounting for these specific factors. Neglecting these elements can result in inaccurate outcomes.

It is also recognized that various external factors, including explosions, earthquakes, and strong winds, can induce oscillatory processes in pipelines. Considering the application of continuously heterogeneous materials in engineering practice, this study aims to investigate the free oscillation of a rectangular section of a pipeline that exhibits variations in length and thickness, while accounting for external environmental resistance.

The analysis of literature data and the problem statement show that the elastic modulus and density of the material can depend on the spatial coordinates [1-6]. It is assumed that the elastic modulus and density depend on the coordinate of the length and thickness of the pipeline. The studies referenced in [3] present fundamental theoretical and experimental investigations into pipeline mechanics, while [4] offers findings related to the durability of main pipelines. Additionally, [5] demonstrates that the modulus of elasticity and density can be treated as continuous functions of the length coordinate.

It is also essential to consider external environmental resistance, as it significantly depends on natural and climatic conditions. In [9]. this article, using the obtained equation, the influence of the length of the pipeline section laid in the ground with different physical and mechanical characteristics is investigated, as well as the influence of the parameter of the longitudinal compressive force on the frequencies of free vibrations of a thin-walled rectilinear gas pipeline under the action of different internal working pressure, for pipelines of different diameters with different wall thicknesses. In work [10] free vibrations of thin-walled gas pipelines of large diameter with semi-underground laying are considered.

In the article [11], the methods of damping parametric vibrations of the pipeline are considered. In [12] the dynamic behavior of infinite rod elements on an elastically viscous base under the action of a point source of disturbance and in [13], the dependence of the frequencies of free vibrations of a thin-walled underground gas pipeline of large diameter on the depth of the laying was studied. In [14, 15, 16], parametric vibrations of a damaged orthotropic geometric shell reinforced with an inhomogeneous rod and rings in a viscoelastic medium, vibrations of inhomogeneous cylindrical shells filled with liquid reinforced with lateral ribs and free vibrations of a conical shell with a mass associated with a spiral and a reinforced transverse rib system in a stiffening medium were studied.

2. PROBLEM STATEMENT

Assuming that the pipe material is continuously heterogeneous and that the modulus of elasticity E and density ρ are continuous functions of the length x and thickness z.

$$E = E_0 \times f_1(x) \times f_2(z); \quad \rho = \rho_0 \times \psi_1(x) \times \psi_2(z) \tag{1}$$

where, E_0, ρ_0, E and ρ correspond to the homogeneous case, while the functions $\psi_1(x)$ and $f_1(x)$ along with their second-order derivatives, are continuous functions.

In contrast to the homogeneous problem, the neutral axis does not align with the central axis in this case. The boundaries z_o and axial deformation are interconnected as follows:

$$\int_{-h}^{+h} \sigma_1 dz = 0; \quad -z_o \chi = 0 \tag{2}$$

Using (1) and (2) one can establish the connection between the bending moment

$$M = \int_{-h}^{+h} z\sigma\, dz \tag{3}$$

It is not difficult to find that the equations of motion are written as follows

$$\begin{gathered} E_o J_o A \frac{\partial^2}{\partial x^2}\left[f(x) \frac{\partial^2 w}{\partial x^2} \right] + K_1(x) w + \\ + \left(K_2(x) + \overline{P}_o \psi(x) \right) \frac{\partial^2 w}{\partial t^2} = 0 \end{gathered} \tag{4}$$

It is noted that the base reaction is related to the bending ratio

$$\begin{gathered} f = K_1(x) + K_2(x) \frac{\partial^2 w}{\partial t^2} \\ A = \frac{1}{J_o}\left[\frac{f(z) z_o 2}{f_2(z) dz} - \int_{-h}^{=h} z^2 fez\, dz \right] \overline{\rho} = 2P_o h \int_{-1/2}^{+1/2} \psi(z) dt \end{gathered} \tag{5}$$

3. PURPOSE AND OBJECTIVES OF THE STUDY

It is important to highlight that the objective of this study is to investigate the simultaneous effects of heterogeneity in both length and thickness, along with the variability in viscoelastic resistance of the external environment. As observed, the equation of motion (4) is complex, making it challenging to solve the problem with arbitrary values of the functions that characterize the heterogeneities of both the pipe material and the foundation. In such cases, it is effective to use the method of separation of variables together with the Bubnov-Gale kin method. In the first stage of solving Equation (4), we will apply the method of separation variables, and represent these functions $w(x,t)$ in the form.

$$w(x,t) = w_o(x)\ell^{i\omega t} \tag{5}$$

where, $w_o(x)$ satisfies the boundary conditions, and ω is the frequency. Substituting Equation (5) into (4) yields.

$$\begin{gathered} f_1(x)\frac{d^4 w_o}{dx^4} + 2f^1(x)\frac{d^3 w_o}{dx^3} + f''(x)\frac{d^2 w_o}{dx^2} + \\ +K_1^1(1 - c\eta u) - \omega^2\left(\bar{K}_2(x) + \bar{\rho}\psi(x)\right)w_o = 0 \end{gathered} \tag{6}$$

Finding the exact solution to Equation (6) presents challenges; therefore, we will utilize the Bubnov-Galerkin orthogonalization method. We will express the functions $w_o(x)$ in the following form:

$$w_o(x) = \sum_{i=1}^{n} a_i\,\theta_i(x) \tag{7}$$

where, a_i is unknown constants and each $\theta_i(x)$ is satisfies homogeneous boundary conditions. In this case the error function from (6) and (7) is written as follows

$$\eta(x) = \sum_{i=1}^{n} a_i \begin{bmatrix} f_t(x)\frac{d^4 a_i}{dx^4} + 2f'(x)\frac{d^3 w_o}{dx^3} + f''(x)\frac{d^2 w_o}{dx^2} + \\ +K_1(1+\eta) - i_0^2(\bar{K}_2(x) + \bar{\rho}\psi(x)w^o \neq 0 \end{bmatrix} \tag{8}$$

Conditions of the orthogonality of Bubnov-Galerkin is

$$\int_0^{\ell} \eta(x)\theta_q(x)dx = 0; \quad q = \overline{1,n} \tag{9}$$

For an arbitrary approximation, ω^2 is determined from a system of linear homogeneous algebraic equations with respect to a_i. For the existence of a nontrivial solution to the system of Equation (9), the main determinant must be equal to zero.

$$\left\|\omega^2\right\| = 0 \tag{10}$$

Equation (10) is a nonlinear algebraic equation, and determining ω^2 using computer techniques is not particularly difficult. However, in engineering practice, the first approximation is usually neglected, in which case the orthogonality conditions are expressed in the following form.

$$\int_o^{\ell} \eta_1(x)\theta_1(x)dx = 0 \tag{11}$$

From here we find;

$$\omega^2 = \frac{\int_o^{\ell} \begin{bmatrix} f_1(x)\frac{d^4\theta_1}{dx^4} + 2f'(x)\frac{d^3\theta_1}{dx^3} + f_1^{11}(x)\frac{d^2\theta_1}{dx^2} + \\ +\bar{K}_1^o(1+\alpha)\eta_1(x)\theta_1(x)dx \end{bmatrix}}{\int_o^{\ell}\left(\bar{K}_2(x) + \bar{\rho}\psi(x)\right)\theta_1^2(x)dx} \tag{12}$$

From we obtain the solution to a similar problem when the pipe is laid on an inhomogeneous foundation;

$$\omega_1^2 = \frac{\int_o^{\ell} \begin{bmatrix} f_1(x)\frac{d^4\theta_1}{dx^4} + 2f'(x)\frac{d^3\theta_1}{dx^3} + \\ +f_1''(x)\frac{d^2\theta_1}{dx} + K_1^o(1 + \eta(x)\theta_1) \end{bmatrix}\theta_1(x)dx}{\tilde{\rho}\int_o^{\ell}\left(\psi(x)\theta_1^2(x)\right)dx} \tag{13}$$

From (12) and (13), the relation between $\bar{\omega}^2$ and ω_1^2;

$$\bar{\omega}_1^2 = \left(\frac{\omega}{\omega_1}\right)^2 = \frac{\bar{\rho}\int_o^{\ell}\psi(x)\theta_1^2(x)dx}{\int_o^{\ell}\left(\bar{K}_2(x) + \bar{\rho}\psi(x)\theta_1^2(x)dx\right)}$$

$$\bar{\omega}_1^2 = \frac{\int_o^{\ell}\psi(x)\theta_1^2(x)dx}{\int_o^{\ell}\bar{\rho}^{-1}\left(\bar{K}_2(x) + \psi(x)\theta_1^2(x)dx\right)} \tag{14}$$

If there is no resistance to the external environment;

$$\bar{\omega}_2 = \frac{\int_o^{\ell}\left[f_1(x)\frac{d^4\theta_1}{dx^4} + 2f(x)\right]\theta_1^2(x)dx}{\rho\ \psi(x)\theta^2(x)dx} \tag{15}$$

From (14), for $\bar{\rho} = \rho_o$, we obtain value $\bar{\omega}_1^2$ when pipe is heterogeneous only in length, while $\psi(x) = 1$ represents case when pipe is heterogeneous only in thickness.

4. CALCULATION WITH VALUES OF CHARACTERISTIC FUNCTIONS

By inserting (15) in (14) and considering that;

$$\begin{gathered} \theta_1 = \sin\pi\rho; \ \ \psi_1 = 1 + \mu\rho; \ \ \psi_2 = 1 + \varepsilon\bar{z}; \ K_1 = K_1^o(1+\alpha\rho) \\ K_2 = K_2^{10}(1+\alpha\rho); \ \varepsilon \in [0,1]; \ \mu \in [0,1]; \ \alpha \in [0,1] \end{gathered} \tag{15}$$

$$\int_0^1 \sin^2\pi\rho\,d\rho = \frac{1}{2}; \ \ \int_0^1 \rho\sin^2\pi\rho\,d\rho = \frac{1}{4}; \ \ \int_0^1 \sin^2\pi\rho d\rho = 0,$$

$$\bar{\omega}_1^2 = \frac{(1 + 0.5\mu)}{C(1 + 0.5\alpha) + (1 + 0.5\mu)} \tag{16}$$

Calculation results are presented in Tables 1 and 2.

Table 1. Frequency dependence on inhomogeneity parameters $C = 0;\ \varepsilon = 0$

μ	$\bar{\omega}_{11}^2$	$\bar{\omega}_{12}^2$
0	1	1.125
0.25	0.889	1
0.50	0.8	0.900
0.75	0.727	0.818
1.0	0.666	0.750

Table 2. The value of a dimensionless frequency depending on parameters characterizing heterogeneity $C = 1;\ \alpha = 0;\ \varepsilon = 0$

ω_1	$\bar{\omega}_{31}^2$	$\bar{\omega}_{32}^2$
0	0.5	1.15
0.25	0.471	1.022
0.50	0.444	0.92
0.75	0.421	0.836
1.0	0.4	0.762

The results of the numerical calculation are shown in Tables 1 and 2. Note that similar calculations can be performed for other approximations and functions characterizing the material. Results of numerical analysis It is shown that the values of ω^{z} significantly depend on the type of approximation, the functions $f(x)$ and $\psi(x)$ and on the characteristics of the external environment.

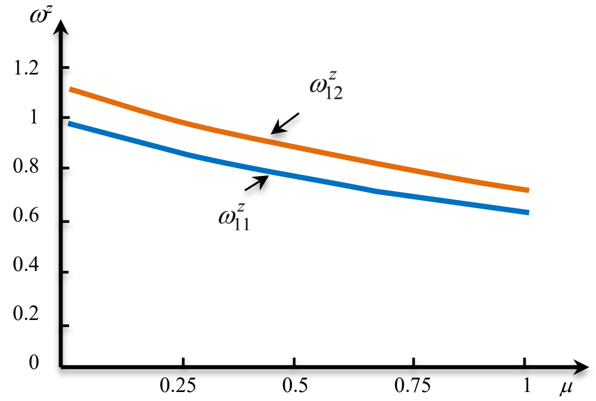

Figure 1. Graph of the dependence of the square of the frequency ω^{z} on the parameters of heterogeneity of different values of density μ compared to the fundamental frequency tone without taking them into account (C=0; ε=0)

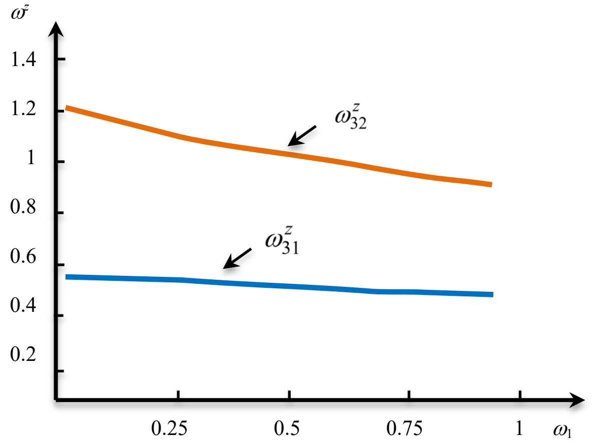

Figure 2. Graph of the dependence of the square of the frequency ω without taking into account the external resistance on the parameters of the inhomogeneity of the elastic modulus along the length compared to without taking into account the external resistance (C=1; α=0, ε=0)

From Figure 1, and it can be seen that at a constant density of $\mu = 1$, the value of the circular ω_1^2 frequency increases, and from Figure 2. it can be seen, that at different values of the resistance coefficient, the values of the circular frequency differ sharply from each other.

5. CONCLUSIONS

Before underwater pipelines are laid on the seabed, certain engineering measures must be taken (Figure 3). To protect the pipeline from undercurrents, as well as to prevent its exit from the intended trajectory (pipeline bed) as a result of free oscillation of the pipeline, special concrete or cast-iron loads are used. Such additional devices increase the level of heterogeneity in the direction of the length and thickness of the pipeline. On the other hand, at great sea depths (the Algerian-Spanish pipeline in the Mediterranean has a depth of 2000 m), laying a pipeline to the seabed is also a difficult engineering task. In the case of lying to a great depth, a long belt (lash) consisting of pipes is made at the initial stage. Then, when the length of the pallet becomes greater than the depth of the sea, it is immersed in water, filling the pipe with water with free swing.

At a later stage, most of the pipeline lies on the seabed, and the rest is suspended in the water by the action of a tensioner applied to the tip. This position of the pipeline is modeled as a semi-infinite rod, the pipeline is deformed by the tension force at the top and the gravity of the rest of the pipeline in the water. As a result, a state of geometric nonlinear deformation is formed in the pipeline.

Equation (4) proposed in the article, is able to give a fairly accurate result when faced with such problems. One of the main conditions for the safe operation of underwater pipelines for a long time is to protect the suspended part of the pipelines from damage from the effects of underwater currents (in this case, the greatest deformation occurs).

1. The influence of underwater currents on the suspended part is modeled.
2. The displacements caused by the influence of underwater currents are taken into account.
3. At the moment when the influence of underwater currents is equal to the weight of the pipeline, the tensile force increases by 50%.

- This study introduces, for the first time, the problem of natural vibrations in a straight section of a pipe that exhibits continuous heterogeneity in both length and thickness, supported by a two-constant Pasternak foundation. The findings highlight the substantial impact of the pipe's material heterogeneity and the surrounding environment on the circular frequency values.
- In this study, as a special case, the natural oscillations of an inhomogeneous orthotropic plate resting on an inhomogeneous viscoelastic base are obtained. The analysis of the obtained results revealed noteworthy effects of orthotropy, material heterogeneity and viscoelastic properties of the supporting medium, as can be seen from the tables and Figures 1 and 2.

The analysis showed that taking into account the heterogeneities of the elastic modulus of the material, the thickness of the pipe and the characteristics of the base has a significant impact on the circular frequency of the structure. This highlights the importance of including all factors in the design and calculation of pipelines.

4. Numerical calculations also revealed that, under a linear variation of heterogeneity with respect to thickness, the effect on frequency is negligible. However, when the modulus of elasticity varies linearly with respect to thickness, this assumption no longer holds true.

These conclusions emphasize the critical need to account for material heterogeneity and foundation characteristics when analyzing vibrational behavior in pipelines. Such considerations facilitate the development of more precise and reliable engineering solutions.

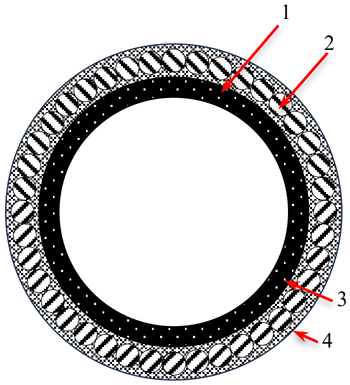

Figure 3. Structure of a pipeline under external protection
1- Metal pipe, 2- Wired mesh prepared for concrete
3- Polyethylene coating, 4- External insulation layer

NOMENCLATURES

Symbols / Parameters

E : The modulus of elasticity
E_0 : The modulus of elasticity to the homogeneous case
ρ : The density
ρ_0 : The density to the homogeneous case
$f_1(x)$ and $\psi_1(x)$: The functions along with their second-order derivatives are continuous functions
$w(x,t)$: Solving the equation
a_i : Unknown constants

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