Simulation of oscillations of composite pipelines conveying pulsating fluid

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Abstract. The article considers the problem of vibrations of straight sections of the pipeline based on the theory of beams. A mathematical model of the dynamics of a straight viscoelastic pipe with a pulsating fluid is developed. The speed of a pulsating fluid is assumed to be harmonically fluctuating and has the following form: $V(t) = \upsilon_0(1 + \mu_1 cos\varpi t)$. The mathematical model of the problem is simplified using the Bubnov-Galerkin approach to the solution of a set of common integro-differential equations with time as an independent variable. A numerical approach based on the removal of the singularity in the relaxation kernel of the integral operator is used to solve integro-differential equations. A numerical approach for the unknowns was used to get the system of algebraic equations. The Gauss technique is used to resolve a set of algebraic equations. The dynamics of fluid-transporting viscoelastic pipes have difficulties that can be solved computationally.

1. Introduction

Pipeline systems are important for the effective functioning of fuel and energy complex. They help to meet the needs of the population with basic resources: oil, natural gas, petroleum products, etc. Extensive net of pipelines, both in the republic and abroad, support the vital functions of countries, being one of the main factors of economic development. Failure of even small sections of pipelines, accompanied by explosions and fires, can cause serious consequences associated with the loss of pumped product, high repair costs, and can lead to significant pollution of the environment [1].

One of the most pressing problems in design of pipelines is a dynamic calculation. As practice shows, when operating a pipeline conveying pulsating oil or gas flows, there occur parametric oscillations. The danger of these oscillations lies in the fact that at certain definite ratios between the natural frequencies of the pipeline oscillations and the excitation frequencies, an unlimited increase in the amplitude of parametric oscillations occurs and a phenomenon of parametric resonance begins. Under conditions of parametric resonance, the structure is subjected to dangerous cyclic effects, which can lead to fatigue failure [2-12].

Parametric resonance of a pipeline was considered by Païdoussis and Issid [13] in the form of a beam with clamped edges; there only the “beam” modes of oscillations were taken into account.

The operation of pipeline systems demonstrates that the pressure and flow pulsations at the injection units' outlet, which are then transmitted to the system, and hydrostatic disturbances that take place when the gate components turn are the sources of these variations. The issue is still far from being resolved despite countless studies devoted to the creation of mathematical models of pipelines oscillating with a pulsing flow of the working fluid. This is because simplified versions of the pipeline center line are taken into account in a number of models, idealizations that are not nearly appropriate for use [14].

Currently, the repair, restoration, and renewal of pipelines damaged as a result of numerous external sources frequently presents challenges to the agricultural sector, the oil and gas industry, housing, and communal services. Uti-

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lizing contemporary, resource-saving, and environmentally friendly technologies, including non-metallic materials, in particular polymer composite materials, is one option to address this issue [15, 16, 17].
This article's focus is on finding solutions to the aforementioned issues, hence its subject matter is quite pertinent.
For application in the oil and gas industry, agriculture, water management, housing, and communal services, this work aims to develop a mathematical model, a numerical algorithm, and a computer program for solving the problem of oscillations of viscoelastic pipes based on the theory of beams.

2. Mathematical model

Consider a viscoelastic pipeline in the form of a straight single-span beam with hinges at both ends. Select a rectangular coordinate system so that the x-axis passes through the centers of gravity of pipe sections in supports with $x=0$ and $x=L$ coordinates. The pipeline axis points' movements along the z-axis depict an unidentified function of deflections w. (x,t). The pipeline's longitudinal oscillations are not taken into account as the liquid flow rate along the pipeline's axis is V.
The equation of pipeline oscillations has the form [13, 18]:

$$EI\left(1-R^*\right)\frac{\partial^4 w}{\partial x^4}+m_1\left(L-x\right)\frac{\partial V}{\partial t}\frac{\partial^2 w}{\partial x^2}+\left(m_1V^2+pF\right)\frac{\partial^2 w}{\partial x^2}+ \\ +2m_1V\frac{\partial^2 w}{\partial x\partial t}+\left(m_1+m_2\right)\frac{\partial^2 w}{\partial t^2}=0. \tag{1}$$

Here *E* is the modulus of elasticity of the pipe material; *J* is the moment of inertia of the pipe section. *x* is an independent variable, the longitudinal axial coordinate of the pipe; m_1 is the fluid mass per unit length of the pipe; m_2 is the pipe mass per unit length; *F* is the cross-sectional area of the pipe; *p* is the internal working pressure; R^* is the integral operator of the form $R^*\varphi(t)=\int_0^t R(t-\tau)\varphi(\tau)d\tau$; $R(t-\tau)$ is the Koltunov-Rzhanitsyn relaxation kernel [19].

3. Discretization and method of solution

We are looking for an approximate solution of equation (1) in the form:

$$w\left(x,t\right)=\sum_{n=1}^{N}w_n\left(t\right)\phi_n\left(x\right), \tag{2}$$

where $w_n\left(t\right)$ are some functions to be determined, and the functions $\phi_n\left(x\right)$ are chosen so that each term of the sum (2) satisfies the boundary conditions. Below the boundary conditions - hinged supports at the edges of the pipe - are considered. In this case, in decomposition of the Bubnov–Galerkin method (2), the approximating functions of the deflection are chosen in the form

$$\phi_n\left(x\right)=\sin\frac{n\pi x}{L}.$$

The speed of the pulsating fluid $V(t)$ is assumed to be harmonically oscillating and has the following form [13]:

$$V(t)=\upsilon_0(1+\mu_1 cos\varpi t), \\ V^2(t)\approx\upsilon_0^2(1+2\mu_1 cos\varpi t), \tag{3}$$

here υ_0 is the constant flow rate of the liquid, μ_1 is the excitation coefficient, ϖ is the frequency of the liquid pulsation.

Substituting (2) into equation (1) and applying the Bubnov-Galerkin method to this equation, we obtain a system of integro-differential equations (IDE) with respect to the coefficients (2). Introducing the following dimensionless values

$$\frac{w}{L},\ \frac{1}{\omega}R(t)$$

and we get a system of IDE with respect to w_k :

$$\ddot{w}_k + 2\upsilon\sqrt{\beta_{12}}\left(1+\mu\cos\omega\tau\right)\sum_{n=1}^{N}\dot{w}_n\gamma_{nk} + \left(1-R^*\right)k^4\pi^4 w_k +$$
$$+\left[\mu\upsilon\sqrt{\beta_{12}}\left(1-\xi\right)\omega\sin\omega\tau - \upsilon^2\left(1+\mu\cos\omega\tau\right)^2 + T_1\right]k^2\pi^2 w_k = 0. \quad (4)$$

$$w_n(0) = w_{0n};\quad \dot{w}_n(0) = \dot{w}_{0n}.$$

Here $\xi = \dfrac{x}{L},\quad \upsilon = \upsilon_0 L\left(\dfrac{m_1}{EL}\right)^{0,5},\quad T_1 = pF\dfrac{L^2}{EI},\quad \beta_{12} = \dfrac{m_1}{m_1+m_2},$

$$\tau = \frac{t}{L^2}\left(\frac{EL}{m_1+m_2}\right)^{0,5},\quad \omega=\overline{\omega}\cdot L^2\left(\frac{m_1+m_2}{EI}\right)^{0,5}.$$

Further, a numerical method is applied to system (4), which describes nonlinear problems of oscillations of viscoelastic pipelines [29, 34]. On its basis, an algorithm for the numerical solution of system (4) is described.

4. Numerical results

With the help of the numerical method [22, 24-30] a system of algebraic equations is obtained. The results of numerical calculations are presented in the form of graphs in Figures 1-5.
Figures 1–5 show the results of calculations related to the straight section of the pipeline conveying fluid. The smallness of coriolis force is used. This allows omitting the terms $2m_1V\dfrac{\partial^2 w}{\partial x\partial t}$ in equations (1).
Figure 1 shows the results of calculations of the influence of the rheological parameter α on the pipeline deflection. The following parameters A=0.05, β=0.001, T_1=1, υ=0.5, ξ=0.1, ω=2 were selected. Judging by curve 2, the deflections vary in time according to a law close to a harmonic one. The curves shown in the figure refer to the following parameter values α = 0.1 (1), α = 0.7 (2). At α = 0.1, a singular, rapidly damping oscillatory process occurs [20-37].

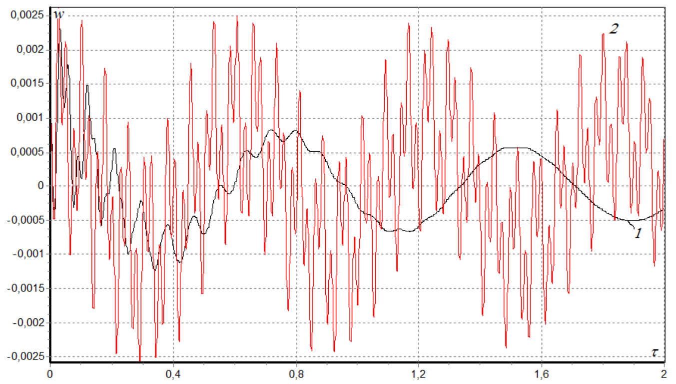

Fig. 1. α=0.1(1); α=0.7(2); A=0.05; β=0.001; T_1=1; υ=0.5; ξ=0.1; ω=2

Figure 2 shows the dependence of the pipe deflection $\frac{w}{L}$ (L is the length of overhang) on dimensionless time τ for various values of mass ratio β_{12}. Mass ratio β_{12} varies from zero to one. In calculations, A=0.05, T_1=1, ξ=0.1, υ=1,5, ω=5 are taken. Judging by the graph, with an increase in β_{12} parameter, the amplitude and frequency of oscillations vary dramatically. This is explained by the fact that as the parameter β_{12} increases, the pipe mass decreases by unit length, i.e. pipe thickness decreases. Thus, an increase in the parameter β_{12} leads to an increase in the amplitude and frequency of oscillations.

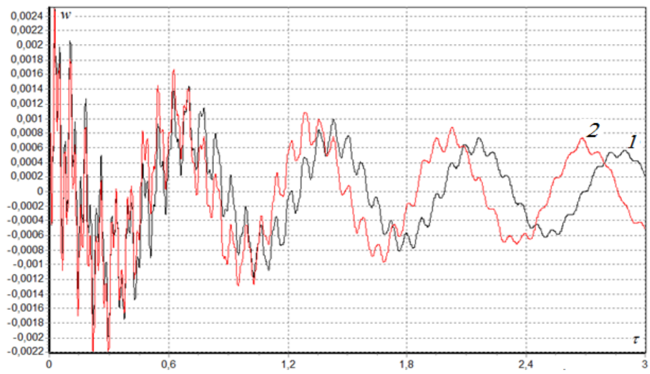

Fig. 2. β_{12}=0.1(1); β_{12}=1(2); A=0.05; α=0.25; β=0.001; T_1=1; ξ=0.1; υ=1.5; ω=5

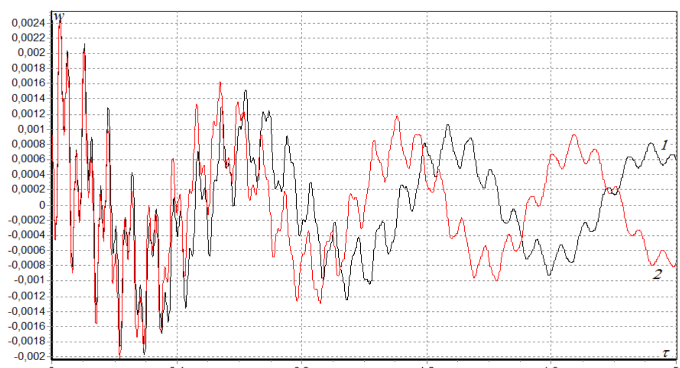

Fig. 3. T_1=1(1), T_1=4 (2), A=0.05; α=0.25; β=0.001; ξ=0.1; β_{12}=0.1; υ=0.5; ω=2.5

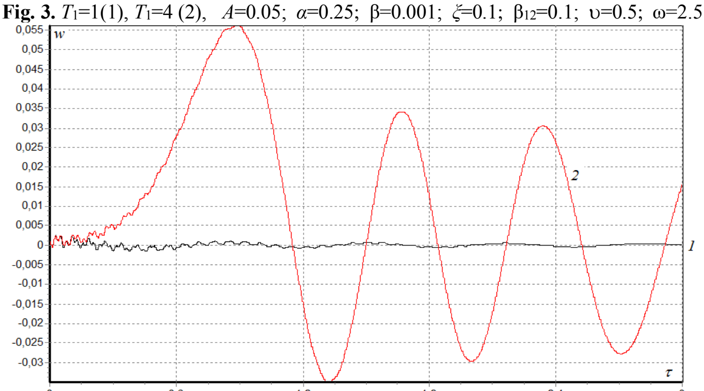

Fig. 4. υ=1.5(1); υ=2.5(2); A=0.05; α=0.25; β=0.001; T_1=1; ξ=0.1; β_{12}=0.5; μ_1=0.6; ω=1.5

Figure 3 shows the dependences w(τ) for various dimensionless parameters of the internal pressure T_1. Dimensionless fluid rate is $\upsilon = 0.5$. As seen, with an increase in parameter T_1, the amplitude and frequency of oscillations of the pipeline increase. Thus, the magnitudes of the deflections determined at different dimensionless parameters of internal pressure T_1 can vary greatly.

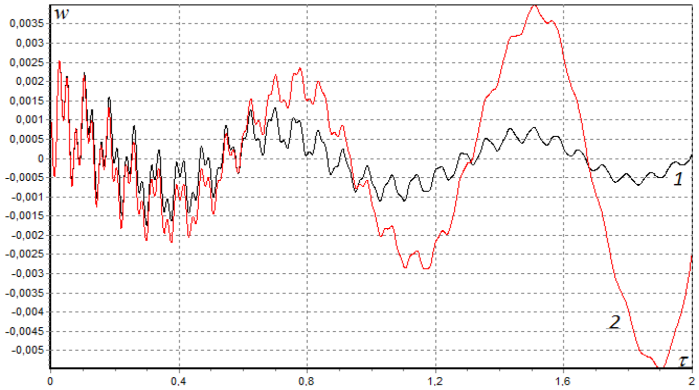

Fig. 5. ω=5 (1); ω=17(2); A=0.05; α=0.25; β=0.001; T_1=1; ξ=0.5; β_{12}=0.5; μ_1=0.4; υ=1.5

Figure 4 shows the dependence of *w(τ)* on time *τ* at various fluid rates υ. At υ = 1.5, the initial excitation, although slowly, attenuates with time. It should also be noted that an increase in fluid rate leads to a sharp increase in amplitude of deflection. The reason of amplitude increase can be explained by the fact that the flow rate is higher than the critical one. Apparently, this rate of fluid flow will be the most dangerous for the pipeline under consideration.
The influence of fluid pulsation frequency ω on the oscillations of viscoelastic pipes has been investigated. The graph in Figure 5 shows the curves w (τ) obtained for the pipe at ω = 5 (curve 1); ω=17 (curve 2). It is seen that an increase in the frequency of fluid pulsation leads to an increase in the amplitude of oscillations. Studies have shown that the results of numerical simulation are consistent with known results given in [13, 18, 32].

5. Conclusions

In this paper, a mathematical model of the dynamics of a straight viscoelastic pipe segment with pulsating fluid flow is developed. A computational technique has been developed to address issues with the dynamics of a liquid-filled pipeline. In order to analyze the oscillatory processes of viscoelastic pipes carrying a pulsating gas liquid, a system of applicable computer programs has been developed on the basis of the developed computational method. Vibration amplitude and frequency are reduced by 20–40% when the viscoelastic qualities of the pipe material are taken into consideration. The structure may be destroyed as a result of oscillatory motions with rapidly growing amplitudes caused by increasing the frequency of fluid pulsations and the excitation coefficient. The outcomes of numerical simulation can be applied at companies in the oil and gas sector and in design firms.

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