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OSCILLATIONS OF AN ANISOTROPIC INHOMOGENEOUS LONGITUDINALLY SUPPORTED CYLINDRICAL SHELL WITH A LIQUID

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Abstract- The free oscillation of an anisotropic, inhomogeneous, longitudinally reinforced cylindrical shell contacting a moving fluid is investigated in the present article. Using the Hamilton urgent urban variation principle, systems of equations of motion of a longitudinally reinforced non-uniform in thickness anisotropic cylindrical shell, which is in contact with a moving fluid, are constructed. To take into account the heterogeneity of the shell material over the thickness, it is assumed that the Young's modulus and the density of the shell material are functions of the normal coordinate. When studying the free oscillations of an anisotropic cylindrical shell inhomogeneous in thickness, which is in contact with a moving fluid and is inhomogeneous over the thickness, two cases are considered: a) liquid inside the shell is at rest; b) the liquid inside the shell moves at a constant speed. In both cases, the frequency equations are constructed and implemented numerically. In the calculation process, the linear and parabolic laws are adopted for the inhomogeneity function. Characteristic dependency curves are constructed.

Keywords: Reinforced Shell, Variation Principle, Fluid, Free Oscillation, Anisotropic Shell.

I. INTRODUCTION

In the design of modern apparatus, machines and structures, calculations on the stability, vibrations, and strength of thin-walled elements of shell-type structures that are in contact with the medium play an important role. Such structures may be in contact with the liquid and subject not only to static loads, but also dynamic. To give greater rigidity, the shells are reinforced with different ribs. However, the behavior of heterogeneous anisotropic thin-walled structural elements with ribs, accounting for their discrete location, the influence of the liquid, has not been adequately studied. Therefore, the development of mathematical models for investigating the behavior of reinforced heterogeneous anisotropic shells, which most fully take into account their work under dynamic loads, and carrying out studies of stability and oscillations on their basis, as well as the choice of rational parameters of a structure in contact with a liquid, are urgent problems.

We note that studies of free vibrations of ribbed isotropic homogeneous cylindrical shells filled with a flowing liquid are devoted to [1, 2]. Effects of the number of ribs, their rigidity, fluid flow rate, various mechanical, physical and geometric dimensions of the shell on the frequencies of natural oscillations and the optimization parameter of a circular ribbed cylindrical shell are studied. Works [3-4] are devoted to the study of free oscillation by an isotropic non-uniform reinforced by the cross systems of the ribs of a cylindrical shell that contacts the moving fluid. Using the variation principle of Hamilton urgent urban, systems of equations of motion of reinforced cross-bars, inhomogeneous in thickness of an anisotropic cylindrical shell contacting a moving fluid, are constructed.

The results of an experimental investigation of the effect of reinforcing ribs and attached solids on the frequencies and shapes of free vibrations thin elastic structurally inhomogeneous shells are presented in [5]. In [6, 7] with the help of an asymptotic method, the frequency equations of smooth cylindrical shells with a filled liquid are constructed, approximate frequencies of the equation and simple calculation formulas are obtained, which allow one to find the values of the minimum natural frequencies of the oscillations of the considered system. Here, forced oscillations of a reinforced shell filled with a liquid are investigated, and the amplitude-frequency characteristics of the considered oscillatory processes are determined.

The work [8, 9, 10] is devoted to the study of the parametric oscillation of a nonlinear and inhomogeneous in thickness rectilinear rod in a viscoelastic medium by the use of the Pasternak contact model. The influence of the main factors - the elasticity of the base, the damageability of the rod and shell material, the dependence of the shear coefficient on the vibration frequency on the characteristics of the longitudinal oscillations of the points of the rod in a viscoelastic medium is studied. In all the investigated cases, the dependencies of the dynamic stability zone of the rod vibrations in a viscoelastic medium on the design parameters on the load-frequency plane are constructed.

II. PROBLEM STATEMENT

An anisotropic, inhomogeneous ribbed shell is considered as a system consisting of its own shell and rigidly connected to it along the contact lines of the ribs. It is assumed that the stress-strain state of the shell can be completely determined within the framework of the linear theory of elastic thin shells based on the Kirchhoff-Love hypotheses, and the Kirchhoff-Clebsch curvilinear rod theory is applicable for the calculation of edges. The coordinate system is chosen so that the coordinate lines coincide with the lines of the principal curvatures of the middle surface of the shell. It is assumed that the edges are placed along the coordinate lines, and their edges, like the edges of the skin, lie in the same coordinate plane. In addition, it is assumed that all the ribs form a regular system. By a regular system of longitudinal and annular edges we mean a system in which the rigidity of all edges, their mutual distances are equal, and the distance from the edge of the shell to the nearest edge is equal to the distance between the edges.

The deformed state of the skin can be determined through three component movements of its median surface u, ϑ and w. In this case, the angles of rotation of the normal elements φ_1, φ_2 relative to the coordinate lines y and x are expressed through w and ϑ using dependencies $\varphi_1 = -\frac{\partial w}{\partial x}$, $\varphi_2 = -\left(\frac{\partial w}{\partial y} + \frac{\vartheta}{R}\right)$, where R is radius of the middle surface of the shell.

To describe the deformed state of the ribs, in addition to the three components of the displacement of the centers of gravity of their cross sections (u_i, ϑ_i, w_i, where i is the longitudinal rod), it is also necessary to determine the angles of twisting φ_{kpi}.

Taking into account that according to the accepted hypotheses there is a constancy of radial deflections along the height of the sections, and also resulting from the conditions of rigid joining of the ribs with the shell of equality of the corresponding twist angles, we write the following relations:

$$u_i(x) = u(x, y_i) + h_i\varphi_1(x, y_i);\ \vartheta_i(x) = \vartheta(x, y_i) + h_i\varphi_2(x, y_i);$$
$$w_i(x) = w(x, y_i); \varphi_i = \varphi_1(x, y_i);\ \varphi_{kpi}(x) = \varphi_2(x, y_i)$$

where, $h_i = 0.5h + H_i^1$, h is shell thickness, H_i^1 is distance from axes, i is the longitudinal rod to the surface of the shell, x_i and y_i are the coordinates of the lines of conjugation of edges with a shell, φ_i, φ_{kpi} are the angles of rotation and twisting of the cross sections of the longitudinal rods.

With respect to external influences, it is assumed that the surface loads acting on the ribbed shell on the liquid side can be reduced to the components q_x, q_y and q_z, applied to the middle surface of the shell. Differential equations of motion and natural boundary conditions for a longitudinally supported orthotropic cylindrical shell with a fluid are obtained on the basis of the variation principle of Hamilton urgent urban. To do this, we first write down the potential and kinetic energies of the system.

To take into account the inhomogeneity in the thickness of the cylindrical shell, we start from the three-dimensional functional. In this case the functional of the total energy of the cylindrical shell has the form:

$$\begin{cases} V = \frac{1}{2}\iint\int_{-\frac{h}{2}}^{\frac{h}{2}} (\sigma_{11}\varepsilon_{11} + \sigma_{22}\varepsilon_{22} + \sigma_{12}\varepsilon_{12} + \\ +\rho(z)\left(\left(\frac{\partial u}{\partial t}\right)^2 + \left(\frac{\partial \vartheta}{\partial t}\right)^2 + \left(\frac{\partial w}{\partial t}\right)^2\right)dxdydz \end{cases} \quad (1)$$

There are various ways to take into account the inhomogeneity of the shell material. One of them is that the Young's modulus and the density of the shell material are taken as functions of the normal coordinate z: $E = E(z)$, $\rho = \rho(z)$ [11]. It is assumed that the Poisson's ratio is constant. In this case, the deformation-tension relationship has the form:

$$\begin{cases} \sigma_{11} = b_{11}(z)\varepsilon_{11} + b_{12}(z)\varepsilon_{22} \\ \sigma_{22} = b_{12}(z)\varepsilon_{11} + b_{22}(z)\ \varepsilon_{22} \\ \sigma_{12} = b_{66}(z)\varepsilon_{12} \end{cases} \quad (2)$$

$$\varepsilon_{11} = \frac{\partial u}{\partial x}\ ,\ \varepsilon_{22} = \frac{\partial \vartheta}{\partial y} + w\ ,\ \varepsilon_{12} = \frac{\partial u}{\partial y} + \frac{\partial \vartheta}{\partial x} \quad (3)$$

Taking into account Equations (2)-(3) and

$$\begin{cases} \iint\int_{-\frac{h}{2}}^{\frac{h}{2}}\left(\rho(z)\left(\frac{\partial u}{\partial t}\right)^2 + \left(\frac{\partial \vartheta}{\partial t}\right)^2 + \left(\frac{\partial w}{\partial t}\right)^2\right)dxdydz = \\ = \iint(\rho_0\left(\left(\frac{\partial u}{\partial t}\right)^2 + \left(\frac{\partial \vartheta}{\partial t}\right)^2 + \left(\frac{\partial w}{\partial t}\right)^2\right) - \\ -2\rho_1\left(\frac{\partial^2 w}{\partial x\partial t}.\frac{\partial u}{\partial t} + \frac{\partial^2 w}{\partial y\partial t}.\frac{\partial \vartheta}{\partial t}\right) + \\ +\rho_2\left(\left(\frac{\partial^2 w}{\partial x\partial t}\right)^2 + \left(\frac{\partial^2 w}{\partial y\partial t}\right)^2\right)dxdy \end{cases}$$

in (1), we can write:

$$\begin{cases} V = \frac{1}{2}\iint\{\tilde{b}_{11}\,\varepsilon_{11}^2 + 2\tilde{b}_{12}\varepsilon_{11}\varepsilon_{22} + 2\tilde{b}_{26}\varepsilon_{12}\varepsilon_{22} + \\ +2\tilde{b}_{16}\varepsilon_{11}\varepsilon_{12} + \tilde{b}_{22}\varepsilon_{22}^2 + \tilde{b}_{66}\varepsilon_{12}^2\}\,dxdy + \\ +\iint(\tilde{\rho}\left(\left(\frac{\partial u}{\partial t}\right)^2 + \left(\frac{\partial \vartheta}{\partial t}\right)^2 + \left(\frac{\partial w}{\partial t}\right)^2\right)dxdy \end{cases} \quad (4)$$

where,

$$\tilde{b}_{11} = \int_{-\frac{h}{2}}^{\frac{h}{2}} b_{11}(z)\,dz\ ,\ \tilde{b}_{12} = \int_{-\frac{h}{2}}^{\frac{h}{2}} b_{12}(z)\,dz\ ,\ \tilde{b}_{22} = \int_{-\frac{h}{2}}^{\frac{h}{2}} b_{22}(z)\,dz$$

$$\tilde{b}_{66} = \int_{-\frac{h}{2}}^{\frac{h}{2}} b_{66}(z)\,dz\ ,\ b_{11}(z) = \frac{E_1(z)}{1-\nu_1\nu_2}\ ,\ b_{22}(z) = \frac{E_2(z)}{1-\nu_1\nu_2}$$

$b_{12}(z)=\dfrac{\nu_2 E_1(z)}{1-\nu_1\nu_2}=\dfrac{\nu_1 E_2(z)}{1-\nu_1\nu_2}$, $b_{66}(z)=G_{12}(z)=G(z)$ are the basic modules of elasticity of an orthotropic material, and $\tilde{\rho}=\int_{-h}^{h.}\rho(z)dz$.

Expressions for the potential energy of elastic deformation *i*th longitudinal edge is [12]:

$$\begin{cases} \mathit{\Pi}_i=\dfrac{1}{2}\int_0^L\left[\tilde{E}_iF_i\left(\dfrac{\partial u_i}{\partial x}\right)^2+\tilde{E}_iJ_{yi}\left(\dfrac{\partial^2 w_i}{\partial x^2}\right)^2+\right. \\ \left.+\tilde{E}_iJ_{zi}\left(\dfrac{\partial^2\vartheta_i}{\partial x^2}\right)^2+\tilde{G}_iJ_{\kappa p\mathrm{i}}\left(\dfrac{\partial\varphi_{\kappa p\mathrm{i}}}{\partial \mathrm{x}}\right)^2\right]dx \end{cases} \tag{5}$$

The kinetic energy of the edges is written in the form [12]:

$$K_i=\rho_iF_i\int_{x_1}^{x_2}\left[\left(\frac{\partial u_i}{\partial t}\right)^2+\left(\frac{\partial\vartheta_i}{\partial t}\right)^2+\left(\frac{\partial w_i}{\partial t}\right)^2+\frac{J_{\kappa pi}}{F_i}\left(\frac{\partial\varphi_{\kappa pi}}{\partial t}\right)\right]dx \tag{6}$$

In the Equations (4) and (6) $F_i, J_{zi}, J_{yi}, J_{kpi}$ are area and moments of inertia of the cross section *i*th longitudinal axis respectively with respect to the axis Oz and an axis parallel to the axis Oy and passing through the center of gravity of the section, as well as its moment of inertia during torsion; $\tilde{E}_i,\tilde{G}_i$ are module of elasticity and shear of material *i*th longitudinal rod, ρ_i is the density of the materials from which *i*th second longitudinal kernel.

The potential energy of external surface loads acting on the side of an ideal fluid applied to the shell is defined as the work performed by these loads when the system is transferred from the deformed state to the initial undeformed state and is represented as:

$$A_0=-\int_0^L\int_0^{2\pi}q_z w\,dxdy \tag{7}$$

The total energy of the system is equal to the sum of the energies of the elastic deformations of the shell and transverse edges, as well as the potential energies of all external loads acting on the side of the ideal fluid:

$$J=V+\sum_{i=1}^{k_1}\left(\Pi_i+K_i\right)+A_0 \tag{8}$$

where, k_1 is number of longitudinal ribs.

Assuming that the main flow velocity is equal to U and the deviations from this velocity are small, we use the wave equation for the perturbed velocity φ potential with respect to [13]:

$$\Delta\tilde{\varphi}-\frac{1}{a_0^2}\left(\frac{\partial^2\tilde{\varphi}}{\partial t^2}+2U\frac{\partial^2\tilde{\varphi}}{R\partial\xi\partial t}+U^2\frac{\partial^2\tilde{\varphi}}{R^2\partial\xi^2}\right)=0 \tag{9}$$

The expression for the total energy of the system (8), the fluid motion Equation (9) is supplemented by contact conditions. On the contact surface of the shell-liquid, the continuity of radial velocities and pressures is observed.

The condition of impermeability or smoothness of flow past the shell wall has the form [13]:

$$\vartheta_r\big|_{r=R}=\frac{\partial\varphi}{\partial r}\bigg|_{r=R}=-\left(\omega_0\frac{\partial w}{\partial t_1}+U\frac{\partial w}{R\partial\xi}\right) \tag{10}$$

Equality of radial pressures from the liquid to shell:

$$q_z=-p_{|r=R} \tag{11}$$

If we substitute in (9) and (10) $U=0$, we obtain the equation of motion and the condition of impermeability or smoothness of flow past the shell wall for a fluid at rest. The frequency equation of a ribbed inhomogeneous orthotropic shell with a flowing liquid is obtained on the basis of the stationarity principle of Hamilton urgent urban action:

$$\delta W=0 \tag{12}$$

where , $W=\int_{t'}^{t''}Jdt$ action on Hamilton, and t' and t'' are given arbitrary moments of time.

Supplementing the total energy of the system (8), the fluid motion Equation (9) with contact conditions, we arrive at the problem of natural oscillations longitudinally under crepe which is inhomogeneous in thickness, of an orthotropic cylindrical shell with a flowing liquid. In other words, the problem of the natural oscillations of a longitudinally supported heterogeneous orthotropic cylindrical shell with a flowing liquid reduces to the joint integration of the expressions for the total energy of the system (8), the fluid motion Equation (9) when conditions (9) and (10) are satisfied on contact surface.

III. PROBLEM SOLUTION

Potential of disturbed velocities φ looking for as:

$$\tilde{\varphi}(\xi,r,\theta,t_1)=f(r)\cos n\varphi\sin\chi\xi\sin\omega_1t_1 \tag{13}$$

Using (10), from condition (7), (8) we have:

$$\begin{cases} \tilde{\varphi}=-\Phi_{\alpha n}\left(\omega_0\dfrac{\partial w}{\partial t_1}+U\dfrac{\partial w}{R\partial\xi}\right) \\ p=\Phi_{\alpha n}\rho_m\left(\omega_0^2\dfrac{\partial^2 w}{\partial t_1^2}+2U\omega_0\dfrac{\partial^2 w}{R\partial\xi\partial t_1}+U^2\dfrac{\partial^2 w}{R^2\partial\xi^2}\right) \end{cases} \tag{14}$$

where,

$$\Phi_{\alpha n}=\begin{cases} I_n(\beta r)/I_n'(\beta r), & M_1<1 \\ J_n(\beta_1 r)/J_n'(\beta_1 r), & M_1>1 \\ \dfrac{R^n}{nR^{n-1}}, & M_1=1 \end{cases} \tag{15}$$

where, $M_1=\dfrac{U+\omega_0R\omega_1/\alpha}{a_0}$, $\beta^2=R^{-2}\left(1-M_1^2\right)\chi^2$, $\beta_1^2=R^{-2}\left(M_1^2-1\right)\chi^2$, I_n is modified Bessel function of the first kind of order *n*, J_n is functions Bessel of the first kind of order *n*, $\omega_0=\sqrt{E_0/\left[\left(1-v^2\right)\rho_0R^2\right]}$ and $\omega_1=\omega/\omega_0$.

In the Equation (8), the variable quantities are $u, \vartheta, w,$. These approximate values are approximated as follows:

$$\begin{cases} u = u_0 \cos\dfrac{\pi x}{l} \sin k\varphi \sin \omega t \ , \ \vartheta = \vartheta_0 \sin\dfrac{\pi x}{l} \cos k\varphi \sin \omega t \\ w = w_0 \sin\dfrac{\pi x}{l} \sin k\varphi \sin \omega t \end{cases} \tag{16}$$

Substituting (16) into (8) after integration, we obtain a function of the variables u_0, ϑ_0, w_0. The stationary value of the obtained function is determined by following system:

$$1)\ \frac{\partial J}{\partial u_0} = 0 \ , \ 2)\ \frac{\partial J}{\partial \vartheta_0} = 0 \ , \ 3)\ \frac{\partial J}{\partial w_0} = 0 \tag{17}$$

A nontrivial solution of a system of linear algebraic Equations (17) of the third order is possible only in the case when ω_1 is the root of its determinant. Definition ω_1 reduces to a transcendental equation, since ω_1 enters the arguments of the Bessel function:

$$\det a_{ij} = 0 \ , \ i, j = 1,3 \tag{18}$$

IV. NUMERICAL RESULTS

The frequency Equation (18) was solved numerically with the following initial data:

$R = 160$ mm , $\tilde{E}_i = 6.67 \times 10^9$ Pa , $a_0 = 1430$ m/sec ,

$h = 0.45$ mm , $L = 800$ mm , $\rho_i = 7.8$ r/cm^3 , $\nu_1 = 0.11$,

$\nu_2 = 0.19$, $\dfrac{I_{kp.i}}{2\pi R^3 h} = 0.5305 \times 10^{-6}$,

$\dfrac{I_{yi}}{2\pi R^3 h} = 0.8289 \times 10^{-6}$, $\dfrac{F_i}{2\pi Rh} = 0.1591 \times 10^{-1}$,

$\dfrac{J_{zi}}{2\pi R^3 h} = 0.13 \times 10^{-6}$, $|h_i| = 0.1375 \times 10^{-1} R$

Two types of laws of variation of inhomogeneity are considered:

Linear $E_1(z) = E_1\left[1 + \alpha\left(\dfrac{z}{h}\right)\right]$, $E_2(z) = E_2\left[1 + \beta\left(\dfrac{z}{h}\right)\right]$,

$\rho(z) = \rho_0\left[1 + \alpha\left(\dfrac{z}{h}\right)\right]$ and Parabolic $E_1(z) = E_1\left[1 + \alpha\left(\dfrac{z}{h}\right)^2\right]$

, $E_2(z) = E_2\left[1 + \beta\left(\dfrac{z}{h}\right)^2\right]$, $\rho(z) = \rho_0\left[1 + \alpha\left(\dfrac{z}{h}\right)^2\right]$

where, α, u, β are parameters of inhomogeneity. Note that, under linear law, the change $|\alpha| < 1$, $|\beta| < 1$, with a parabolic change α, β are arbitrary.

The results of the calculation are shown in Figures 1 and 2. Figure 1 shows the frequency dependence of the parameter ω_1 of the relative flow rate U^* for various laws of variation of inhomogeneity over the thickness of the shell, and for different ratios E_1 / E_2. It is seen that the increase in speed, decrease E_1 / E_2 leads to a decrease in frequency. Note that $U^* = 0$ corresponds to a fluid at rest.

Figure 2 illustrates the influence of the number of longitudinal ribs k_1 on frequency parameters ω_1 oscillations of the considered system. It can be seen that with increasing k_1 frequency parameters ω_1 the oscillations of the system are first increased, and then at a certain value k_1 begin to decrease. This is due to the fact that, with increasing k_1 the weight of the rods increases and this leads to a significant effect of their inertial properties on the oscillation process.

Comparisons of these graphs show that taking into account the inhomogeneity leads to a decrease in the values of the natural frequencies of the oscillations of the considered system in comparison with the natural frequencies of oscillations of the same system when the shell is homogeneous. In addition, with a decrease in the ratio E_1 / E_2 of the oscillation frequencies of the system under consideration also decreases in comparison with the natural frequencies of oscillations of the same system when the shell is isotropic.

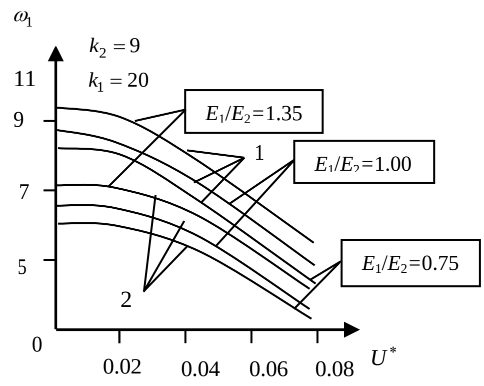

Figure 1. Dependence of the oscillation frequency parameter on the fluid velocity, 1- linear law, 2- parabolic law

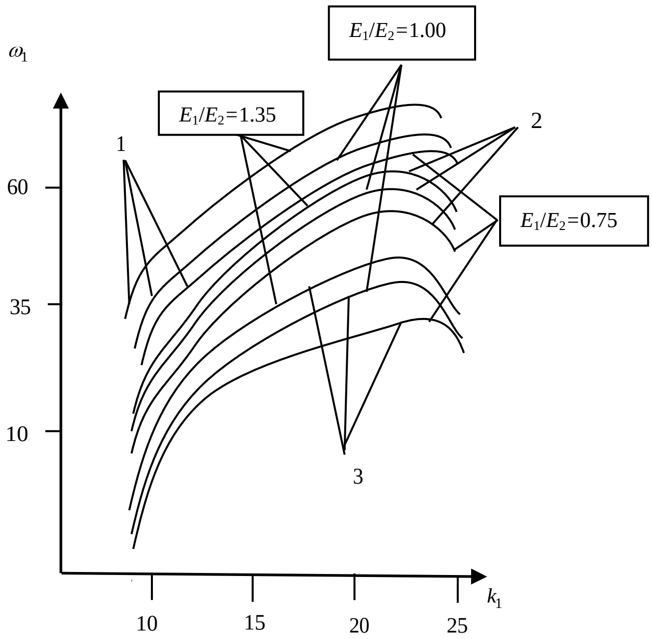

Figure 2. Dependence of the frequency parameter on the number of longitudinal edges, 1- homogeneous shell, 2- linear law, 3- parabolic law

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BIOGRAPHIES

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