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VIBRATIONS OF HETEREGENEOUNS, FLUID-FILLED CYLINDRICAL SHELLS STIFFENED BY LONGITUDINAL RIBS

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Abstract- In this paper, we study one of the dynamical strength characteristics, the frequency of natural vibrations of a fluid-filled cylindrical shell made of a fiberglass and stiffened by longitudinal ribs inhomogeneous in thickness, in circumference and along the generatrix under the Navier boundary conditions. Using the Hamilton-Ostrogradsky variational principle, the frequency equations for calculating natural vibrations of the system under investigation are constructed. In the course of calculations, linear laws for the heterogeneity function were accepted. The constructed frequency equations are realized numerically. The results of calculations of eigen frequencies of vibrations are represented in the form of dependence on the inhomogeneity parameter, on the number of lateral ribs under various values of wave formation parameters. The characteristically dependence curves are constructed.

Keywords: Longitudinally Stiffened Shell, Variational Principle, Fluid, Free Vibrations, Heterogeneity.

1. INTRODUCTION

Polymer, hydro carbon, metal, organic-based composites, porous aluminum are widely used in various branches of technology. The basic constant load acting on a shell is its proper weight. To reduce this load, the use of lightweight porous materials with low bulk density and other useful properties is promising, but they have lower strength characteristics. To compensate for this shortcoming, technological heterogeneity is created, and another material with higher strength characteristics is introduced for creating heterogeneity in load-carrying structures.

As a result of this, technological heterogeneity appears in the structure. Furthermore, to apart more rigidity, the thin-walled part of the shell is stiffened by ribs and this significantly increases its strength with a slight increase in the mass of the structure even if the ribs have a small height. The use of polymeric materials in particular of fiberglass in engineering practice, makes sure to take into account anisotropy of elastic properties when studying low frequency vibrations of shells.

Therefore, there arises a necessity to develop methods for calculating such heterogeneous shells and studying influence of heterogeneity on the frequency of their natural vibrations. We need algorithms for calculation of resonance frequencies reducing to failure of heterogeneous shells.

Note that paper [1] studies free vibrations of an orthotropic, soil-contacting cylindrical shell heterogeneous in thickness and stiffened by annular ribs. To account heterogeneity of the material of the shell in thickness, it is accepted that the Young modulus and density of the material are the functions of normal coordinate. Using the Hamilton-Ostrogradsky variational principle, the frequency equations were constructed and implemented numerically. In the course of calculations, linear and parabolic laws for the heterogeneity function were accepted. The characteristic curves of dependence were structured.

The paper [2] was devoted to the study of free vibrations of a longitudinally stiffened orthotropic, flowing fluid-contacting cylindrical shell heterogeneous in thickness. Using the Hamilton-Ostrogradsky variational principle, and accepting that the Young modulus and the material density are the functions of a normal coordinate, the frequency equations were structured and implemented numerically

In the paper [3], frequencies of free vibrations of a structurally anisotropic, flowing flow-contacting homogeneous cylindrical shell made of a fiberglass and stiffened by annular ribs are found under Navier boundary conditions. The results of calculations of natural frequencies of vibrations are represented in the form of dependences on spinning angle of a fiberglass for a shell made of a textile fiberglass and on the velocity of flowing fluid for various values of wave formations parameters and different ratios between the parameters characterizing geometrical sizes of the shell.

The papers [4, 5, 6] were devoted to the research of parametric vibrations of a linear rod nonlinear and heterogeneous in thickness in a viscous-elastic medium by using the Pasternak contact model. The influence of the main factors, elasticity of the foundation, damageability of the rod and shell material, dependence of the shift factor on the frequency of vibration on the characteristics of longitudinal vibrations of the points of the bar in a viscoelastic medium, was studied. In all the cases under investigation the dependences of the dynamic stability zone of the rod vibration in a viscoelastic medium on the parameters of the construction on the plane a load-frequency were structured.

The paper [7] studies free vibrations of a longitudinally stiffened, orthotropic, moving fluid-contacting cylindrical shell heterogeneous in thickness. Using the Hamilton-Ostrogradsky variational principle, the systems of equations of motion of a longitudinally stiffened, orthotropic, flowing fluid-contacting cylindrical shell heterogeneous in thickness, were structured. Heterogeneity of the shell material in thickness was taken into account accepting that the Young modulus and the shell material's density are the functions of a normal coordinate. Frequency equations were structured and implemented numerically. In the course of calculation, linear and parabolic laws for the heterogeneity function were accepted. The characteristically curves of dependences were structured. If the shell has geometrical and physical nonlinearity, the equations describing its stress-strain state become complex nonlinear partial differential equations and, in the paper, [8] a method of successive approximation was structured for solving them. Derivation of these equations are given in [9, 10]. In [10] a two-step method of successive perturbation of parameters was developed to reduce the error of linearization of the equation and calculation time.

2. PROBLEM STATEMENT

The problem under consideration is solved by means of the Hamilton-Ostrogradsky variational principle. To apply the Hamilton-Ostrogradsky principle we write the total energy of the structure under consideration. The structure studied consists of a cylindrical form heterogeneous shell and stiffening longitudinal ribs the number of which vary. Furthermore, the structure is fluid-contacting (Figure 1(a)).

To account the heterogeneity in thickness of the cylindrical shell, we will procced from a three-dimensional functional. In this case, the functional of total energy of the cylindrical shell is of the form:

$$V=\frac{1}{2}\iint_{-\frac{h}{2}}^{\frac{h}{2}}\left(\sigma_{11}\varepsilon_{11}+\sigma_{22}\varepsilon_{22}+\sigma_{12}\varepsilon_{12}+\right.$$
$$\left.+\rho\left(\frac{\partial u}{\partial t}\right)^2+\left(\frac{\partial \vartheta}{\partial t}\right)^2+\left(\frac{\partial w}{\partial t}\right)^2\right)dxdydx \quad (1)$$

There are various ways to account for heterogeneity of the shell material. One of them is that the Young modulus and the shell material's density are accepted as functions of a normal, lateral and longitudinal coordinate [11]. It is assumed that the Poisson ratio is constant. In this case the stress strain-state is of the form:

$$\sigma_{11}=\frac{E(x,\theta,z)}{1-v^2}\left(\varepsilon_{11}+v\varepsilon_{22}\right)$$
$$\sigma_{22}=\frac{E(x,\theta,z)}{1-v^2}\left(\varepsilon_{22}+v\varepsilon_{11}\right) \quad (2)$$
$$\sigma_{12}=G\left(x,\theta,z\right)\varepsilon_{12}$$

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

Assume that

$$E\left(x,\theta,z\right)=E_0 f_1(z) f_2(x) f_3(\theta)$$
$$\rho(z,x)=\rho_0 f_1(z) f_2(x) f_3(\theta) \quad (4)$$

Taking into account (4) in (2), we get:

$$\sigma_{11}=\frac{E_0}{1-v^2}\left(\varepsilon_{11}+v\varepsilon_{22}\right) f_1(z) f_2(x) f_3(\theta)$$
$$\sigma_{22}=\frac{E_0}{1-v^2}\left(\varepsilon_{22}+v\varepsilon_{11}\right) f_1(z) f_2(x) f_3(\theta) \quad (5)$$
$$\sigma_{12}=G\varepsilon_{12}=\frac{E_0}{2\left(1+v\right)}\varepsilon_{12} f_1(z) f_2(x) f_3(\theta)$$

where, E_0 is an elasticity modulus of shell's homogeneous material, ρ_0 is the density of the shell's homogeneous material. Allowing for (5), the functional of total energy of the cylindrical shell is of the form:

$$V=\frac{RE_0}{2(1-\nu^2)}\int_{-h/2}^{h/2} f_1(z)dz\times$$
$$\times\iint\left\{\varepsilon_{11}^2+2(1-\nu)\varepsilon_{11}\varepsilon_{22}+\varepsilon_{22}^2+\varepsilon_{12}^2\right\}\times$$
$$\times f_2(x) f_3(\theta)dxd\theta+\int_{-\frac{h}{2}}^{\frac{h}{2}} f_1(z)dz\times \quad (6)$$
$$\times\iint\left(\rho_0\left(\frac{\partial u}{\partial t}\right)^2+\left(\frac{\partial \vartheta}{\partial t}\right)^2+\left(\frac{\partial w}{\partial t}\right)^2\right) f_2(x) f_3(\theta)Rdxd\theta$$

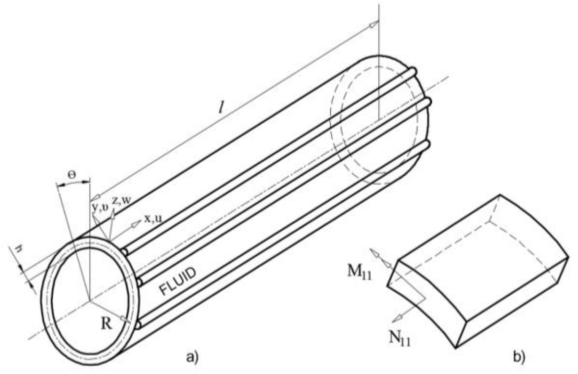

Figure 1. Longitudinally stiffened heterogeneous cylindrical shell

The expression for potential energy of elastic deformation of the *i*th longitudinal bar is as follows:

$$\prod_i = \frac{1}{2}\int_0^l \left[\tilde{E}_i F_i \left(\frac{\partial u_i}{\partial x}\right)^2 + \tilde{E}_i J_{yi}\left(\frac{\partial^2 w_i}{\partial x^2}\right)^2 + \right.$$
$$\left. + \tilde{E}_i J_{zi}\left(\frac{\partial^2 \vartheta_i}{\partial x^2}\right)^2 + \tilde{G}_i J_{kpi}\left(\frac{\partial^2 \varphi_{kpi}}{\partial x}\right)^2 \right] dx \quad (7)$$

The kinetic energy of ribs are written as follows:

$$K_i = \rho_i F_i \int_0^l \left[\left(\frac{\partial u_i}{\partial t}\right)^2 + \left(\frac{\partial \vartheta_i}{\partial t}\right)^2 + \left(\frac{\partial w_i}{\partial t}\right)^2 + \frac{J_{\kappa pi}}{F_i}\left(\frac{\partial \varphi_{\kappa pi}}{\partial t}\right)^2 \right] dx \quad (8)$$

In expressions (7) and (8) u_i, ϑ_i, w_i are displacements of the points of rods used in stiffening, F_i is the area of cross-section of the *i*-rod attached to the shell in the direction of the generatrix, $\tilde{E}_i$ is an elasticity modulus when stretching the *i*th rod attached to the cylindrical shell in the direction of the generatrix, J_{yi} and J_{zi} are the moments of inertia of the *i*th rod with respect to the axis passing from the gravity center of the lateral cross-section, J_{kpi} is the inertia moment when twisting the *i*th rod, t is time, ρ_i is the density of the material of the *i*th longitudinal rod, $\varphi_i(x), \varphi_{\kappa pi}(x)$ are the angles of rotation and torsion of the rod's cross-section and are expressed by the displacement of the shell as follows:

$$\varphi_{kpi}(x) = \varphi_2(x, y_i) = -\left(\frac{\partial w}{\partial y} + \frac{\vartheta}{R}\right)\Bigg|_{y=y_i}$$

$$\varphi_i(x) = \varphi_1(x, y_i) = -\frac{\partial w}{\partial x}\Big|_{y=y_i}$$

The potential energy of external surface loads acting as viewed from fluid and applied to the shell is determined as a work performed by these loads when taking the system from the deformed state to initial under formed state and is represented in the form:

$$A_0 = -R\int_0^l \int_0^{2\pi} q_r w dx d\theta \quad (9)$$

The total energy of the system equals the sum of energy of elastic deformations of the shell and all longitudinal ribs and also potential energies of external loads acting as viewed from fluid:

$$J = V + \sum_{j=1}^{k_2}\left(\Pi_j + K_j\right) + A_0 \quad (10)$$

where, k_2 is the amount of longitudinal ribs.

The surface load q_r, acting as viewed from fluid on a longitudinally stiffened shell is determined from the solution of the equation of motion of ideal fluid [12]:

$$\Delta\varphi - \frac{1}{a_0^2}\frac{\partial^2 \varphi}{\partial t^2} = 0 \quad (11)$$

where, φ is a perturbation potential, and a_0 is velocity of perturbations propagation in fluid.

On the contact surface a shell-fluid we observe continuity of radial velocities and pressures. The condition of impermeability or smooth flow at the shell wall is of the form:

$$\vartheta_r\big|_{r=R} = \frac{\partial \varphi}{\partial r}\Big|_{r=R} = -\omega_0 \frac{\partial w}{\partial t_1} \quad (12)$$

Equality of radial pressures as viewed from fluid on the shell:

$$q_r = -p_{|r=R} \quad (13)$$

By means (11), (12) and (13), we can represent pressure p as viewed from fluid on the shell, in the form

$$p = \omega_0^2 \Phi_{\alpha n} \rho_m \frac{\partial^2 w}{\partial t_1^2} \quad (14)$$

where,

$$\Phi_{\alpha n} = \begin{cases} K_n(\beta r)/K_n'(\beta R), & M_1 < 1 \\ N_n(\beta_1 r)/N_n'(\beta_1 R), & M_1 > 1 \\ \dfrac{R^n}{nr^{n-1}}, & M_1 = 1 \end{cases} \quad (15)$$

In (15)

$$M_1 = \frac{\omega/\mathrm{m}}{a_0}$$

$$\beta^2 = R^{-2}\left(1 - M_1^2\right)\chi^2$$

$$\beta_1^2 = R^{-2}\left(M_1^2 - 1\right)\chi^2$$

$$t = \omega_0 t$$

$$\omega_0 = \sqrt{\frac{b_{11}}{\rho_0 R^2}}$$

$$\omega_1 = \sqrt{\frac{\rho_0 R^2 \omega^2}{b_{11}}} = \frac{\omega}{\omega_0}$$

$$\xi = x/L$$

where, K_n is *n*th order modified Bessel function of second kind, and N_n is *n*th order Bessel or Neumann function of second kind.

It is a considered that the hard contact conditions between the shell and rods are satisfied:

$$u_i(x) = u(x, y_i) + h_i\varphi_1(x, y_i)$$
$$\vartheta_i(x) = \vartheta(x, y_i) + h_i\varphi_2(x, y_i)$$
$$w_i(x) = w(x, y_i)$$
$$\varphi_i(x) = \varphi_1(x, y_i)$$
$$\varphi_{\kappa pi}(x) = \varphi_2(x, y_i)$$
$$h_i = 0.5h + H_i^1$$

where, H_i^1 is the distance from the *i*th rod to the surface of the cylindrical shell, h_i is the thickness of the *i*th longitudinal rod.

It is supposed that on the lines $x = 0$ and $x = l$ the following Navier boundary conditions are fulfilled:

$$\vartheta = 0,\ w = 0$$
$$N_{11} = 0,\ M_{11} = 0 \quad (16)$$

where, l is the length of the shell, and T_{11}, M_{11} are force and moment acting on cross-sections of the cylindrical shell (Figure 1(b)).

The frequency equation of a ridge heterogeneous shell with flowing fluid was obtained on the base of Ostrogradsky-Hamilton principle of stationarity of action:

$$\delta W = 0 \quad (17)$$

where, $W = \int_{t'}^{t''} J dt$ is Hamilton's action, t' and t'' are the given arbitrary times.

Complementing with contact conditions (12) and (13) the total energy of the system (10) and the equation of motion of fluid (11), we arrive at a problem of natural vibrations of a fluid-contacting cylindrical shell heterogeneous in the main coordinate directions and stiffened by longitudinal ribs. In other words, a problem of natural vibrations of a fluid-contacting cylindrical shell heterogeneous in the main coordinate directions is reduced to joint integration of the expression for total energy of the system (10), the equation of motion of fluid (11) subject to conditions (12) and (13) on their contact surface and boundary conditions (16).

3. PROBLEM SOLUTION

In the expression (10) u, ϑ, w are varying quantities. These unknown quantities are approximated as follows:

$$\begin{aligned} u &= u_0 \cos\chi\xi \cos n\theta \sin\omega_1 t_1 \\ \vartheta &= \vartheta_0 \sin\chi\xi \sin n\theta \sin\omega_1 t_1 \\ w &= w_0 \sin\chi\xi \cos n\theta \sin\omega_1 t_1 \end{aligned} \quad (18)$$

where, u_0, ϑ_0, w_0 are unknown constants; χ, n are wave numbers in longitudinal and peripheral directions, respectively, $\xi = x/R$, $\chi = kR = \frac{m\pi R}{l}$, $t_1 = \omega_0 t$ and ω is a desired frequency.

To calculate work (9), by means of (14) we find the contact surface force q_r. When simplifying (10) the following dependences are accepted [13]:

$$f_1(x) = 1 + \alpha\frac{z}{h},\ f_2(x) = 1 + \beta\frac{x}{l},\ f_3(x) = 1 + \gamma\frac{\theta}{2\pi R} \quad (19)$$

where, α, β, γ are constant parameters of heterogeneity in the direction along the normal, along the shell's generatrix and in the peripheral direction, respectively, and $\alpha, \beta, \gamma \in [0,1]$.

Substituting solution (19) in (10) and taking into account expression (18), for the total energy (10) we get a second order polynomial with respect to constants u_0, ϑ_0, w_0:

$$\begin{aligned} J_i &= \varphi_{11}u_0^2 + \varphi_{22}\vartheta_0^2 + \varphi_{33}w_0^2 + \varphi_{44}u_0\vartheta_0 + \\ &+ \varphi_{55}u_0 w_0 + \varphi_{66}\vartheta_0 w_0 \end{aligned}$$

The expressions for the coefficients $\varphi_{11}, \varphi_{22}, \varphi_{33}, \varphi_{44}, \varphi_{55}, \varphi_{66}$ have a bulky form, therefore we do not give them here. If we vary the expression Π with respect to the constants u_0, ϑ_0, w_0 and equate to zero the coefficients of independent variations, we get the following system of homogeneous algebraic equations:

$$\begin{cases} 2\varphi_{11}u_0 + \varphi_{44}\vartheta_0 + \varphi_{55}w_0 = 0 \\ \varphi_{44}u_0 + 2\varphi_{22}\vartheta_0 + \varphi_{66}w_0 = 0 \\ \varphi_{55}u_0 + \varphi_{66}\vartheta_0 + 2\varphi_{33}w_0 = 0 \end{cases} \quad (20)$$

Since the system (20) is a homogeneous system of linear algebraic equations, the necessary and sufficient condition for its non-zero solution is the equality of its principle determinant to zero. As a result, we get the following frequency equation:

$$\begin{vmatrix} 2\varphi_{11} & \varphi_{44} & \varphi_{55} \\ \varphi_{44} & 2\varphi_{22} & \varphi_{66} \\ \varphi_{55} & \varphi_{66} & 2\varphi_{33} \end{vmatrix} = 0 \quad (21)$$

We write equation (21) in the form

$$4\varphi_{11}\varphi_{22}\varphi_{33} + \varphi_{44}\varphi_{55}\varphi_{66} - \varphi_{55}^2\varphi_{22} - \varphi_{66}^2\varphi_{11} - \varphi_{44}^2\varphi_{33} = 0 \quad (22)$$

Equation (22) was calculated by the numerical method.

4. NUMERICAL RESULTS

As equation (22) is contained in the sought-for modified *n*th order second kind Bessel function K_n and the Neumann function, it is a transcendental equation. For finding its roots the value of the left hand side of the equation is calculated for the small steps of ω_1 and an interval is found according to the change of sign.

The found interval is calculated again for smaller steps of ω_1 and again is determined according to the change of sign. This proses is continued until the necessary accuracy is obtained. The roots of the Equation (22) calculated to within 0.001.

The parameters contained in the problem solution were accepted as:

$$\rho_0 = \rho_j = 1850\frac{\text{kg}}{\text{m}^3},\ \tilde{E}_i = 6.67\times 10^9\frac{\text{H}}{\text{m}^2},\ m = 1,\ n = 8$$

$$h_i = 0.45,\ R = 160\ \text{cm}, \rho_m = 1\frac{\text{gr}}{\text{cm}^3}, h_i = 0.45\ \text{mm}$$

$$v = 0.35, \frac{l}{R} = 3, \frac{h}{R} = \frac{1}{6}, \alpha = 0.4, R = 160\ \text{cm}, F_i = 5.2\ \text{mm}^2$$

$$I_{kp.i} = 0.23\ \text{mm}^4, I_{yi} = 5.1\ \text{mm}^4, I_{zi} = 1.3\ \text{mm}^4$$

The results of calculations are given in Figure 2 in the form of dependence of the frequency parameter on the amount of longitudinally stiffening rods k_1 on the shell surface, in Figure 3 in the form of dependence of the frequency parameter on the heterogeneity parameter in the direction of the shell's generatrix β.

As can be seen from Figure 2 with increasing the amount of longitudinal ribs, the value of the frequency parameter at first increases, and then decreases attain maximum. This is explained by the fact that with increasing the amount of longitudinal ribs, at first the rigidity of the structure increases. Further, with increasing the number of longitudinal ribs their inertial properties prevail. As the heterogeneity parameter increases in the direction of the shell generatrix β as can be seen from Figure 3, the value of frequency parameter increases.

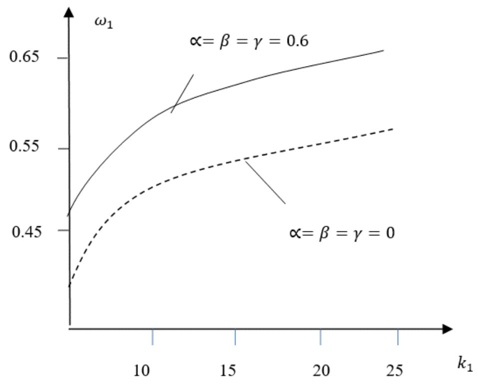

Figure 2. Dependence of frequency operator on k_1

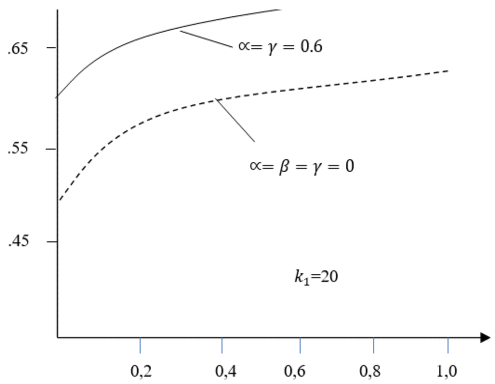

Figure 3. Dependence of frequency operator on β

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BIOGRAPHIES

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Javad Mahdavi Tabatabaei was born in Tabriz, Iran, on July 06, 1981. He received the B.Sc. degree from Mahabad Branch, Islamic Azad University, Iran and the M.Sc. degree from Azerbaijan Architecture and Construction University, Baku, Azerbaijan in Civil Engineering in 2003 and 2009, respectively. He is studying Ph.D. in Civil Engineering at Azerbaijan Architecture and Construction University. Currently, he is Academic Member in Department of Civil Engineering, Faculty of Engineering and Architecture, Istanbul Rumeli University, Istanbul, Turkey. He is also Director of International Relations Office at the same university. He has published 15 papers in international conferences and journals. his scientific interests are construction with suitable energy managing, optimum architecture, energy efficiency and saving in buildings, and sustainable energies based buildings.