



VIBRATIONS OF AN INHOMOGENEOUS CYLINDRICAL SHELL SUPPORTED BY INHOMOGENEOUS LONGITUDINAL FINS WITH LIQUID

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Abstract - Due to the demands of technology, the study of the dynamic behavior of structural elements, taking into account their adequate material properties, is of great importance. Modern mechanical engineering very often sets tasks for calculating thin-walled structures with mutually exclusive properties: on the one hand, the structures under study must combine high strength and reliability, and on the other, cost-effectiveness and lightness. For a successful combination of the above properties, the use of orthotropic materials and plastics in structures is quite justified.

Depending on the mechanical and thermal treatment, the type of technology, and the composition of the material, the structural materials have a property of uniformity and isotropy. On the other hand, such structures come into contact with the environment of various nature. In many cases, there is a need for reinforcement to improve the performance of such thin-walled structures.

1. INTRODUCTION

In [1], free vibrations of a cylindrical coating reinforced by inhomogeneous, isotropic, and inhomogeneous rings in contact with a liquid were studied. The Hamilton-Ostrogradsky variational principle was used to solve the problem. It is generally assumed that the heterogeneity of the rings used in fittings varies exponentially, and the heterogeneity of the cylindrical coating varies linearly in the direction of its thickness. The liquid was received perfectly. The rigid contact between the rods and the cylindrical cover is considered. With the help of contact conditions, a frequency equation is constructed, the roots are found by the numerical method, and characteristic curves are constructed. At work [2] a similar task was performed for an inhomogeneous orthotropic cylindrical coating reinforced with inhomogeneous spindles. In [3], the issues of dance movements of cylindrical and conical coverings were investigated, taking into account the resistance of the external environment (Pasternak), and a comprehensive report was conducted, the results of which are presented in tables and curves of the relationship between the characteristic parameters. And in [4], solutions to issues of practical importance are presented, mainly taking into account the resistance of rectangular and round plates and cylindrical coatings of Fuss-Winkler and viscoelastic base. [5, 6] in their work, a frequency equation was constructed to calculate the frequencies of free oscillation of cylindrical plates of a rectangular profile in contact with a viscoelastic medium, the roots were found, and the influence of physical, mechanical, geometric, and inhomogeneities, viscosity parameters, and geometric hole sizes characterizing the cylindrical plate and the external environment on these frequencies was studied. The analysis shows that the dances of an inhomogeneous cylindrical shell reinforced with inhomogeneous rods dynamically in contact with a moving liquid have not been studied. The presented article considered just such a question - free vibrations of a cylindrical coating reinforced by inhomogeneous, anisotropic, inhomogeneous shafts

and rings in contact with a liquid. The Hamilton-Ostrogradsky variational principle was used to solve the problem. It is generally assumed that the heterogeneity of shafts and rings used in fittings varies exponentially, and the heterogeneity of the cylindrical coating varies linearly in the direction of its thickness. The liquid was received perfectly. The rigid contact between the rods and the cylindrical cover is considered. With the help of contact conditions, a frequency equation is constructed, the roots are found by the numerical method, and characteristic curves are constructed.

Suppose that in contact with an ideal liquid, an inhomogeneous orthotropic cylindrical coating along the visor is reinforced with inhomogeneous shafts and rings (Fig. 1). According to the Hamilton-Ostrogradsky variation principle [7]:

$$\delta \int_{t_0}^{t_1} (K - W - A_m) dt = 0. \quad (1)$$

$$K = V_k + \sum_{i=1}^{k_1} K_i; W = V_p + \sum_{i=1}^{k_1} \Pi_i. \quad (2)$$

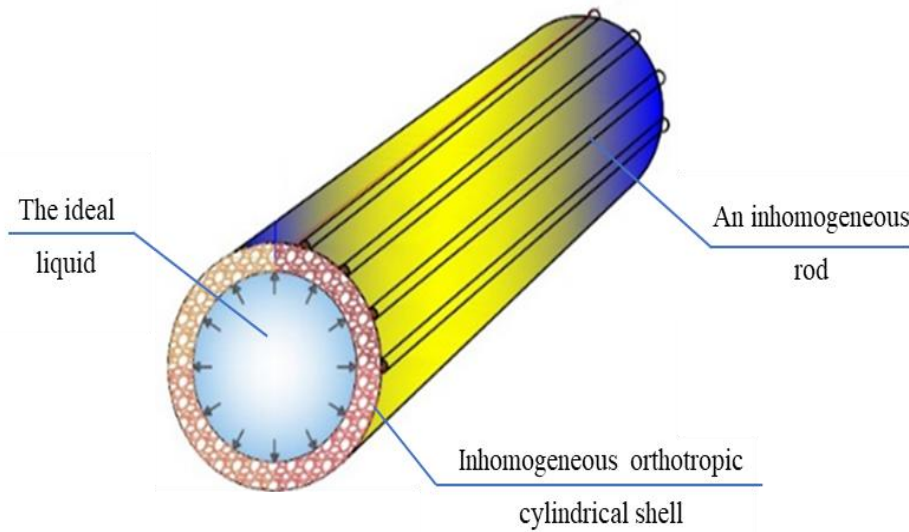


Figure 1. An inhomogeneous orthotropic cylindrical coating reinforced with inhomogeneous shafts and rings in contact with a liquid.

Where V_p, V_k – are, respectively, the potential and kinetic energies of the cylindrical coating, Π_i, K_i – of the i th shaft, and A_m – are the work of the forces acting on the cylindrical coating with a liquid in the displacements of the coating points. To take into account the heterogeneity of the cylindrical coating of the shafts, we consider that in the direction in which the coating generates the elastic modulus and density of the shafts, it is a function of the coordinate. Thus, the expressions of their energy will look like this:

$$V_p = \frac{Rh}{2} \iint (\sigma_{11}\varepsilon_{11} + \sigma_{12}\varepsilon_{12} + \sigma_{22}\varepsilon_{22}) ds, \quad (3)$$

$$\sigma_{11} = b_{11}(x)\varepsilon_{11} + b_{12}(x)\varepsilon_{22}, \quad \sigma_{22} = b_{12}(x)\varepsilon_{11} + b_{22}(x)\varepsilon_{22}, \quad \sigma_{12} = b_{66}(x)\varepsilon_{12},$$

$$\varepsilon_{11} = \frac{\partial \varphi}{\partial x}; \varepsilon_{22} = \frac{\partial v}{\partial y}; \varepsilon_{12} = \frac{\partial U}{\partial y} + \frac{\partial v}{\partial x},$$

$$\tilde{b}_{11} = \int_0^l b_{11}(x) dx; \tilde{b}_{12} = \int_0^l b_{12}(x) dx; \tilde{b}_{22} = \int_0^l b_{22}(x) dx; \tilde{b}_{66} = \int_0^l b_{66}(x) dx;$$

$$\begin{aligned}
 b_{11}(x) &= \frac{E_1(x)}{1-\nu_1\nu_2}; b_{22}(x) = \frac{E_2(x)}{1-\nu_1\nu_2}; b_{66}(x) = G_{12}(x) = G(x); \\
 b_{12}(x) &= \frac{\nu_2 E_1(x)}{1-\nu_1\nu_2} = \frac{\nu_1 E_2(x)}{1-\nu_1\nu_2}, \\
 V_k &= \int_0^{2\pi} \int_0^l \rho(x) \left(\left(\frac{\partial u}{\partial t} \right)^2 + \left(\frac{\partial \mathcal{G}}{\partial t} \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right) dx d\varphi \\
 \Pi_i &= \frac{1}{2} \int_0^l \left[\tilde{E}_i(x) F_i \left(\frac{\partial u_i}{\partial x} \right)^2 + \tilde{E}_i(x) J_{xi} \left(\frac{\partial^2 \mathcal{G}_i}{\partial x^2} \right)^2 + \tilde{E}_i(x) J_{zi} \left(\frac{\partial^2 w_i}{\partial x^2} \right)^2 + \right. \\
 &\quad \left. + G_i(x) J_{kpi} \left(\frac{\partial \varphi_{kpi}}{\partial x} \right)^2 \right] dx \\
 &\quad (4)
 \end{aligned}$$

$$\begin{aligned}
 K_i &= \int_0^l \tilde{\rho}_i(x) F_i \left[\left(\frac{\partial u_i}{\partial t} \right)^2 + \left(\frac{\partial \mathcal{G}_i}{\partial t} \right)^2 + \left(\frac{\partial w_i}{\partial t} \right)^2 + \frac{J_{kpi}}{F_i} \left(\frac{\partial \varphi_{kpi}}{\partial t} \right)^2 \right] dx \\
 A_m &= - \int_0^{2\pi} \int_0^l q_z w dx d\varphi. \quad (6)
 \end{aligned}$$

In expressions (3) - (6) u , \mathcal{G} , w - are the displacements of the points of the cylindrical plate, $\tilde{E}_i(x)$ - is the modulus of elasticity of shaft i , $\tilde{\rho}_i(x)$ - i is the density of the shaft material, F_i - i shaft cross-sectional area, I_{xi}, I_{kpi} - kpi-moments of inertia of the shaft cross-section - i , $G_i(x)$ - is the elastic modulus of shaft sliding - i , u_i, \mathcal{G}_i, w_i - offsets of shaft points i , k_1 is the number of shafts, q_z - is the pressure force exerted by the liquid on the cylindrical shell.

A cylindrical cover mounted on spindles is understood to mean a system consisting of a cylindrical cover and a spindle rigidly attached to it along coordinate lines. It is assumed that the coordinate axes coincide with the lines of curvature of the cylindrical coating head, along these lines the shaft is in rigid contact with the coating. Thus, the following conditions are met between the cylindrical coating and the spindles [7]:

$$\begin{aligned}
 u_i(x) &= u(x, y_i); \quad \mathcal{G}_i(x) = \mathcal{G}(x, y_i); \quad w_i(x) = w(x, y_i), \\
 \varphi_i(x) &= \varphi_1(x, y_i); \quad \varphi_1(x, y_i) = - \frac{\partial w}{\partial x} \Big|_{y=y_i}. \quad (7)
 \end{aligned}$$

The pressure p created in the liquid is expressed in the following expression [8]:

$$p = \Phi_{an} \rho_m \left(\omega_0^2 \frac{\partial^2 w}{\partial t_1^2} + 2U \omega_0 \frac{\partial^2 w}{R \partial \xi \partial t_1} + U^2 \frac{\partial^2 w}{R^2 \partial \xi^2} \right). \quad (8)$$

Here

$$\Phi_{mk} = \begin{cases} I_k(\beta r) / I_k(\beta R), & M_1 < 1 \\ J_k(\beta_1 r) / J_k(\beta_1 R), & M_1 > 1. \\ \frac{r^k}{kR^{k-1}}, & M_1 = 1 \end{cases}$$

$$M_1 = \frac{U + R\omega / m}{a_0}, \beta^2 = R^{-2}(1 - M_1^2)m^2, \beta_1^2 = R^{-2}(M_1^2 - 1)m^2,$$

I_k - k - th compilation is a modified Bessel function of the first kind, J_k - k - is the Bessel function of the first kind of the k th order, a_0 - is the velocity of sound propagation in a liquid, U is the velocity of the fluid, $\xi = \frac{x}{l}$, m is the number of waves in the direction of the x -axis.

The following contract conditions are satisfied between the liquid and the cylindrical shell [8]:

$$\mathcal{G}_r|_{r=R} = -\left(\omega \frac{\partial w}{\partial t} + U \frac{\partial w}{\partial x}\right). \quad (9)$$

$$q_z = -P|_{r=R}. \quad (10)$$

We will assume that at the edges of the cylindrical lid, the Navy conditions satisfy [9]:

$$\mathcal{G} = w = M_{11} = N_{11} = 0, \text{ by } (x = 0, x = l). \quad (11)$$

Thus, dancing a cylindrical coating reinforced with inhomogeneous rings in dynamic contact with a liquid is a solution to the problem of the total energy of a structure consisting of a cylindrical coating reinforced with discretely distributed inhomogeneous rings, in the inner region of which liquid flows. (7), (9), (10) contact and (11) are brought to a joint integration under boundary conditions.

Let's look at the shell offsets as follows:

$$\begin{aligned} u &= u_0 \cos \frac{\pi mx}{l} \sin k\varphi \sin \omega t, \\ \mathcal{G} &= \mathcal{G}_0 \sin \frac{\pi mx}{l} \cos k\varphi \sin \omega t, \\ w &= w_0 \sin \frac{\pi mx}{l} \sin k\varphi \sin \omega t. \end{aligned} \quad (12)$$

Where, u_0, \mathcal{G}_0, w_0 are unknown constants, m, k these are the wave numbers of the cylindrical shell in the longitudinal and circular directions.

If we use solutions (12), formulas (3) and (4), and contact conditions (7), we obtain:

$$\begin{aligned} \Pi_i &= \frac{m^2 \pi^2}{2l^2} [F_i I_1 \sin^2 k\varphi_i u_0^2 + (J_{xi} I_2 + J_{kpi} I_3) \cos^2 k\varphi_i \mathcal{G}_0^2 + \\ &+ (J_{zi} I_2 + J_{kpi} I_3) \sin^2 k\varphi_i w_0^2 + k J_{kpi} I_3 \sin 2k\varphi_i \mathcal{G}_0 w_0] \sin^2 \omega t, \end{aligned}$$

$$K_i = \omega^2 F_i [I_{10} \sin^2 k\varphi_i u_0^2 + I_{11} \left(1 + \frac{J_{kpi}}{F_i R^2}\right) \cos^2 k\varphi_i \mathcal{G}_0^2 +$$

$$+I_{11} \left[\left(1 + \frac{J_{kpi} k^2}{F_i R^2} \right) \sin^2 k \varphi_i w_0^2 + I_{11} \frac{J_{kpi}}{F_i R^2} \sin 2k \varphi_i \vartheta_0 w_0 \right] \sin^2 \omega t, \quad (13)$$

$$V_p = \frac{\pi R h}{2} \left[\left(\frac{\pi^2 m^2}{e^2} I_4 + \frac{k^2}{R^2} I_5 \right) u_0^2 + \left(\frac{k^2}{R^2} I_6 + \frac{\pi^2 m^2}{e^2} I_5 \right) v_0^2 + I_5 w_0^2 + \right. \\ \left. + \left(\frac{2\pi k m}{l R} I_7 + \frac{2\pi k m}{l R} I_5 \right) u_0 v_0 - \frac{2\pi m}{l} I_7 u_0 w_0 - \frac{2k}{R} I_6 v_0 w_0 \right] \sin^2 \omega t.$$

$$V_k = \omega^2 \pi \left(I_8 u_0^2 + I_9 v_0^2 + I_8 w_0^2 \right) \sin^2 \omega t.$$

$$A = -\frac{\pi l}{2R} \rho_m \Phi_{mn} \left(-\omega^2 + 2Um\omega - U^2 m^2 \right) w_0^2$$

in expressions (13)

$$I_1 = \int_0^l E_i(x) \cos^2 \frac{m\pi x}{l} dx; I_2 = \int_0^l E_i(x) \sin^2 \frac{m\pi x}{l} dx; I_3 = \int_0^l G_i(x) \sin^2 \frac{m\pi x}{l} dx;$$

$$I_{10} = \int_0^l \tilde{\rho}(x) \cos^2 \frac{\pi x}{l} dx; I_{11} = \int_0^l \tilde{\rho}(x) \sin^2 \frac{\pi x}{l} dx;$$

$$I_{10} = \int_0^l \tilde{\rho}(x) \cos^2 \frac{\pi x}{l} dx; I_{11} = \int_0^l \tilde{\rho}(x) \sin^2 \frac{\pi x}{l} dx;$$

$$I_4 = \int_0^l b_{11}(x) \sin^2 \frac{\pi x}{l} dx; I_5 = \int_0^l b_{66}(x) \cos^2 \frac{\pi x}{l} dx; I_6 = \int_0^l b_{22}(x) \sin^2 \frac{\pi x}{l} dx;$$

$$I_7 = \int_0^l b_{12} \sin^2 \frac{\pi x}{l} dx; I_8 = \int_0^l \rho(x) \cos^2 \frac{\pi x}{l} dx; I_9 = \int_0^l \rho(x) \sin^2 \frac{\pi x}{l} dx.$$

Using expressions (13), we obtain:

$$K - W - A = \left\{ \left[\omega^2 \left(\pi I_8 + \sum_{i=1}^{k_1} F_i I_{10} \sin^2 k \varphi_i \right) - \right. \right. \\ \left. \left[-\left[\frac{\pi R h}{2} \left(\frac{\pi^2 m^2}{e^2} I_4 + \frac{k^2}{R^2} I_5 \right) + \frac{m^2 \pi^2}{2l^2} \sum_{i=1}^{k_1} F_i I_{11} \sin^2 k \varphi_i \right] \right] u_0^2 + \left\{ \omega^2 \left(\pi I_9 + \right. \right. \right. \\ \left. \left. \left. + \sum_{i=1}^{k_1} F_i I_{11} \left(1 + \frac{J_{kpi}}{F_i R^2} \right) \cos^2 k \varphi_i \right) - \frac{\pi R h}{2} \left(\frac{k^2}{R^2} I_6 + \frac{\pi^2 m^2}{e^2} I_5 \right) - \right. \right. \\ \left. \left. \left. + \frac{m^2 \pi^2}{2l^2} \sum_{i=1}^{k_1} \left(J_{xi} I_2 + J_{kpi} I_3 \right) \cos^2 k \varphi_i \right\} v_0^2 + \left\{ \omega^2 \left(\pi I_8 + \right. \right. \right.$$

$$\begin{aligned}
 & + \sum_{i=1}^{k_1} F_i I_{11} \left(1 + \frac{J_{kpi} k^2}{F_i R^2} \right) \sin^2 k \varphi_i \Big) - \left[\frac{\pi R h}{2} I_5 + \right. \\
 & \left. + \frac{m^2 \pi^2}{2l^2} \sum_{i=1}^{k_1} (J_{zi} I_2 + J_{kpi} I_3) \sin^2 k \varphi_i \right] - \\
 & - \frac{\pi l}{2R} \rho_m \Phi_{mn} \left(-\omega^2 + 2Um\omega - U^2 m^2 \right) \Big\} w_0^2 - \\
 & - \frac{\pi R h}{2} \left(\frac{2\pi k m}{lR} I_7 + \frac{2\pi k m}{lR} I_5 \right) u_0 v_0 + \left[\frac{\pi^2 m R h}{l} I_7 \right] u_0 w_0 + \\
 & + \left\{ \sum_{i=1}^{k_1} F_i I_{11} \frac{J_{kpi}}{F_i R^2} \sin 2k \varphi_i - \right. \\
 & \left. - \left[-\pi k h I_6 + \frac{m^2 \pi^2}{2l^2} k J_{kpi} I_3 \sin 2k \varphi_i \right] \vartheta_0 w_0 \right\} \sin^2 \omega t.
 \end{aligned}$$

If we apply the Hamilton-Ostrogradsky variation principle, then, looking at the constants u_0, ϑ_0, w_0 , we get the following system of equations:

$$\begin{aligned}
 & 2 \left\{ \omega^2 \left(\pi I_8 + \sum_{i=1}^{k_1} F_i I_{10} \sin^2 k \varphi_i \right) - \left[\frac{\pi R h}{2} \left(\frac{\pi^2 m^2}{e^2} I_4 + \frac{k^2}{R^2} I_5 \right) \right] + \right. \\
 & \left. + \frac{m^2 \pi^2}{2l^2} \sum_{i=1}^{k_1} F_i I_{11} \sin^2 k \varphi_i \right\} u_0 - \frac{\pi R h}{2} \left(\frac{2\pi k m}{lR} I_7 + \frac{2\pi k m}{lR} I_5 \right) v_0 + \left[\frac{\pi^2 m R h}{l} I_7 \right] w_0 = 0
 \end{aligned} \tag{14}$$

$$\begin{aligned}
 & - \frac{\pi R h}{2} \left(\frac{2\pi k m}{lR} I_7 + \frac{2\pi k m}{lR} I_5 \right) u_0 + 2 \left\{ \omega^2 \left(\pi I_9 + \right. \right. \\
 & \left. \left. + \sum_{i=1}^{k_1} F_i I_{11} \left(1 + \frac{J_{kpi}}{F_i R^2} \right) \cos^2 k \varphi_i \right) - \frac{\pi R h}{2} \left(\frac{k^2}{R^2} I_6 + \frac{\pi^2 m^2}{e^2} I_5 \right) + \right. \\
 & \left. + \frac{m^2 \pi^2}{2l^2} \sum_{i=1}^{k_1} (J_{xi} I_2 + J_{kpi} I_3) \cos^2 k \varphi_i \right\} v_0 + \left\{ \sum_{i=1}^{k_1} F_i I_{11} \frac{J_{kpi}}{F_i R^2} \sin 2k \varphi_i - \right. \\
 & \left. - \left[-\pi k h I_6 + \frac{m^2 \pi^2}{2l^2} k J_{kpi} I_3 \sin 2k \varphi_i \right] w_0 \right\} = 0 \\
 & \left[\frac{\pi^2 m R h}{l} I_7 \right] u_0 + \left\{ \sum_{i=1}^{k_1} F_i I_{11} \frac{J_{kpi}}{F_i R^2} \sin 2k \varphi_i - \left[-\pi k h I_6 + \frac{m^2 \pi^2}{2l^2} k J_{kpi} I_3 \sin 2k \varphi_i \right] \right\} \vartheta_0 -
 \end{aligned}$$

$$\begin{aligned}
 & -2\left\{\omega^2(\pi I_8 + \sum_{i=1}^{k_1} F_i I_{11} \left(1 + \frac{J_{kpi} k^2}{F_i R^2}\right) \sin^2 k\varphi_i)\right\} - \\
 & - \left[\frac{\pi R h}{2} I_5 + \frac{m^2 \pi^2}{2l^2} \sum_{i=1}^{k_1} (J_{zi} I_2 + J_{kpi} I_3) \sin^2 k\varphi_i\right] - \\
 & - \sum_{j=1}^{k_2} \left(\frac{J_1 F_j}{R^2} + J_1 J_{xj} \left(\frac{1}{R^2} - \frac{m^2 \pi^2}{l^2}\right)\right) \sin^2 \frac{m\pi x_j}{l} + \\
 & + \frac{\pi l}{2R} \rho_m \Phi_{mn} \left(-\omega^2 + 2Um\omega - U^2 m^2\right) \Big\} w_0 = 0.
 \end{aligned}$$

Since the resulting system (14) is a system of linear homogeneous algebraic equations, the presence of its nontrivial solution is a necessary and sufficient condition for its main determinant to be zero. As a result, we obtain the following frequency equation:

$$\det \begin{bmatrix} a_{pq} \end{bmatrix} = 0, \quad p, q = 1, 2, 3, \tag{15}$$

The constants a_{pq} are the coefficients of the unknown constants u_0, ϑ_0, w_0 in the system (14). Equation (14) is a transcendental equation in terms of the desired frequency ω . Its roots are calculated numerically. It is accepted that,

$$\rho(x) = \rho_0 \left(1 + \alpha \frac{x}{l}\right), E_1(x) = E_{10} \left(1 + \beta \frac{x}{l}\right),$$

$$E_2(x) = E_{20} \left(1 + \gamma \frac{x}{l}\right), \tilde{E}_i(x) = \tilde{E}_{i0} \left(1 + \delta e^{\frac{x}{l}}\right), \tilde{\rho}_i(x) = \tilde{\rho}_{i0} \left(1 + \varepsilon e^{\frac{x}{l}}\right),$$

$$G(x) = G_0 \left(1 + \beta \frac{x}{l}\right), G_i(x) = G_{i0} \left(1 + \delta e^{\frac{x}{l}}\right), \omega_0 = \sqrt{\frac{E_{10}}{(1-\nu^2)\rho_0 R^2}}, \quad \omega_1 = \omega/\omega_0,$$

Where $\alpha, \beta, \gamma, \delta, \varepsilon, \sigma, \mu, \tau$ are the inhomogeneity parameters. The following values were taken for the parameters characterizing the liquid, shell, and rod during the calculation:

$$E_{10} = 18,3QPa, E_{20} = 2,77QPa, G_0 = 3,5QPa, R = 160mm, L = 800mm,$$

$$\rho_m / \rho_0 = 0,15, \tilde{E}_{i0} = 6,67QPa; a_0 = 1800 \frac{m}{san}; h = 0,45sm,$$

$$I_{zi} = 1,3mm^4, h_i = h_j = 1,39sm; F_i = 5,2mm^2; I_{kpi} = 0,23mm^4, I_{xi} = 5,1mm^4,$$

$$\nu_1 = \nu_2 = 0,35, U / a_0 = 0,005.$$

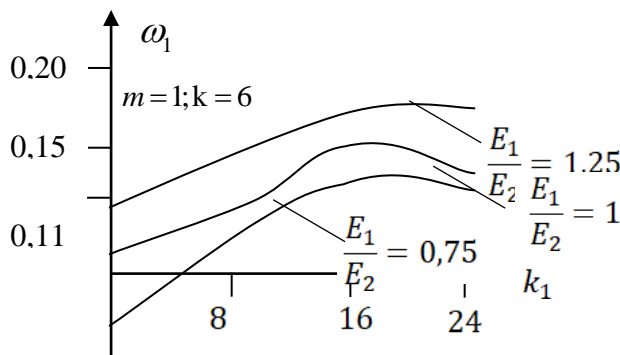


Figure 2. Dependence of the frequency parameter on the number of rods.

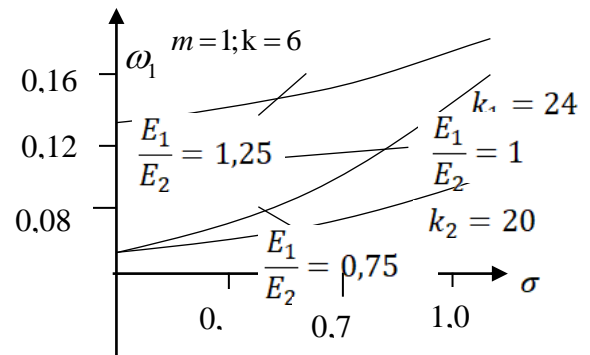


Figure 3. Dependence of the frequency parameter on the inhomogeneity parameter.

CONCLUSIONS

The results of calculating the frequency parameter of the system based on the number of rods are shown in Figure 2; Figure 3 shows the dependence of the frequency parameter of the system on the inhomogeneity parameter for a cylindrical shell made of orthotropic material with different properties. During the calculation, the heterogeneity parameters were taken as $\alpha = \beta = \gamma = 0,5$; $\varepsilon = \delta = \sigma = \mu = \tau = 0,3$. Figure 2 shows that as the number of rods increases, the oscillation frequency of the system first increases, and after a certain value begins to decrease. This is because as the number of rods increases, their mass increases and their inertial influence on the dance process increases. As can be seen from Figure 3, as the value of the inhomogeneity parameter increases, the natural oscillation frequencies of the system increase.

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