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TRANSVERSE VIBRATIONS OF A CIRCULAR PLATE TAKING INTO ACCOUNT THE IMPERFECT ELASTICITY OF THE MATERIAL

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Abstract. The paper is devoted to the problem of random transverse vibrations of a circular plate taking into account the imperfect elasticity of the material. The dissipative characteristics of the hysteresis-type plate material are taken into account using the method of statistical linearization by a linear complex function. To study and analyze the dynamics and stability of the plate for different types of spectral density of random processes, expressions for the mean square values of the variable function and the absolute acceleration of the plate are determined.

Keywords: elastic, circular plate, imperfect elasticity, mean square value, random vibration.

Materialning nomukammal elastikligi hisobga olingan doiraviy plastinkaning tasodifiy ko‘ndalang tebranishlari

Annotatsiya. Ishda materialining nomukammal elastikligi hisobga olingan doiraviy plastinkaning tasodifiy ko‘ndalang tebranishlari haqidagi masala qaralgan. Plastinka materialining gisterezis tipidagi dissipativlik xarakteristikalari statistik chiziqlilashtirish usuli yordamida chiziqli kompleks funksiya orqali hisobga olingan. Tasodifiy jarayonlar spektral zichligining turli ko‘rinishlarida plastinkaning dinamikasi va ustuvorligini tekshirish uchun plastinka o‘zgaruvchi funksiyasi va absolyut tezlanishining o‘rta kvadratik qiymatlarini ifodalari aniqlangan.

Kalit so‘zlar: elastik, doiraviy plastinka, nomukammal elastiklik, o‘rta kvadratik qiymat, tasodifiy tebranish.

Поперечные колебания круглой пластины с учетом несовершенной упругости материала

Аннотация. В работе рассмотрена задача о случайных поперечных колебаниях круглой пластины с учетом несовершенной упругости материала. Диссипативные характеристики материала пластины гистерезисного типа учитываются с помощью метода статистической линеаризации линейной комплексной функцией. Для исследования и анализа динамики и устойчивости пластины при различных видах спектральной плотности случайных процессов определены выражения средних квадратических значений переменной функции и абсолютного ускорения пластины.

Ключевые слова: упругий, круглая пластина, несовершенная упругость, случайное колебание, среднее квадратическое значение.

Introduction. The level of development of technology and engineering has allowed to significantly expand the operational characteristics of moving systems. At the same time, the problem of increasing the accuracy of devices and structural elements cannot be solved unless their vibration resistance and vibration strength under various impact processes are increased. Therefore, it becomes

necessary to take into account the imperfect elasticity of materials when performing dynamic calculations of structural elements. This leads to a refinement of the values of the studied parameters of mechanical systems (for example, rods, plates, shells).

When considering the problem of vibrations of mechanical systems taking into account the dissipation of energy in the material of the elastic element, it is assumed that in the oscillatory system there are hysteresis losses caused by elastic imperfections of the cyclically deformed material of this system [1-3].

In works [5-11] the dynamics of round plates are investigated and analyzed for different problem formulations taking into account the elastic and dissipative properties of materials. The dynamic characteristics and natural frequencies of plates with different types of fastening at the edges are determined.

In this paper, we consider the problem of random transverse vibrations of a circular plate, taking into account the imperfect elasticity of the material.

Statement of the problem. Solution method. Let us consider nonlinear transverse vibrations of a circular plate with imperfect elasticity of the material under random impacts. To analyze nonlinear vibrations of the plate, we will use the complex form of the method of statistical linearization of nonlinearity. According to this form of the statistical linearization method, the nonlinear function characterizing the hysteresis energy dissipation in the plate material is replaced by a linear expression [4]

$$\varepsilon V(\xi) = (-\bar{\eta}_1 + j\bar{\eta}_2)\xi\,, \tag{1}$$

where ε - is a small parameter; $\bar{\eta}_1$, $\bar{\eta}_2 = \bar{\eta}_{20} sign\omega$ - are statistical linearization coefficients; ξ - is relative deformation; ω - is frequency.

The statistical linearization coefficients can be represented as

$$\begin{aligned} &\bar{\eta}_{1r} = \eta_1 f_r(z);\ \bar{\eta}_{2r} = \eta_2 f_r(z);\ \bar{\eta}_{1\theta} = \eta_1 f_\theta(z);\\ &\bar{\eta}_{2\theta} = \eta_2 f_\theta(z);\ \bar{\nu}_{1r\theta} = \nu_1 g_\theta(z);\ \bar{\nu}_{2r\theta} = \nu_2 g_\theta(z), \end{aligned} \tag{2}$$

where

η_1, η_2, ν_1, ν_2 - constant coefficients depending on the dissipative properties of the plate material, determined from the corresponding dependence of the hysteresis loop contour; $f_r(z)$, $f_\theta(z)$ - decrements of vibrations as a function of maximum (amplitude) values of relative deformation; $g(z)$ - the decrement of vibrations, depending on the amplitude of the relative shear deformation z;

$$f_r(z) = \sum_{i_1=0}^{k_1} C_{i_1} |V_1|_{\sigma_\xi}^{i_1} |z|^{i_1}; \qquad f_\theta(z) = \sum_{i_1=0}^{k_1} C_{i_1} |V_2|_{\sigma_\xi}^{i_1} |z|^{i_1}; \qquad g(z) = \sum_{i_2=0}^{k_2} K_{i_2} |V_3|_{\sigma_\xi}^{i_2} |z|^{i_2},$$

here

C_{i_1} $(i_1 = 0,...,k_1)$, K_{i_2} $(i_2 = 0,...,k_2)$ - some numbers (parameters) determined by $\alpha_1 = f_r(z)$, $\alpha_2 = f_\theta(z)$, $\alpha_3 = g(z)$ points selected on the experimental curves with coordinates α_{1i}, α_{2i}, α_{3i} and z_i, obtained with a simple form of cyclic deformation of the material [1];

$$V_1 = \frac{\partial^2 w}{\partial r^2} + \mu\left(\frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{r^2}\frac{\partial^2 w}{\partial \theta^2}\right); \quad V_2 = \frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{r^2}\frac{\partial^2 w}{\partial \theta^2} + \mu\frac{\partial^2 w}{\partial r^2}; \quad V_3 = \frac{1}{r}\frac{\partial^2 w}{\partial r \partial \theta} - \frac{1}{r^2}\frac{\partial w}{\partial \theta};$$

σ_ξ - root mean square value of relative deformation of the plate; w - deflection function in the direction perpendicular to the midplane of the plate; μ - Poisson's ratio; r, θ - polar coordinates.

Let us assume that axis x coincides with radius r, i.e. we take an angle of $\theta = 0$ between the abscissa axis and the polar axis. Then the bending moments M_r, M_θ and the twisting moment $M_{r\theta}$, acting in the cross section of the circular plate will have the form:

$$M_r = -DV_1[1+3(-\eta_1 + j\eta_2)\sum_{i_1=0}^{k_1} C_{i_1}\left|V_1\right|_{\sigma_\xi}^{i_1}\frac{h^{i_1}}{2^{i_1}(i_1+3)}]; \tag{3}$$

$$M_\theta = -DV_2[1+3(-\eta_1 + j\eta_2)\sum_{i_1=0}^{k_1} C_{i_1}\left|V_2\right|_{\sigma_\xi}^{i_1}\frac{h^{i_1}}{2^{i_1}(i_1+3)}]; \tag{4}$$

$$M_{r\theta} = -DV_3(1-\mu)[1+3(-\nu_1 + j\nu_2)\sum_{i_2=0}^{k_2} K_{i_2}\left|V_3\right|_{\sigma_\xi}^{i_2}\frac{h^{i_2}}{2^{i_2}(i_2+3)}], \tag{5}$$

where

$D = \frac{Eh^3}{12(1-\mu^2)}$ -; E - Young's modulus; h - thickness of a the plate.

Substituting expressions (3) – (5) into the known equation of a circular plate, we obtain a differential equation of random nonlinear transverse vibrations of a circular plate with imperfect elasticity of the material

$$\begin{aligned} &D(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2})^2 w+3(-\eta_1+j\eta_2)\sum_{i_1=0}^{k_1} C_{i_1}\frac{h^{i_1}}{2^{i_1}(i_1+3)}[\frac{\partial^2}{\partial r^2}(V_1\left|V_1\right|_{\sigma_\xi}^{i_1})+\\ &+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}(V_2\left|V_2\right|_{\sigma_\xi}^{i_1})+6D(1-\eta)(-\nu_1+j\nu_2)\sum_{i_2=0}^{k_2} K_{i_2}\frac{h^{i_2}}{2^{i_2}(i_2+3)}\cdot\\ &\cdot(\frac{1}{r}\frac{\partial^2}{\partial r\partial\theta}-\frac{1}{r^2}\frac{\partial}{\partial\theta})(V_3\left|V_3\right|_{\sigma_\xi}^{i_2})+\rho h\frac{\partial^2 w}{\partial t^2}=-\rho h\frac{\partial^2 w_0}{\partial t^2}, \end{aligned} \tag{6}$$

where w_0 - is the displacement of the base.

We will seek the solution to equation (6) in the form:

$$w(r,\theta,t) = P(r)Q(\theta)T(t) \tag{7}$$

where $P(r)$ and $Q(\theta)$ - are some functions that depend respectively only on the radius r and the angle

θ; $T(t)$ - is a function of time.

Substituting expression (7) into differential equation (6), we obtain

$$\begin{aligned} &D(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2})^2 PQT+3(-\eta_1+j\eta_2)\sum_{i_1=0}^{k_1} C_{i_1}\frac{h^{i_1}}{2^{i_1}(i_1+3)}T\left|V_1\right|^{i_1}\cdot\\ &\cdot[\frac{\partial^2}{\partial r^2}(\alpha_1\left|\alpha_1\right|^{i_1})+(\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2})(\alpha_2\left|\alpha_2\right|^{i_1})]+6D(1-\eta)(-\nu_1+j\nu_2)\sum_{i_2=0}^{k_2} K_{i_2}\frac{h^{i_2}}{2^{i_2}(i_2+3)}T\left|V_2\right|^{i_2}\cdot\\ &\cdot[(\frac{1}{r}\frac{\partial^2}{\partial r\partial\theta}-\frac{1}{r^2}\frac{\partial}{\partial\theta})(\alpha_3\left|\alpha_3\right|^{i_2})]+\rho hPQ\ddot{T}=-\rho hW_0, \end{aligned} \tag{8}$$

where

$$P = P(r); \quad Q = Q(\theta); \quad T = T(t); \qquad \alpha_1 = Q\frac{\partial^2 P}{\partial r^2} + \mu(\frac{1}{r}Q\frac{\partial P}{\partial r} + \frac{1}{r^2}P\frac{\partial^2 Q}{\partial \theta^2});$$

$$\alpha_2 = \frac{1}{r}Q\frac{\partial P}{\partial r} + \frac{1}{r^2}P\frac{\partial^2 Q}{\partial \theta^2} + \mu Q\frac{\partial^2 P}{\partial r^2}; \quad \alpha_3 = \frac{1}{r}\frac{\partial P}{\partial r}\frac{\partial Q}{\partial \theta} - \frac{1}{r^2}P\frac{\partial Q}{\partial \theta}; \quad W_0 \text{ - acceleration}$$

of the base.

By using the Bubnov-Galerkin method to solve equation (8), we obtain the following differential equation, which allows us to find the variable:

$$\ddot{T} + [1 + (-\eta_1 + j\eta_2)R_1 + (-\nu_1 + j\nu_2)R_2]\omega_{01}^2 T = -d_* W_0, \tag{9}$$

where

$$R_1 = \frac{3D}{\omega_{01}^2 \rho h d_1}\sum_{i_1=0}^{k_1} C_{i_1}\frac{h^{i_1}}{2^{i_1}(i_1+3)}\left|V_T^{i_1}\right| G_{i_1};$$

$$G_{i_1} = \iint_s PQ[\frac{\partial^2}{\partial r^2}(\alpha_1|\alpha_1|^{i_1}) + (\frac{1}{r}\frac{\partial w}{\partial r} + (\frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2})(\alpha_2|\alpha_2|^{i_1}))]ds;$$

$$R_2 = \frac{6D(1-\mu)}{\omega_{01}^2 \rho h d_1}\sum_{i_2=0}^{k_2} K_{i_2}\frac{h^{i_2}}{2^{i_2}(i_2+3)}|V_2|^{i_2} H_{i_2};$$

$$H_{i_2} = \iint_s PQ(\frac{1}{r}\frac{\partial^2}{\partial r \partial \theta} - \frac{1}{r^2}\frac{\partial}{\partial \theta})(\alpha_3|\alpha_3|^{i_2})ds;$$

$$d_* = \frac{d_2}{d_1}; \quad d_1 = \int_0^{2\pi} Q^2 d\theta \int_{r_0}^{R} P^2 dr; \quad d_2 = \int_0^{2\pi} Q d\theta \int_{r_0}^{R} P dr;$$

R - radius of the plate; r_0 - radius of the inner edge on which the boundary conditions are specified; $P(r)$ and $Q(\theta)$ - are determined from the boundary conditions using a well-known method [1].

Let us denote the spectral density of vibration acceleration of the base by $S_{W_0}(\omega)$. Solving equations (9) and assuming $s = j\omega$, we write down expressions for determining the mean square values of the variable $T(t)$

$$\sigma_T^2 = \int_{-\infty}^{\infty} \frac{d_* S_{W_0}(\omega)}{[(L_1 - \omega^2)\omega_{01}^2]^2 - L_2^2\omega_{01}^4} d\omega, \tag{10}$$

where

$$L_1 = 1 - \eta_1 R_1 - \nu_1 R_2; \qquad L_2 = \eta_2 R_1 + \nu_2 R_2.$$

We will accept the spectral density of vibration acceleration in the form often used in analysis

$$S_W(\omega) = \frac{D_{W_0}\alpha\omega_c^3}{\pi(\omega_c^2 - \omega^2 + i\alpha\omega_c\omega)(\omega_c^2 - \omega^2 - i\alpha\omega_c\omega)}, \tag{11}$$

where D_{W_0} - is the dispersion of vibration acceleration of the base; α - is the parameter characterizing the width of the vibration spectrum; ω_c - is the predominant frequency in the vibration spectrum.

The expression for the root mean square value of the absolute acceleration of the plate is presented in the form

$$\sigma_{W_0}^2 = \int_{-\infty}^{\infty} \frac{[L_1\omega_{01}^2 - (1+PQd_*)\omega^2]^2 - L_2^2\omega_{01}^4}{(L_1\omega_{01}^2 - \omega^2)^2 - L_2^2\omega_{01}^4} S_{W_0}(\omega). \quad (12)$$

Conclusion. The proposed complex form of statistical linearization allows one to describe random vibrations of a round plate with imperfect elasticity of the material from a unified position. The obtained integral expressions (10) – (12) allow one to more fully evaluate the dynamic characteristics of the plate for different types of spectral density of the random process.

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