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PROBLEM OF ABSORBER NONLINEAR TRANSVERSE VIBRATIONS OF AN ELASTIC ROD UNDER RANDOM IMPACTS

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Abstract. In this paper, the problem of nonlinear vibrations of an elastic rod of variable cross-section with a dynamic absorber under random effects is considered. In order to evaluate the efficiency of the dynamic absorber and select the optimal parameters of the system, analytical expressions for the mean square values of the variable function of amplitudes and absolute acceleration of the rod are determined

Keywords: elastic, variable cross-section rod, vibration, dynamic absorber, hysteresis, dissipative, random impact.

Tasodifiy qo‘zg‘alishlarda elastik sterjenning chiziqlimas ko‘ndalang tebranishlarini so‘ndirish masalasi

Annotatsiya. Ushbu ishda tasodifiy qo‘zg‘alishlarda ko‘ndalang kesimi o‘zgaruvchan elastik sterjenning dinamik so‘ndirgich bilan birgalikdagi chiziqlimas tebranishlari masalasi qaralgan. Dinamik so‘ndirgichning effektivligini baholash va sistema optimal parametrlarini tanlash maqsadida tebranishlardan himoyalanuvchi sterjenning amplitudaviy o‘zgaruvchi funksiyasi va absolyut tezlanishining o‘rta kvadratik qiymatlarini analitik ifodalari aniqlangan.

Kalit so‘zlar: elastik, ko‘ndalang kesimi o‘zgaruvchan sterjen, tebranish, dinamik so‘ndirgich, gisterezis, dissipativ, tasodifiy qo‘zg‘alish.

Задача гашения нелинейных поперечных колебаний упругого стержня при случайных воздействиях

Аннотация. В данной работе рассмотрена задача нелинейных колебаний упругого стержня переменного поперечного сечения с динамическим гасителем при случайных воздействиях. С целью оценки эффективности динамического гасителя и выбора оптимальных параметров системы определены аналитические выражения средних квадратических значений переменной функции амплитуд и абсолютного ускорения стержня.

Ключевые слова: эластичный, стержень переменного поперечного сечения, колебание, динамический гаситель, гистерезис, диссипативный, случайное воздействие.

Introduction. In all fields of technology, including aviation, shipbuilding, and mechanical engineering, various methods are used to protect devices and their elements from harmful vibrations. The use of dynamic absorbers is effective in this regard. The issues of mathematical modeling of various types of complex objects in combination with dynamic vibration absorbers, studying the dynamics of systems, their priority, and the characteristics of vibrations in various processes are relevant. Scientific monographs and research results have been published on these issues, various models of dynamic

vibration absorbers have been developed, recommendations have been developed for mathematical modeling of vibration-protected concentrated and distributed mass mechanical systems, methods for testing their dynamics and vibration absorber [1-4].

In mathematical modeling and selection of optimal parameters of protected objects and dynamic vibration absorbers, it is important to fully take into account the elastic-dissipative properties of their materials and express them through substantiated models and hypotheses.

Hypotheses based on the expression of imperfect elasticity of materials in mechanical systems through hysteresis-type dissipative characteristics and obtaining accurate calculation results have been developed and applied, including [5-7].

Numerous scientific papers have been published on the issues of damping transverse, longitudinal, torsional and other vibrations of rod devices of constant and variable cross-section in various technological processes [2,4,8-12].

In [4], the dynamics of kinematic and random vibrations of rods with a fixed cross-section and hysteresis-type dissipative characteristics was investigated.

The article is devoted to the study of nonlinear random vibrations of a rod of variable cross-section in combination with a dynamic vibration absorber. The dissipative properties of the elastic rod and the damping element materials of the dynamic absorber are of the hysteresis type and are taken into account by means of single-valued nonlinear functions. Using the statistical linearization method, linear complex functions are taken into account in the equations of these functions [4].

Problem statement. solution methodology. Let the rod there are a length l, a height h, and a variable width $b(x)$.

The motion of a rod of variable cross-section with elastic-dissipative characteristics of the hysteresis type during transverse random vibrations together with a dynamic absorber is expressed in the form of a system of differential equations:

$$\begin{aligned}&\frac{\partial^2 M}{\partial x^2}-c\left[1+(-\theta_1+j\theta_2)\left(D_0+f\left(\sigma_{\zeta_{ot}}\right)\right)\right]\zeta\delta(x-x_0)=-\rho F\frac{\partial^2 w_a}{\partial t^2};\\&m\frac{\partial^2 w(x_0)}{\partial t^2}+m\frac{\partial^2 \zeta}{\partial t^2}+c\left[1+(-\theta_1+j\theta_2)\left(D_0+f\left(\sigma_{\zeta_{ot}}\right)\right)\right]\zeta=-m\frac{\partial^2 w}{\partial t^2}.\end{aligned} \tag{1}$$

here M is bending moment; $\rho,\ F=F(x)$ are respectively, the density of the rod material and the variable cross-sectional area; $w(x_0)$ is displacement of the rod point with the dynamic absorber installed; x_0 is dynamic absorber attachment point; $\delta(x)$ is Dirac's delta function; c,m are respectively, the stiffness and mass of the dynamic absorber; ζ is displacement of the dynamic absorber relative to the rod; θ_1,θ_2 are coefficients that depend on the dissipative properties of the dynamic absorber material and are determined from the hysteresis surface; $j^2=-1;\ f\left(\sigma_{\zeta_{ot}}\right)$ is the decrement of vibrations, and ζ_{ot} is a function of the absolute value of the relative deformation, i.e.

$$f\left(\sigma_{\zeta_{ot}}\right)=D_1\sigma_{\zeta_{ot}}+D_2\sigma^2_{\zeta_{ot}}+D_s\sigma^s_{\zeta_{ot}},$$

$D_0,D_1,...,D_s$ are experimentally determined parameters of the hysteresis loop and depend on the damping properties of the dynamic absorber material [4]; $\sigma_{\zeta_{ot}}$ is root mean square value of the relative deformation of the elastic damping element of the dynamic absorber; w_a is absolute displacement of the rod

$$w_a=w_0+w,$$

in this w_0 is base displacement; w is rod bending.

Let us write the relationship between stress and relative strain deformation in the rod material as follows:

$$\sigma_k=E\left(1+(-\eta_1+j\eta_2)\left[C_0+f\left(\sigma_{\xi_{ot}}\right)\right]\right)\xi_{ot},$$

here E is modulus of elasticity; $\eta_1, \eta_2 = \eta_{22} sgn(\omega)$ are constant coefficients that depend on the elastic dissipative properties of the tergen material and are determined from the hysteresis surface; $f\left(\sigma_{\xi_{ot}}\right)$ is the decrement of vibrations, and ξ_{ot} is a function of the absolute value of the relative deformation, i.e.

$$f\left(\sigma_{\xi_{ot}}\right) = C_1\sigma_{\xi_{ot}} + C_2\sigma_{\xi_{ot}}^2 + C_n\sigma_{\xi_{ot}}^n,$$

$C_0, C_1, ..., C_n$ are experimentally determined parameters of the hysteresis loop and depend on the damping properties of the rod material; $\sigma_{\xi_{ot}}$ is root mean square value of the relative deformation of the rod.

Substituting the bending moment expression into the system of (1) differential equations and calculating according to the methodology presented in [4], let us obtain the following system of differential equations:

$$\begin{aligned}
&EI\frac{\partial^2}{\partial x^2}\left\{\frac{\partial^2 w}{\partial x^2}\left[1 + C_0(-\eta_1 + j\eta_2) + \frac{24}{h^3}(-\eta_1 + j\eta_2)\int_0^{h/2} f\left(\sigma_{\xi_{ot}}\right) z^2 dz\right]\right\} + \\
&+2E\frac{\partial I}{\partial x}\frac{\partial}{\partial x}\left\{\frac{\partial^2 w}{\partial x^2}\left[1 + C_0(-\eta_1 + j\eta_2) + \frac{24}{h^3}(-\eta_1 + j\eta_2)\int_0^{h/2} f\left(\sigma_{\xi_{ot}}\right) z^2 dz\right]\right\} + \\
&+E\frac{\partial^2 I}{\partial x^2}\frac{\partial^2 w}{\partial x^2}\left\{\frac{\partial^2 w}{\partial x^2}\left[1 + C_0(-\eta_1 + j\eta_2) + \frac{24}{h^3}(-\eta_1 + j\eta_2)\int_0^{h/2} f\left(\sigma_{\xi_{ot}}\right) z^2 dz\right]\right\} - \\
&-c\left(1 + (-\theta_1 + j\theta_2)\left(D_0 + f\left(\sigma_{\zeta_{ot}}\right)\right)\right)\zeta\delta(x - x_0) + \rho F\frac{\partial^2 w}{\partial t^2} = -\rho F\frac{\partial^2 w_0}{\partial t^2}; \\
&m\frac{\partial^2 w(x_0)}{\partial t^2} + m\frac{\partial^2 \zeta}{\partial t^2} + c\left(1 + (-\theta_1 + j\theta_2)\left(D_0 + f\left(\sigma_{\zeta_{ot}}\right)\right)\right)\zeta = -m\frac{\partial^2 w_0}{\partial t^2},
\end{aligned} \tag{2}$$

here $I = \frac{bh^3}{12};\ b = b(x);\ E$ is modulus of elasticity.

We seek the solution of the system of differential equations (2) as:

$$w(x,t) = \sum_{i=1}^{\infty} u_i(x) q_i(t), \tag{3}$$

in this $q_i(t)$ is function of time; $u_i(x)$ is a special form of rod vibrations.

Substituting expression (3) into the system of (2) differential equations and after some substitutions, we obtain the following

$$\begin{aligned}
&\sum_{i=1}^{\infty}\left\{\left[\ddot{q}_i + \left(1 + C_0\left(-\eta_1 + j\eta_2\right)\right)p_i^2 q_i\right]u_i + \frac{EI}{\rho F}\left(-\eta_1 + j\eta_2\right)Tq_i\frac{\partial^2}{\partial x^2}\left(\frac{\partial^2 u_i}{\partial x^2}\left|\frac{\partial^2 u_i}{\partial x^2}\right|^k\right)\right\} + \\
&+\frac{E}{\rho F}\frac{\partial^2 I}{\partial x^2}\sum_{i=1}^{\infty}\frac{\partial^2 u_i}{\partial x^2}q_i\left[1 + C_0\left(-\eta_1 + j\eta_2\right) + \left(-\eta_1 + j\eta_2\right)T\left|\frac{\partial^2 u_i}{\partial x^2}\right|^k\right] + \\
&+\frac{2E}{\rho F}\frac{\partial I}{\partial x}\frac{\partial}{\partial x}\left\{\sum_{i=1}^{\infty}\frac{\partial^2 u_i}{\partial x^2}q_i\left[1 + C_0\left(-\eta_1 + j\eta_2\right) + \left(-\eta_1 + j\eta_2\right)T\left|\frac{\partial^2 u_i}{\partial x^2}\right|^k\right]\right\} - \\
&-\frac{c}{\rho F}\left(1 + \left(-\theta_1 + j\theta_2\right)\left(D_0 + f\left(\sigma_{\zeta_{ot}}\right)\right)\right)\zeta\delta\left(x - x_0\right) + \frac{\partial^2 w}{\partial t^2} = -\frac{\partial^2 w_0}{\partial t^2}; \\
&\sum_{i=1}^{\infty}u_{i0}\ddot{q}_i + \ddot{\zeta} + n_0^2\left(1 + \left(-\theta_1 + j\theta_2\right)\left(D_0 + f\left(\sigma_{\zeta_{ot}}\right)\right)\right)\zeta = -\frac{\partial^2 w_0}{\partial t^2},
\end{aligned} \tag{4}$$

$$T = 3\sum_{k=1}^{n} C_k q_{ia}^k \frac{h^k}{2^k (k+3)};\ u_i = u_i(x);\ q_i(t) = q_i;\ q_{ia} = |q_i|;\ n_0^2 = \frac{c}{m}.$$

in this

(4) multiply both parts of the first equation of the system of differential equations by $u_m(x)$ and integrate over the interval $[0;l]$. Using the orthogonality condition and the property of Dirac's delta function, after some calculations, we obtain the following system of differential equations:

$$\begin{aligned}
&\ddot{q}_i + \left\{ \left(1 + C_0(-\eta_1 + j\eta_2)\right) p_i^2 + \frac{EI}{\rho F d_{2i}} (-\eta_1 + j\eta_2) T \int_0^l u_i \frac{\partial^2}{\partial x^2} \left(\frac{\partial^2 u_i}{\partial x^2} \left| \frac{\partial^2 u_i}{\partial x^2} \right|^k \right) dx + \right. \\
&+ \frac{E}{\rho F d_{2i}} \frac{\partial^2 I}{\partial x^2} \int_0^l u_i \frac{\partial^2 u_i}{\partial x^2} \left[1 + C_0(-\eta_1 + j\eta_2) + (-\eta_1 + j\eta_2) T \left| \frac{\partial^2 u_i}{\partial x^2} \right|^k \right] dx + \\
&\left. + \frac{2E}{\rho F d_{2i}} \frac{\partial I}{\partial x} \int_0^l \frac{\partial}{\partial x} \left[\sum_{i=1}^{\infty} \frac{\partial^2 u_i}{\partial x^2} \left[1 + C_0(-\eta_1 + j\eta_2) + (-\eta_1 + j\eta_2) T \left| \frac{\partial^2 u_i}{\partial x^2} \right|^k \right] dx \right\} q_i - \right. \\
&- \mu\mu_0 n_0^2 \left(1 + (-\theta_1 + j\theta_2)\left(D_0 + f\left(\sigma_{\zeta_{ot}}\right)\right)\right)\zeta = -d_i \frac{\partial^2 w_0}{\partial t^2}; \\
&u_{i0}\ddot{q}_i + \ddot{\zeta} + n_0^2 \left(1 + (-\theta_1 + j\theta_2)\left(D_0 + f\left(\sigma_{\zeta_{ot}}\right)\right)\right)\zeta = -\frac{\partial^2 w_0}{\partial t^2},
\end{aligned} \tag{5}$$

$$\mu = \frac{m}{\rho F l};\ \mu_0 = \frac{l}{d_{2i}};\ d_i = \frac{d_{1i}}{d_{2i}};\ d_{1i} = \int_0^l u_i dx;\ d_{2i} = \int_0^l u_i^2 dx.$$

in this

To determine the variables q_i and ζ, we reduce the system of differential equations (5) to a system of algebraic equations using the differential operator $s = \frac{d}{dt}$, that is,

$$\begin{aligned}
&s^2 + \left\{ \left(1 + C_0(-\eta_1 + j\eta_2)\right) p_i^2 + \frac{EI}{\rho F d_{2i}} (-\eta_1 + j\eta_2) T \int_0^l u_i \frac{\partial^2}{\partial x^2} \left(\frac{\partial^2 u_i}{\partial x^2} \left| \frac{\partial^2 u_i}{\partial x^2} \right|^k \right) dx + \right. \\
&+ \frac{E}{\rho F d_{2i}} \frac{\partial^2 I}{\partial x^2} \int_0^l u_i \frac{\partial^2 u_i}{\partial x^2} \left[1 + C_0(-\eta_1 + j\eta_2) + (-\eta_1 + j\eta_2) T \left| \frac{\partial^2 u_i}{\partial x^2} \right|^k \right] dx + \\
&\left. + \frac{2E}{\rho F d_{2i}} \frac{\partial I}{\partial x} \int_0^l \frac{\partial}{\partial x} \left[\sum_{i=1}^{\infty} \frac{\partial^2 u_i}{\partial x^2} \left[1 + C_0(-\eta_1 + j\eta_2) + (-\eta_1 + j\eta_2) T \left| \frac{\partial^2 u_i}{\partial x^2} \right|^k \right] dx \right\} q_i - \right. \\
&- \mu\mu_0 n_0^2 \left(1 + (-\theta_1 + j\theta_2)\left(D_0 + f\left(\sigma_{\zeta_{ot}}\right)\right)\right)\zeta = -d_i W_0; \\
&u_{i0} s^2 q_i + \left[s^2 + n_0^2 \left(1 + (-\theta_1 + j\theta_2)\left(D_0 + f\left(\sigma_{\zeta_{ot}}\right)\right)\right)\right]\zeta = -W_0,
\end{aligned} \tag{6}$$

in this $W_0 = \frac{\partial^2 w_0}{\partial t^2}$ is base acceleration.

From the system of algebraic equations (6), we write the expressions for determining the mean square values of the variables $q_i \left(i = \overline{1,n}\right)$ and ζ, and the substitution $s = j\omega$ ($j = \sqrt{-1}$; ω is frequency), as follows:

$$\sigma_{q_i}^2 = \int_{-\infty}^{\infty} \left| \frac{d_i \omega^2 - (d_i + \mu\mu_0) N_0}{\omega^4 - (N_0 + N_1 + u_{i0}\mu\mu_0 N_0)\omega^2 + N_1 N_0} \right| S_{W_0}(\omega) d\omega; \tag{7}$$

$$\sigma_{\zeta}^2 = \int_{-\infty}^{\infty} \left| \frac{(1-u_{i0}d_i)\omega^2 - N_1}{\omega^4 - (N_0 + N_1 + u_{i0}\mu\mu_0 N_0)\omega^2 + N_1 N_0} \right| S_{W_0}(\omega)\, d\omega; \tag{8}$$

here $S_{W_0}(\omega)$ is spectral density of fundamental accelerations.

Considering that the absolute acceleration of the rod consists of the sum of the relative acceleration and the base acceleration, using expression (7), we obtain an expression for the root-mean-square values of the absolute accelerations of a rod of variable cross-section protected from vibrations:

$$\sigma_{W_a}^2 = \int_{-\infty}^{\infty} \left| 1 - \omega^2 u_i \frac{d_i\omega^2 - (d_i + \mu\mu_0)N_0}{\omega^4 - (N_0 + N_1 + u_{i0}\mu\mu_0 N_0)\omega^2 + N_1 N_0} \right| S_{W_0}(\omega)\, d\omega; \tag{9}$$

Conclusion. Using the obtained integral expressions (7)-(9), the dynamics and priority of nonlinear random vibrations of the rod with a variable cross-section in combination with the absorber can be examined in various forms of the spectral density of random processes and analyzed as a result of numerical calculations. This allows us to evaluate the vibration damping efficiency of the dynamic absorber and select the optimal design parameters.

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