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VIBRATIONS OF PIECE-HOMOGENEOUS PLATES

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Abstract: The article presents in a general three-dimensional formulation the problem of oscillation of two-layer piecewise homogeneous viscoelastic plates of constant thickness. General vibration equations are derived, expressions are given for displacements and stresses at internal points of the plate in terms of functions describing displacements and deformations of the points of the contact plane

Key words: oscillation equations, two-layer plate, displacement, elastic, viscoelastic, boundary conditions, initial conditions, operator, Lamé coefficients, differential equation, Fourier integral, complex frequency

Annotatsiya: Maqolada umumiy uch o‘lchamli formulada doimiy qalinlikdagi ikki qatlamli parcha-parcha bir hil viskoelastik plitalarning tebranish muammosi keltirilgan. Umumiy tebranish tenglamalari olinadi, kontakt tekisligi nuqtalarining siljishlari va deformatsiyalarini tavsiflovchi funktsiyalar nuqtai nazaridan plastinkaning ichki nuqtalaridagi siljishlar va kuchlanishlar uchun ifodalar beriladi.

Kalit so‘zlar: tebranish tenglamalari, ikki qavatli plastinka, siljish, elastik, yopishqoq elastik, chegara shartlari, boshlang‘ich shartlar, operator, Lame koeffitsientlari, differentsial tenglama, Furye integrali, kompleks chastota

Аннотация: В статье представлена в общей трехмерной постановке формулируется задача о колебании двухслойных кусочно-однородных вязкоупругих пластин постоянной толщины. Выводятся общие уравнения колебания, даются выражения для перемещений и напряжений во внутренних точках пластинки через функции, описывающие перемещения и деформации точек плоскости контакта.

Ключевые слова: уравнения колебаний, двухслойная пластина, перемещения, упругие, вязкоупругие, граничные условия, начальные условия, оператор, коэффициенты Ламе, дифференциальное уравнение, интеграл Фурье, комплексная частота

INTRODUCTION

Plates are one of the main elements of many building structures.

In many cases, the plates are not uniform in thickness, in particular, they are piecewise homogeneous (two-layer, etc.).

At present, there is practically no theory of oscillation of piecewise homogeneous plates, and therefore the development of the theory and methods for calculating such plates is an urgent problem in structural mechanics[1, 2, 3, 4, 5].

In this chapter, in a general three-dimensional formulation, the problem of oscillation of two-layer piecewise homogeneous viscoelastic plates of constant thickness is formulated. General vibration equations are derived, and expressions are given for displacements and stresses at internal points of the plate in terms of functions describing displacements and deformations of the points of the contact plane[6, 7, 8, 9, 10].

For piecewise homogeneous plates, there is neither purely transverse nor purely longitudinal vibration, as shown, is a sixth-order equation in derivatives, which for a homogeneous plate of constant thickness turns into a product of two integro-differential operators describing longitudinal and transverse vibrations[11, 12].

METHODOLOGY of RESEARCH

Accurate three-dimensional boundary value problem for piecewise homogeneous plates

Consider a piecewise-homogeneous viscoelastic plate of constant thickness as a piecewise-homogeneous layer of the same geometry, with the thickness of the upper component equal to h_0 and the lower component h_1. The plate occupies the region $-\infty<(x, y)<\infty$; $-h_1 \le z \le h_0$, while the homogeneity interface coincides with the plane $z=0$.

The movement of the material of the constituent layers of the plate in Cartesian coordinates (x, y, z) *is* described by the equations of motion in stresses

$$\frac{\partial \sigma_{xx}^{(k)}}{\partial x}+\frac{\partial \sigma_{xy}^{(k)}}{\partial y}+\frac{\partial \sigma_{xz}^{(k)}}{\partial z}=\rho_k \frac{\partial^2 u^{(k)}}{\partial t^2};$$
$$\frac{\partial \sigma_{xy}^{(k)}}{\partial x}+\frac{\partial \sigma_{yy}^{(k)}}{\partial y}+\frac{\partial \sigma_{yz}^{(k)}}{\partial z}=\rho_k \frac{\partial^2 \upsilon^{(k)}}{\partial t^2}; \qquad (1.1.1)$$
$$\frac{\partial \sigma_{xz}^{(k)}}{\partial x}+\frac{\partial \sigma_{zy}^{(k)}}{\partial y}+\frac{\partial \sigma_{zz}^{(k)}}{\partial z}=\rho_k \frac{\partial^2 w^{(k)}}{\partial t^2};$$

Where $\sigma_{ij}^{(\kappa)}$ are the stress tensor components; $u^{(k)}$, $\upsilon^{(\kappa)}$, $w^{(\kappa)}$ – displacement vector components[13, 14, 15, 16, 17].

In this case, both stresses, displacements, and density in each of the layers will be denoted by the corresponding index “0”or “1”, i.e., k takes the values “0” and “1”.

The dependences of stress $\sigma_{ij}^{(k)}$ on strains $\varepsilon_{ij}^{(k)}$ at the points of the plate are described by linear operator equations, that is, we will assume that they are given in the form of Boltzmann relations:

$$\sigma_{ij}^{(k)} = L_k(\varepsilon^{(k)}) + 2M_k(\varepsilon_{ij}^{(k)}); \qquad (1.1.2)$$

$$\sigma_{ij}^{(k)} = M_k(\varepsilon_{ij}^{(k)}); \ (i \neq j; \ \ i, j = x, y, z).$$

Where viscoelastic operators L_k and M_k are linear integral operators of the form

$$L_k(\zeta) = \lambda_k\left[\zeta(t) - \int_0^t f_1^{(k)}(t-\xi)\zeta(\xi)d\xi\right];$$

$$M_k(\zeta) = M_k\left[\zeta(t) - \int_0^t f_2^{(k)}(t-\xi)\zeta(\xi)d\xi\right]; \qquad (11.3)$$

where $f_j^{(k)}(t)$ – kernels of viscous operators, λ_k, μ_k – elastic constants or Lame coefficients[18, 19, 20, 21].

Let us introduce the potentials $\Phi^{(k)}$ and $\vec{\Psi}^{(k)}$ longitudinal and transverse waves according to the formula:

$$\vec{U}^{(k)} = grad\Phi^{(k)} + rot\,\vec{\Psi}^{(k)}$$

$$\vec{U}^{(k)} = \vec{U}^{(k)}(\mathrm{u}^{(k)}, \mathrm{v}^{(k)}, \mathrm{w}^{(k)}). \qquad (1.1.4)$$

where $\vec{U}^{(k)}$ – displacement vector of plate points.

Then instead of equations (1.1.1) we obtain integro-differential equations:

$$N_k(\Delta\Phi^{(k)}) = \rho_k \frac{\partial^2\Phi^{(k)}}{\partial t^2}; \quad M_k(\Delta\vec{\Psi}^{(k)}) = \rho_k \frac{\partial^2\vec{\Psi}^{(k)}}{\partial t^2}; \qquad (1.1.5)$$

where the operator N_k is

$$N_k = L_k + 2M_k$$

Δ – three-dimensional Laplace operator

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}.$$

By virtue of the Helmholtz theorem /35/ in the absence of internal sources, the vector potential of $\vec{\psi}^{(k)}$ transverse waves must satisfy the condition

$$div\vec{\Psi}^{(k)} = 0; \qquad \vec{\Psi}^{(k)} = \vec{\Psi}^{(k)}(\Psi_1^{(k)}, \Psi_2^{(k)}, \Psi_3^{(k)}). \qquad (1.1.6)$$

Condition (1.1.6) for the components of the vector $\vec{\psi}^{(k)}$ takes the form

$$\frac{\partial \psi_1^{(k)}}{\partial x}+\frac{\partial \psi_2^{(k)}}{\partial y}+\frac{\partial \psi_3^{(k)}}{\partial z}=0, \qquad (1.1.7)$$

that is, we obtain a closing equation for determining the vector potential $\vec{\psi}^{(k)}$.

Equations (1.1.5) and condition (1.1.6) are sufficient for finding general solutions for the scalar and vector potentials $\Phi^{(k)}$ and $\vec{\psi}^{(k)}$.

Vibrations of a viscoelastic piecewise homogeneous plate are caused by external forces applied to the surfaces of the plate[22, 23, 24, 25]. Therefore, the boundary conditions take the form:

at $z=h_0$ (on the upper surface of the plate)

$$\sigma_{zz}^{(0)}=f_{zz}^{(0)}(x,y,t); \quad \sigma_{xz}^{(0)}=f_{xz}^{(0)}(x,y,t);$$
$$\sigma_{yz}^{(0)}=f_{yz}^{(0)}(x,y,t); \qquad (1.1.8)$$

at $z=0$ (contact plane)

$$\sigma_{zz}^{(0)}=\sigma_{zz}^{(1)}; \quad \sigma_{xz}^{(0)}=\sigma_{xz}^{(1)}; \quad \sigma_{yz}^{(0)}=\sigma_{yz}^{(1)};$$
$$u^{(0)}=u^{(1)}; \ \upsilon^{(0)}=\upsilon^{(1)}; \quad w^{(0)}=w^{(1)}; \qquad (1.1.9)$$

at $z=-h_1$ (on the bottom surface of the plate) [26, 27, 28, 29, 30]

$$\sigma_{zz}^{(1)}=f_{z}^{(1)}(x,y,t); \quad \sigma_{xz}^{(1)}=f_{xz}^{(1)}(x,y,t);$$
$$\sigma_{yz}^{(1)}=f_{yz}^{(1)}(x,y,t). \qquad (1.1.10)$$

The initial conditions of the problem are zero, that is,

$$\frac{\partial \Phi^{(k)}}{\partial t}=\Phi^{(k)}=\frac{\partial \vec{\Psi}^{(k)}}{\partial t}=\vec{\Psi}^{(k)}=0. \qquad (1.1.11)$$

Displacements $u^{(k)}$, $\upsilon^{(k)}$, $w^{(k)}$, strains $\varepsilon_{ij}^{(k)}$ and stresses $\sigma_{ij}^{(k)}$ in Cartesian coordinates through the potentials $\Phi^{(k)}$ and $\vec{\psi}^{(k)}$ longitudinal and transverse waves are determined by the following formulas /73/[31, 32, 33, 34].

For travel:

$$u_k=\frac{\partial \Phi^{(k)}}{\partial x}+\frac{\partial \Psi_3^{(k)}}{\partial y}-\frac{\partial \Psi_2^{(k)}}{\partial z}; \qquad \upsilon_k=\frac{\partial \Phi^{(k)}}{\partial y}+\frac{\partial \Psi_1^{(k)}}{\partial z}-\frac{\partial \Psi_3^{(k)}}{\partial x};$$
$$w_k=\frac{\partial \Phi^{(k)}}{\partial z}+\frac{\partial \Psi_2^{(k)}}{\partial x}-\frac{\partial \Psi_1^{(k)}}{\partial y}; \qquad (1.1.12)$$

For deformations:

$$\varepsilon_{xx}^{(k)}=\frac{\partial^2 \Phi^{(k)}}{\partial x^2}+\frac{\partial^2 \Psi_3^{(k)}}{\partial x \partial y}-\frac{\partial^2 \Psi_2^{(k)}}{\partial y \partial z};$$
$$\varepsilon_{yy}^{(k)}=\frac{\partial^2 \Phi^{(k)}}{\partial y^2}+\frac{\partial^2 \Psi_1^{(k)}}{\partial y \partial z}-\frac{\partial^2 \Psi_3^{(k)}}{\partial y \partial x};$$

$$\varepsilon_{zz}^{(k)} = \frac{\partial^2 \Phi^{(k)}}{\partial z^2} + \frac{\partial^2 \Psi_2^{(k)}}{\partial x \partial z} - \frac{\partial^2 \Psi_1^{(k)}}{\partial y \partial z};$$

$$\varepsilon_{xy}^{(k)} = 2\frac{\partial^2 \Phi^{(k)}}{\partial x \partial y} + \frac{\partial^2 \Psi_1^{(k)}}{\partial x \partial z} - \frac{\partial^2 \Psi_2^{(k)}}{\partial y \partial z} + \frac{\partial^2 \Psi_3^{(k)}}{\partial y^2} - \frac{\partial^2 \Psi_3^{(k)}}{\partial x^2}; \qquad (1.1.13)$$

$$\varepsilon_{yz}^{(k)} = 2\frac{\partial^2 \Phi^{(k)}}{\partial y \partial z} + \frac{\partial^2 \Psi_2^{(k)}}{\partial x \partial y} - \frac{\partial^2 \Psi_2^{(k)}}{\partial x \partial z} + \frac{\partial^2 \Psi_1^{(k)}}{\partial z^2} - \frac{\partial^2 \Psi_1^{(k)}}{\partial y^2};$$

$$\varepsilon_{xz}^{(k)} = 2\frac{\partial^2 \Phi^{(k)}}{\partial x \partial z} + \frac{\partial^2 \Psi_3^{(k)}}{\partial y \partial z} - \frac{\partial^2 \Psi_2^{(k)}}{\partial z^2} + \frac{\partial^2 \Psi_2^{(k)}}{\partial x^2} - \frac{\partial^2 \Psi_1^{(k)}}{\partial x \partial y};$$

For voltages:

$$\sigma_{xx}^{(k)} = L_k(\Delta \Phi^{(k)}) + 2M_k\left(\frac{\partial^2 \Phi^{(k)}}{\partial x^2} + \frac{\partial^2 \Psi_3^{(k)}}{\partial x \partial y} - \frac{\partial^2 \Psi_2^{(k)}}{\partial x \partial z}\right);$$

$$\sigma_{yy}^{(k)} = L_k(\Delta \Phi^{(k)}) + 2M_k\left(\frac{\partial^2 \Phi^{(k)}}{\partial y^2} + \frac{\partial^2 \Psi_1^{(k)}}{\partial y \partial z} - \frac{\partial^2 \Psi_3^{(k)}}{\partial x \partial y}\right);$$

$$\sigma_{zz}^{(k)} = L_k(\Delta \Phi^{(k)}) + 2M_k\left(\frac{\partial^2 \Phi^{(k)}}{\partial z^2} + \frac{\partial^2 \Psi_2^{(k)}}{\partial x \partial z} - \frac{\partial^2 \Psi_1^{(k)}}{\partial y \partial z}\right);$$

$$\sigma_{xy}^{(k)} = M_k\left(2\frac{\partial^2 \Phi^{(k)}}{\partial x \partial y} - \frac{\partial^2 \Psi_3^{(k)}}{\partial x^2} + \frac{\partial^2 \Psi_3^{(k)}}{\partial y^2} + \frac{\partial^2 \Psi_1^{(k)}}{\partial x \partial z} - \frac{\partial^2 \Psi_2^{(k)}}{\partial y \partial z}\right); \qquad (1.1.14)$$

$$\sigma_{yz}^{(k)} = M_k\left(2\frac{\partial^2 \Phi^{(k)}}{\partial y \partial z} - \frac{\partial^2 \Psi_1^{(k)}}{\partial y^2} + \frac{\partial^2 \Psi_1^{(k)}}{\partial z^2} + \frac{\partial^2 \Psi_2^{(k)}}{\partial x \partial y} - \frac{\partial^2 \Psi_3^{(k)}}{\partial x \partial z}\right);$$

$$\sigma_{xz}^{(k)} = M_k\left(2\frac{\partial^2 \Phi^{(k)}}{\partial x \partial y} + \frac{\partial^2 \Psi_2^{(k)}}{\partial x^2} - \frac{\partial^2 \Psi_2^{(k)}}{\partial z^2} - \frac{\partial^2 \Psi_1^{(k)}}{\partial x \partial y} + \frac{\partial^2 \Psi_3^{(k)}}{\partial y \partial z}\right);$$

Thus, the exact three-dimensional problem of vibration of a viscoelastic piecewise homogeneous plate of constant thickness is reduced to solving the vibration equations (1.1.5) in potentials $\Phi^{(k)}$ and $\vec{\Psi}^{(k)}$ under boundary conditions (1.1.8), (1.1.9), (1.1.10) and zero initial conditions (1.1.11)[35, 36, 37, 38, 39].

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