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Research Article

ANALYSIS OF THE GENERAL EQUATIONS OF THE TRANSVERSE VIBRATION OF A PIECEWISE HOMOGENEOUS VISCOELASTIC PLATE

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ABSTRACT

This article discusses the analysis of the general equations of the transverse vibration of a piecewise homogeneous viscoelastic plate obtained in the "Oscillation of bilayer plates of constant thickness".

KEYWORDS

Analysis, approximate, vibrations, two-layer plate, boundary value problem, stresses, deformation, oscillation equations.

INTRODUCTION

The general equations of vibrations of piecewise homogeneous viscoelastic plates of constant thickness, described in [1-7], are complex in structure and contain derivatives of any order in coordinates x, y and time t, and therefore are not suitable for solving applied problems and performing engineering calculations. To solve applied problems, instead of general equations, it is advisable to use approximate ones, which include one or another finite order in derivatives [8-11]. The classical equations for the transverse oscillation of a plate contain derivatives of no higher than the 4th order, and for piecewise homogeneous or two-layer plates, the simplest approximate oscillation equation is a sixth-order equation. If in the operators (3.8) given in [12-17] we

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confine ourselves to the first two terms, then from equation (3.11).

$$L_1(W_2) = F_1(x,y,t)$$

where the operators L_1 and $F_1(x,y,t)$ are equal:

$$\begin{aligned} L_1 = {} & (M_{1(n)}K_{2(n)} - M_{2(n)}K_{1(n)})(H_{3(n)}E_{4(n)} - H_{4(n)}E_{3(n)}) + \\ & + (M_{1(n)}K_{3(n)} - M_{3(n)}K_{1(n)})(H_{4(n)}E_{2(n)} - H_{2(n)}E_{4(n)}) + \\ & + (M_{1(n)}K_{4(n)} - M_{4(n)}K_{1(n)})(H_{2(n)}E_{3(n)} - H_{3(n)}E_{2(n)}) - \\ & - (M_{2(n)}K_{3(n)} - M_{3(n)}K_{2(n)})(H_{4(n)}E_{1(n)} - H_{1(n)}E_{4(n)}) - \\ & - (M_{2(n)}K_{4(n)} - M_{4(n)}K_{2(n)})(H_{1(n)}E_{3(n)} - H_{3(n)}E_{1(n)}) + \\ & + (M_{3(n)}K_{4(n)} - M_{4(n)}K_{3(n)})(H_{1(n)}E_{2(n)} - H_{2(n)}E_{1(n)}); \end{aligned}$$

$$\begin{aligned} F_1 = {} & -[K_{1(n)}(H_{2(n)}E_{3(n)} - H_{3(n)}E_{2(n)}) + K_{2(n)}(H_{3(n)}E_{1(n)} - H_{1(n)}E_{3(n)}) + \\ & + K_{3(n)}(H_{1(n)}E_{2(n)} - H_{2(n)}E_{1(n)})]\{M_0^{-1}(f_z^{(0)})\} + \\ & + [M_{1(n)}(H_{2(n)}E_{3(n)} - H_{3(n)}E_{2(n)}) + M_{2(n)}(H_{3(n)}E_{1(n)} - H_{1(n)}E_{3(n)}) + \\ & + M_{3(n)}(H_{1(n)}E_{2(n)} - H_{2(n)}E_{1(n)})]\{M_1^{-1}(\frac{\partial f_{xz}^{(0)}}{\partial x} + \frac{\partial f_{yz}^{(0)}}{\partial y})\} - \\ & -(M_{1(n)}(K_{2(n)}E_{3(n)} - K_{3(n)}E_{2(n)}) + M_{2(n)}(K_{3(n)}E_{1(n)} - K_{1(n)}E_{3(n)}) + \\ & + M_{3(n)}(K_{1(n)}E_{2(n)} - K_{2(n)}E_{1(n)})]\{M_1^{-1}(f_z^{(1)})\} + \\ & +(M_{1(n)}(K_{2(n)}H_{3(n)} - K_{3(n)}H_{2(n)}) + M_{2(n)}(K_{2(n)}H_{1(n)} - K_{1(n)}H_{2(n)}) + \\ & + M_{3(n)}(K_{1(n)}H_{2(n)} - K_{2(n)}H_{1(n)})]\{M_1^{-1}(\frac{\partial f_{xz}^{(1)}}{\partial x} + \frac{\partial f_{yz}^{(1)}}{\partial y})\}; \end{aligned}$$

We obtain an approximate integrodifferential equation

$$\begin{aligned} & Q_1\left(\frac{\partial^4 W}{\partial t^4}\right) + Q_2\left(\Delta\frac{\partial^2 W}{\partial t^2}\right) + Q_3\left(\Delta^2 W\right) + Q_4\left(\frac{\partial^6 W}{\partial t^6}\right) + Q_5\left(\Delta\frac{\partial^4 W}{\partial t^4}\right) + \\ & + Q_6\left(\Delta^2\frac{\partial^2 W}{\partial t^2}\right) + Q_7\left(\Delta^3 W\right) = F_1(x,y,t). \end{aligned} \qquad (1)$$

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where the operators Q_j and $F_1(x,y,t)$ are equal:

$$Q_1 = M_1^{-2}\left(h_0\rho_0 + h_1\rho_1\right)^2;$$

$$Q_2 = -2M_1^{-2}(2(h_0P_2D_0 + h_1D_1)(h_0\rho_0 + h_1\rho_1) + \\ + (P_2 - 1)(h_0\rho_0(h_0 + h_1) - (h_0^2D_0\rho_0 + h_1^2D_1\rho_1)));$$

$$Q_3 = 4(P_2 - 1)(h_0^2P_2D_0 + h_1^2D_1 + h_1^2D_1 + 2h_0h_1P_2D_0);$$

$$Q_4 = -\frac{1}{6}M_1^{-2}(h_0^2\rho_0M_0^{-1}(3h_1^2\rho_1^2 + h_0\rho_0(h_0\rho_0 + 4h_1\rho_1))(2 - D_0) + \\ + h_1^2\rho_1M_1^{-1}(3h_0^2\rho_0^2 + h_1\rho_1(h_1\rho_1 + 4h_0\rho_0))(2 - D_1));$$

$$Q_5 = -\frac{1}{6}M_1^{-2}(h_0^2P_2\rho_0^2M_0^{-2}(2P_2(4D_0(1 - D_0) + (P_2 - 1)(4 + D_0^2)) - \\ - h_1^4\rho_1^2M_1^{-2}(2(4D_1^2 - 4D_1 - 1) - (P_2 - 1)D_1(2 - D_1)) + \\ + 6h_0^2h_1^2(\rho_0\rho_1M_0^{-1}M_1^{-1}(4(P_2^2D_0 + D_1) + (P_2 - 1)(2P_2(1 - D_0) - P_2D_1(2 - D_0) \\ + D_1(1 + D_0))) + +M_1^{-1}(\rho_0^2 + \rho_1^2)) + \\ + 2P_2h_0h_1(2\rho_0\rho_1M_0^{-1}M_1^{-1})(h_0^2(2 + 4D_0 - D_0^2) + h_1^2(2P_2 - P_2D_1 + 5D_1 - D_1^2)) + \\ + h_0^2h_1^2M_0^{-2}((P_2 - 1)(4 - 3D_0) + 2D_1(4 - D_0)) + 2h_1^2\rho_1^2M_1^{-2}D_0(4 - D_1)); \quad (2)$$

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$$Q_6=\frac{1}{3}M_1^{-2}(h_0^{\ 2}P_2\rho_0M_0^{-1}(2P_2((P_2-1)(2+9D_0-3D_0^2))-2D_0(1-3P_2+4D_0))+$$
$$+h_1^4\rho_1M_1^{-1}(4D_1(1-2D_1)-4D_1+(P_2-1)D_1(3-D_1))+$$
$$+3h_0^2h_1^2((4P_2D_0(P_2(1-D_1)-D_1)-(P_2-1)(2(P_2-1)D_1(1-D_0)-$$
$$+P_2(2-D_0-2D_0D_1)))\rho_0M_0^{-1}+(4D_1(1+D_0+P_2D_0)-(P_2-1)(6D_0D_1(P_2-1)-$$
$$-6P_2D_0+D_1))\rho_1M_1^{-1})-2h_0h_1P_2(\rho_0M_0^{-1}(2h_0^{\ 2}((P_2-1)(D_0^2-2D_0-1)-$$
$$-2D_1(1+D_0))-h_1^2(2(P_2-1)+D_1(P_2+3))))-$$
$$-4\rho_1M_1^{-1}(h_0^{\ 2}+h_1^{\ 2})(2(P_2-1)(1-D_1)+P_2D_1+(1+D_1))))));$$

$$Q_7=\frac{2}{3}(h_0^4P_2D_0(4D_0-5(P_2-1)+h_1^4D_1(4D_1-(P_2-1))-$$
$$+3h_0^2h_1^2(8P_2D_0D_1-(P_2-1)((2(P_2+1)D_0D_1-3P_2D_0-D_1(1-D_1)))-$$
$$-4h_0h_1P_2D_0(h_0^{\ 2}(P_2-1)+2D_1)+h_1^2(2(P_2-1)+(P_2+1)D_0)));$$

and

$$F_1(x,y,t)=M_1^{-2}\frac{\partial^2}{\partial t^2}((h_0\rho_0+h_1\rho_1)(f_z^{(0)}-f_z^{(1)}))+$$
$$+(h_0+h_1)(h_1\rho_1(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})+h_0\rho_0(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))+ \qquad (3)$$
$$+(h_0^2D_0\rho_0+h_1^2D_1\rho_1)((\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})-(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))-$$
$$-2\Delta(2M_1^{-2}((h_0P_2D_0+h_1D_1)(M_0f_z^{(0)}-M_1f_z^{(1)}))+$$

$$+2P_2h_0h_1)(D_0M_0^{-1}(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})+D_1M_1^{-1}(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))+$$
$$+M_1^{-1}(h_0^2P_2D_0+h_1^2D_1)(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})+(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2})).$$

If the plate is homogeneous, and W is the transverse displacement of the points of the “middle” surface - the plane of the plate, then in this case the dependences

$$N_0=N_1;\ \ M_0=M_1;\ \ P_2=1;\ \ h_0=h_1;\ \ C_0=C_1;\ \ D_0=D_1.$$

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and equation (1) becomes the equation

$$((1-C_0)^2\lambda_{10}^{(1)}+(1+C_0)^2\Delta)((\lambda_{20}^{(1)}+\Delta)+$$
$$+\frac{h_0^2}{6}((3D_0(\lambda_{20}^{(1)}+\Delta)^2)+4D_0\lambda_{20}^{(1)}\Delta)+4\lambda_{10}^{(1)}(\lambda_{20}^{(1)}+\Delta)))(W)=$$
$$=\frac{1}{h_0}(M_0^{-2}\frac{\partial^2}{\partial t^2}((f_z)+h_0(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2}))- \quad (4)$$
$$-4D_0M_0^{-1}\Delta((f_z)+h_0\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2})))$$

Where on the left is the product of two operators: the first describes the process of longitudinal oscillation, and the second describes the transverse oscillation [18-27].

Similarly, an approximate equation is introduced from the general equation (1.3.12) given in [1] and we obtain for $\left(\frac{\partial U_1}{\partial y}-\frac{\partial V_1}{\partial x}\right)$

$$(G_1\frac{\partial}{\partial t^2}+G_2\Delta+G_3\frac{\partial^4}{\partial t^4}+G_4\Delta\frac{\partial^2}{\partial t^2}+G_5\Delta^2+G_6\frac{\partial^6}{\partial t^6}+$$
$$+G_7\Delta+G_8\Delta^2+G_9\Delta^3)(\frac{\partial U_1}{\partial y}-\frac{\partial V_1}{\partial x})=F_2(x,y,t), \quad (5)$$

Where the operators G_j and $F_2(x,y,t)$ are equal:

$$G_1=M_1^{-1}(h_0\rho_0+h_1\rho_1)\ ;$$

$$G_2=-(h_0P_2+h_1)\ ;$$

$$G_3=\frac{1}{6}M_1^{-2}(h_0^2(h_0\rho_0+3h_1\rho_1)\rho_0M_0^{-1}+h_1^2(h_1\rho_1+3h_0\rho_0)\rho_1M_1^{-1});$$

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$$G_4 = -\frac{1}{6}(h_0^2(2P_2h_0\rho_0M_0^{-1} + 3h_1(\rho_0M_0^{-1} + \rho_1M_1^{-1})) + \\ + h_1^2(2h_1\rho_1M_1^{-1} + 3P_2h_0(\rho_0M_0^{-1} + \rho_1M_1^{-1})));$$

$$G_5 = \frac{1}{6}M_1^{-2}(h_0^2(P_2h_0 + 3h_1) + h_1^2(h_1 + 3P_2h_0)); \quad (6)$$

$$G_6 = \frac{1}{120}(h_0^5P_2\rho_0^2M_0^{-2}(10\rho_1M_1^{-1} + \rho_0M_0^{-1}) + h_1^5\rho_1M_1^{-1}(10\rho_0M_0^{-1} + \rho_1M_1^{-1}) + \\ + 5h_0h_1\rho_0\rho_1M_0^{-1}M_1^{-1}(h_0^3\rho_0M_0^{-1}(3 - 3D_0 - D_0^2) - h_1^3P_2\rho_1M_1^{-1}(3 - 3D_1 - D_1^2)));$$

$$G_7 = \frac{1}{120}(-13(h_0^5P_2\rho_0^2M_0^{-2} + h_1^5\rho_1^2M_1^{-2}) + 20(h_0^5P_2 + h_1^5)\rho_0\rho_1M_0^{-1}M_1^{-1} - \\ - 5h_0h_1(h_0^3\rho_0M_0^{-1}((3 - 3D_0 - D_0^2)\rho_0M_0^{-1} - (D_0 - 4)\rho_1M_1^{-1}) + \\ + h_1^3P_2\rho_1M_1^{-1}((3 - 3D_1 - D_1^2)\rho_1M_1^{-1} - (D_0 - 4)\rho_1M_1^{-1}\rho_0M_0^{-1})));$$

$$G_8 = \frac{1}{120}(23(h_0^5P_2\rho_0^2M_0^{-1} + h_1^5\rho_1^2M_1^{-2}) + 10(h_0^5P_2\rho_1M_1^{-1} + h_1^5\rho_0M_0^{-1}) + \\ + 5h_0h_1(h_0^3(\rho_1M_1^{-1} - (D_0 - 4)\rho_0M_0^{-1}) + h_1^4(\rho_0M_0^{-1} - (D_1 - 4)\rho_1M_1^{-1})));$$

$$G_9 = \frac{1}{120}(-24(h_0^5P_2\rho_0^2M_0^{-2} + h_1^5\rho_1^2M_1^{-2}) + 6(h_0^5P_2 + h_1^5)\rho_0\rho_1M_0^{-1}M_1^{-1} - \\ - 6h_0h_1(h_0^3\rho_0M_0^{-1}((1 - 3D_0 - D_0^2)\rho_0M_0^{-1} - (D_0 - 2)\rho_1M_1^{-1}) + \\ + h_1^3P_2\rho_1M_1^{-1}((3 - D_1 - D_1^2)\rho_1M_1^{-1} - (D_0 - 2)\rho_1M_1^{-1}\rho_0M_0^{-1})));$$

and

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$$F_2(x,y,t)=P_2(N_0^{-1}(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}-\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})+N_1^{-1}(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}-\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))+$$
$$+\frac{1}{2}(P_2h_1^2\rho_1M_1^{-1}(N_0^{-1}\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}-\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})-$$
$$-h_0^2\rho_0M_0^{-1}(N_1^{-1}\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}-\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))\frac{\partial^2}{\partial t^2}-$$
$$-\frac{1}{2}(P_2h_1^2(N_0^{-1}\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}-\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})-$$
$$-h_0^2(N_1^{-1}\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}-\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))\frac{\partial^2}{\partial x^2}.$$

Approximate equation (1) is simplified in special cases when solving specific vibration problems [28-31]. For example, operators (2) are greatly simplified when the Poisson's ratios of both components are constant, or when the thicknesses of both components are equal, and so on [32-35].

For example, if $h_0=h_1$ and $\nu_0=\nu_1$, operators in Q_j в (6) have the form:

$$Q_1=M_1^{-2}h_0^2(\rho_0+\rho_1)^2;$$

$$Q_2=-2M_1^{-2}h_0^2(2D_0(P_2+1)(\rho_0+\rho_1)+(P_2+1)(2\rho_0-D_0(\rho_0-\rho_1)));$$

$$Q_3=4(P_2-1)h_0^{\,2}D_0(3P_2+1);$$

$$Q_4=-\frac{1}{6}M_1^{-2}h_0^{\,4}(2-D_0)(\rho_0M_0^{-1}(3\rho_1^2+\rho_0(\rho_0+4\rho_1))+ \quad (7)$$
$$+\rho_1M_1^{-1}(3\rho_0^2+\rho_1(\rho_1+4\rho_0)));$$

$$Q_5=-\frac{1}{6}h_0^{\,4}(P_2\rho_0^2M_0^{-2}(4D_0(4-D_0)+P_2(8D_0(1-D_0)+5)+$$

$$+(P_2-1)(12-6D_0+D_0^2))+2\rho_0\rho_1 M_0^{-1}M_1^{-1}(2(6D_0+P_2^2(2+5D_0)+$$
$$+P_2(2+9D_0-D_0^2))+(P_2-1)P_2(2-3D_0+D_0^2)+D_0(1+D_0))+$$
$$+\rho_1^2 M_1^{-2}(8(1+D_0-D_0^2)+4P_2D_0(4-D_0)+(P_2-1)D_0(2-D_0)));$$

$$Q_6=\frac{1}{3}h_0^2(\rho_0 M_0^{-1}(4P_2D_0(2+5P_2-3D_0(P_2-1))+(P_2-1)(P_2(20-8D_0-13D_0^2)+$$

$$+6D_0(1-D_0)))+\rho_1 M_1^{-1}D_0(4(4+D_0)+4P_2(4+2P_2+5D_0)+$$
$$+17(P_2-1)(D_0+2P_2(1-D_0))));$$
$$Q_7=\frac{4}{3}h_0^4 D_0(D_0(4-15P_2-5P_0^2)+(P_2-1)(1-13P_2)); \quad (7)$$

The sixth order operator in equation (1) can also be represented as a product of second and fourth-order operators if the plate is elastic and the coefficients Q_j are related by

$$Q_2\cdot Q_4\cdot Q_7=Q_1\cdot Q_5\cdot Q_7+Q_3\cdot Q_4\cdot Q_6.$$

For a two-layer elastic plate with given parameters of its components, relation (7) gives a 10th order algebraic equation with respect to the ratio, while the sixth order operator in (1) can be represented as a product of two lower-order operators

$$\left(A_1\frac{\partial^2}{\partial t^2}+A_2\frac{\partial^2}{\partial x^2}\right)\cdot\left(A_3\frac{\partial^2}{\partial t^2}+A_4\frac{\partial^2}{\partial x^2}+A_5\frac{\partial^4}{\partial t^4}+A_1\frac{\partial^4}{\partial x^4}\right)(W)=0,$$

if the coefficients Q_j and A_3 are related by dependencies

$$Q_1=A_1A_2;\quad Q_2=A_1A_4+A_2A_3;\quad Q_3=A_2A_4;$$

$$Q_4=A_1A_5;\quad Q_5=A_2A_5;\quad Q_6=A_1A_6;\quad Q_7=A_2A_6;$$

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Despite the fact that equation (1) is approximate, it is rather complicated. Operators (2) contain all the parameters and operators that characterize both the mechanical and rheological properties of the material of a piecewise homogeneous plate and its geometric dimensions.

CONCLUSION

- The study of vibrations of piecewise-homogeneous plates in an exact three-dimensional formulation allows, without involving any hypotheses, to derive the general and based on them approximate equations for the vibrations of such plates.
- It is shown that the simplest approximate equation for the oscillation of a two-layer plate is the equation of the sixth order in terms of derivatives, which describes its longitudinal-transverse oscillation.
- For an elastic two-layer plate, the sixth-order operator decomposes into the product of the operators of the second - longitudinal and fourth - transverse oscillations, if the thicknesses of the plate components satisfy the derived equation containing the parameters of these components.
- Formulas were obtained for determining displacements and stresses through the desired functions at any point of a two-layer plate.

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