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Research Article

EQUATION OF 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” [1].

KEYWORDS

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

INTRODUCTION

The general equations of oscillation of piecewise homogeneous viscoelastic plates of constant thickness, described in [1], are complex in structure and contain derivatives of any order concerning x, y coordinates and time t, and, therefore, are not suitable for solving applied problems and performing engineering calculations [2-5].

To solve applied problems, instead of general equations, it is advisable to use approximate ones that include one or another finite order in derivatives [6-8].

The main part

The classical equations of transverse vibration of a plate contain derivatives of no higher than 4th order, and for piecewise homogeneous or two-layer plates, the simplest approximate equation of vibration is a sixth-order equation [9-12].

If in the operators (1.3.8) given in [1] we restrict ourselves to the first two terms, then from equation (1.3.11)

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

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

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

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

we obtain the approximate integral-differential equation

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

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

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

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$$
\begin{aligned}
Q_2 &= -2M_1^{-2}(2\left(h_0P_2D_0 + h_1D_1\right)\left(h_0\rho_0 + h_1\rho_1\right) + \\
&\quad + \left(P_2 - 1\right)(h_0\rho_0\left(h_0 + h_1\right) - (h_0^{\,2}D_0\rho_0 + h_1^{\,2}D_1\rho_1)));\\
Q_3 &= 4(P_2 - 1)(h_0^{\,2}P_2D_0 + h_1^{\,2}D_1 + h_1^{\,2}D_1 + 2h_0h_1P_2D_0);\\
Q_4 &= -\frac{1}{6}M_1^{-2}(h_0^{\,2}\rho_0M_0^{-1}(3h_1^{\,2}\rho_1^2 + h_0\rho_0(h_0\rho_0 + 4h_1\rho_1))(2 - D_0) + \\
&\quad + h_1^2\rho_1M_1^{-1}(3h_0^2\rho_0^2 + h_1\rho_1(h_1\rho_1 + 4h_0\rho_0))(2 - D_1));
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
Q_5 &= -\frac{1}{6}M_1^{-2}(h_0^{\,2}P_2\rho_0^2M_0^{-2}(2P_2(4D_0(1 - D_0) + (P_2 - 1)(4 + D_0^2)) - \\
&\quad - h_1^4\rho_1^2M_1^{-2}(2(4D_1^2 - 4D_1 - 1) - (P_2 - 1)D_1(2 - D_1)) + \\
&\quad + 6h_0^2h_1^2(\rho_0\rho_1M_0^{-1}M_1^{-1}(4(P_2^2D_0 + D_1) + (P_2 - 1)(2P_2(1 - D_0) - P_2D_1(2 - D_0) \\
&\quad + D_1(1 + D_0))) + +M_1^{-1}(\rho_0^2 + \rho_1^2)) + \\
&\quad + 2P_2h_0h_1(2\rho_0\rho_1M_0^{-1}M_1^{-1})(h_0^{\,2}(2 + 4D_0 - D_0^2) + h_1^2(2P_2 - P_2D_1 + 5D_1 - D_1^2)) + \\
&\quad + h_0^2h_1^2M_0^{-2}((P_2 - 1)(4 - 3D_0) + 2D_1(4 - D_0)) + 2h_1^2\rho_1^2M_1^{-2}D_0(4 - D_1));\\
Q_6 &= \frac{1}{3}M_1^{-2}(h_0^{\,2}P_2\rho_0M_0^{-1}(2P_2((P_2 - 1)(2 + 9D_0 - 3D_0^2)) - 2D_0(1 - 3P_2 + 4D_0)) + \\
&\quad + h_1^4\rho_1M_1^{-1}(4D_1(1 - 2D_1) - 4D_1 + (P_2 - 1)D_1(3 - D_1)) + \\
&\quad + 3h_0^2h_1^2((4P_2D_0(P_2(1 - D_1) - D_1) - (P_2 - 1)(2(P_2 - 1)D_1(1 - D_0) - \\
&\quad + P_2(2 - D_0 - 2D_0D_1)))\rho_0M_0^{-1} + (4D_1(1 + D_0 + P_2D_0) - (P_2 - 1)(6D_0D_1(P_2 - 1) - \\
&\quad - 6P_2D_0 + D_1))\rho_1M_1^{-1}) - 2h_0h_1P_2(\rho_0M_0^{-1}(2h_0^{\,2}((P_2 - 1)(D_0^2 - 2D_0 - 1) - \\
&\quad - 2D_1(1 + D_0)) - h_1^2(2(P_2 - 1) + D_1(P_2 + 3)))) - \\
&\quad - 4\rho_1M_1^{-1}(h_0^{\,2} + h_1^{\,2})(2(P_2 - 1)(1 - D_1) + P_2D_1 + (1 + D_1))))));\\
Q_7 &= \frac{2}{3}(h_0^4P_2D_0(4D_0 - 5(P_2 - 1) + h_1^4D_1(4D_1 - (P_2 - 1)) - \\
&\quad + 3h_0^2h_1^2(8P_2D_0D_1 - (P_2 - 1)((2(P_2 + 1)D_0D_1 - 3P_2D_0 - D_1(1 - D_1))) - \\
&\quad - 4h_0h_1P_2D_0(h_0^{\,2}(P_2 - 1) + 2D_1) + h_1^2(2(P_2 - 1) + (P_2 + 1)D_0)));
\end{aligned} \tag{3}
$$

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$$F_1(x,y,t)=M_1^{-2}\frac{\partial^2}{\partial t^2}((h_0\rho_0+h_1\rho_1)(f_z^{(0)}-f_z^{(1)}))+$$
$$+(h_0+h_1)(h_1\rho_1(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})+h_0\rho_0(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))+$$
$$+(h_0^2D_0\rho_0+h_1^2D_1\rho_1)((\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})-(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))- \quad (4)$$
$$-2\Delta(2M_1^{-2}((h_0P_2D_0+h_1D_1)(M_0f_z^{(0)}-M_1f_z^{(1)}))+$$
$$+2P_2h_0h_1)(D_0M_0^{-1}(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})+D_1M_1^{-1}(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))+$$
$$+M_1^{-1}(h_0^2P_2D_0+h_1^2D_1)(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2})+(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2})).$$

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 dependencies are satisfied

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

and equation (1) goes into the equation

$$((1-C_0)^2\lambda_{10}^{(1)}+(1+C_0)^2\Delta)((\lambda_{20}^{(1)}+\Delta)+$$
$$+\frac{h_0^2}{6}((3D_0(\lambda_{20}^{(1)}+\Delta)^2)+4D_0\lambda_{20}^{(1)}\Delta)+4\lambda_{10}^{(1)}(\lambda_{20}^{(1)}+\Delta)))(W)=$$
$$=\frac{1}{h_0}(M_0^{-2}\frac{\partial^2}{\partial t^2}((f_z)+h_0(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(0)}}{\partial y^2}))- \quad (5)$$
$$-4D_0M_0^{-1}\Delta((f_z)+h_0\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2}+\frac{\partial^2 f_{yz}^{(1)}}{\partial y^2})))$$

Here on the left is the product of two operators: the first describes the process of longitudinal oscillation, and the second describes the transverse vibration.

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

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

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

$$G_1=M_1^{-1}(h_0\rho_0+h_1\rho_1)\ ;$$
$$G_2=-(h_0P_2+h_1)\ ;$$
$$G_3=\frac{1}{6}M_1^{-2}(h_0^2(h_0\rho_0+3h_1\rho_1)\rho_0M_0^{-1}+h_1^2(h_1\rho_1+3h_0\rho_0)\rho_1M_1^{-1});$$
$$G_4=-\frac{1}{6}(h_0{}^2(2P_2h_0\rho_0M_0^{-1}+3h_1(\rho_0M_0^{-1}+\rho_1M_1^{-1}))+ \\ +h_1^2(2h_1\rho_1M_1^{-1}+3P_2h_0(\rho_0M_0^{-1}+\rho_1M_1^{-1})));$$
$$G_5=\frac{1}{6}M_1^{-2}(h_0^2(P_2h_0+3h_1)+h_1^2(h_1+3P_2h_0)); \quad (7)$$
$$G_6=\frac{1}{120}(h_0^5P_2\rho_0^2M_0^{-2}(10\rho_1M_1^{-1}+\rho_0M_0^{-1})+h_1^5\rho_1M_1^{-1}(10\rho_0M_0^{-1}+\rho_1M_1^{-1})+ \\ +5h_0h_1\rho_0\rho_1M_0^{-1}M_1^{-1}(h_0^3\rho_0M_0^{-1}(3-3D_0-D_0^2)-h_1^3P_2\rho_1M_1^{-1}(3-3D_1-D_1^2)));$$
$$G_7=\frac{1}{120}(-13(h_0^5P_2\rho_0^2M_0^{-2}+h_1^5\rho_1^2M_1^{-2})+20(h_0^5P_2+h_1^5)\rho_0\rho_1M_0^{-1}M_1^{-1}- \\ -5h_0h_1(h_0^3\rho_0M_0^{-1}((3-3D_0-D_0^2)\rho_0M_0^{-1}-(D_0-4)\rho_1M_1^{-1})+ \\ +h_1^3P_2\rho_1M_1^{-1}((3-3D_1-D_1^2)\rho_1M_1^{-1}-(D_0-4)\rho_1M_1^{-1}\rho_0M_0^{-1})));$$
$$G_8=\frac{1}{120}(23(h_0^5P_2\rho_0^2M_0^{-1}+h_1^5\rho_1^2M_1^{-2})+10(h_0^5P_2\rho_1M_1^{-1}+h_1^5\rho_0M_0^{-1})+ \\ +5h_0h_1(h_0^3(\rho_1M_1^{-1}-(D_0-4)\rho_0M_0^{-1})+h_1^4(\rho_0M_0^{-1}-(D_1-4)\rho_1M_1^{-1})));$$
$$G_9=\frac{1}{120}(-24(h_0^5P_2\rho_0^2M_0^{-2}+h_1^5\rho_1^2M_1^{-2})+6(h_0^5P_2+h_1^5)\rho_0\rho_1M_0^{-1}M_1^{-1}- \\ -6h_0h_1(h_0^3\rho_0M_0^{-1}((1-3D_0-D_0^2)\rho_0M_0^{-1}-(D_0-2)\rho_1M_1^{-1})+ \\ +h_1^3P_2\rho_1M_1^{-1}((3-D_1-D_1^2)\rho_1M_1^{-1}-(D_0-2)\rho_1M_1^{-1}\rho_0M_0^{-1})));$$

and

$$F_2(x,y,t) = P_2(N_0^{-1}(\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2} - \frac{\partial^2 f_{yz}^{(0)}}{\partial y^2}) + N_1^{-1}(\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2} - \frac{\partial^2 f_{yz}^{(1)}}{\partial y^2})) +$$
$$+\frac{1}{2}(P_2 h_1^2 \rho_1 M_1^{-1}(N_0^{-1}\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2} - \frac{\partial^2 f_{yz}^{(0)}}{\partial y^2}) -$$
$$-h_0^2 \rho_0 M_0^{-1}(N_1^{-1}\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2} - \frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))\frac{\partial^2}{\partial t^2} - \qquad (8)$$
$$-\frac{1}{2}(P_2 h_1^2 (N_0^{-1}\frac{\partial^2 f_{xz}^{(0)}}{\partial x^2} - \frac{\partial^2 f_{yz}^{(0)}}{\partial y^2}) -$$
$$-h_0^2 (N_1^{-1}\frac{\partial^2 f_{xz}^{(1)}}{\partial x^2} - \frac{\partial^2 f_{yz}^{(1)}}{\partial y^2}))\frac{\partial^2}{\partial x^2}.$$

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

Approximate equation (1) is simplified in particular cases when solving specific oscillation problems. For example, operators (2) are greatly simplified when the Poisson ratios of both components are constant, or when the thicknesses of both components are equal, and so on.

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

$$Q_1 = M_1^{-2} h_0^2 \left(\rho_0 + \rho_1\right)^2;$$
$$Q_2 = -2M_1^{-2} h_0^2 (2D_0(P_2+1)(\rho_0+\rho_1) + (P_2+1)(2\rho_0 - D_0(\rho_0 - \rho_1)));$$
$$Q_3 = 4(P_2-1)h_0^{\,2} D_0(3P_2+1);$$
$$Q_4 = -\frac{1}{6} M_1^{-2} h_0^{\,4}(2-D_0)(\rho_0 M_0^{-1}(3\rho_1^2 + \rho_0(\rho_0+4\rho_1)) +$$
$$+\rho_1 M_1^{-1}(3\rho_0^2 + \rho_1(\rho_1+4\rho_0))); \qquad (9)$$
$$Q_5 = -\frac{1}{6} h_0^{\,4}(P_2\rho_0^2 M_0^{-2}(4D_0(4-D_0) + P_2(8D_0(1-D_0)+5) +$$
$$+(P_2-1)(12-6D_0+D_0^2)) + 2\rho_0\rho_1 M_0^{-1} M_1^{-1}(2(6D_0 + P_2^2(2+5D_0) +$$
$$+P_2(2+9D_0-D_0^2)) + (P_2-1)P_2(2-3D_0+D_0^2) + D_0(1+D_0)) +$$
$$+\rho_1^2 M_1^{-2}(8(1+D_0-D_0^2) + 4P_2 D_0(4-D_0) + (P_2-1)D_0(2-D_0)));$$

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$$Q_6 = \frac{1}{3} h_0^{\,2} (\rho_0 M_0^{-1} (4P_2 D_0 (2 + 5P_2 - 3D_0 (P_2 - 1)) + (P_2 - 1)(P_2 (20 - 8D_0 - 13D_0^2) +$$
$$+ 6D_0 (1 - D_0))) + \rho_1 M_1^{-1} D_0 (4(4 + D_0) + 4P_2 (4 + 2P_2 + 5D_0) +$$
$$+ 17(P_2 - 1)(D_0 + 2P_2 (1 - D_0))));$$
$$Q_7 = \frac{4}{3} h_0^{\,4} D_0 (D_0 (4 - 15P_2 - 5P_0^2) + (P_2 - 1)(1 - 13P_2)); \qquad (10)$$

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

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

For a two-layer elastic plate with given parameters of its components, relation (7) gives a 10th-order algebraic equation concerning the relation h_2 / h_1 h_2/h_1, the sixth-order operator in (1) can be represented as the 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 Q_2 and A_j A_3 linked by dependencies

$$Q_1 = A_1 A_2;$$
$$Q_2 = A_1 A_4 + A_2 A_3;$$
$$Q_3 = A_2 A_4;$$
$$Q_4 = A_1 A_5;$$
$$Q_5 = A_2 A_5;$$
$$Q_6 = A_1 A_6;$$
$$Q_7 = A_2 A_6;$$

Conclusions

1. The study of vibrations of piecewise-homogeneous plates in an accurate three-dimensional formulation allows us to derive the general and approximate equations of vibration of such plates based on them without using any hypotheses.

2. It is shown that the simplest approximate equation of vibration of a two-layer plate is a sixth-order equation with respect to derivatives describing its longitudinal-transverse vibration.

3. For an elastic two-layer plate, the sixth-order operator splits into the product of the second-longitudinal and fourth-order transverse-wave operators if the thicknesses of the plate components satisfy the derived equation containing the parameters of these components.

4. Formulas are obtained for determining displacements and stresses through the sought-for functions at any point of a two-layer plate.

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