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A System of Integro-Differential Equations of a Viscoelastic Shell, Taking into Account the Temperature Field

Akbarov Ummatali Yigitalievich,[1]

[1] Candidate of Physical and Mathematical Sciences, Associate Professor, Kokand State Pedagogical Institute

E-mail: akbarov.ummatali1961@gmail.com

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***Corresponding author:**
Akbarov Ummatali Yigitalievich [1]
akbarov.ummatali1961@gmail.com

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Abstract

In this paper, we present a system of integro-differential equations for coupled dynamic problems of a viscoelastic shell located in a temperature field and their special cases.

Keywords: Equation, integro-differential equation, mathematical model, viscoelastic, orthotropic shell, temperature, deformation, stress, elastic modul, integral operator

Introduction

Materials with a nonlinear deformation pattern, for example, composites, alloys and some types of metals are widely used in various fields: construction, aircraft engineering, mechanical engineering, etc. Therefore, the study of dynamic problems of structures taking into account geometric nonlinearity and taking into account the temperature field is an urgent problem.

High rates of construction, the creation of unique structures and structures, the need to fulfill very complex industrial orders require further development of the theory of calculation of structures such as rod, plate and shell.

In this regard, the correct consideration of material properties such as plasticity, viscoelasticity, heterogeneity, anisotropy, nonlinearity, etc. is of great theoretical and practical importance, guarantees the approximation of theory, design calculation to actual conditions, ensures reliability and durability of structures at the lowest cost of materials.

The theory of viscoelasticity has been widely used in the calculations of elements of thin-walled structures such as rod, plate and shell. At the same time, it should be borne in mind that time accounting is mandatory when solving almost any problem of calculating thin-walled structures.

Classical works on the theory of vibrations of thin-walled structures, vibrations and stability are covered in [1-7].

In [8-11], the mathematical foundations of the theory of viscoelasticity, the formulation of various dynamic problems of plates and shells, methods for solving nonlinear dynamic problems of the theory of viscoelasticity with and without taking into account temperature are described.

A mathematical model and formulation of dynamic problems of a viscoelastic orthotropic shell are considered, taking into account the interconnectedness of temperature and strain fields.

We proceed to derive the equation of vibration of a viscoelastic shell.

Materials and Methods

Let the shell be nonuniform ongpeta in thickness and in the median surface up to a temperature $T(x, y, z, t)$ varying with time. Let's direct the axis z along the normal to the median surface in the direction of the center of curvature, and choose the origin at the point of the median surface. Ox и Oy Let the axes and coincide with the directions of the lines of principal curvatures of the shell. Denote the thickness of the shell by h, and its dimensions along the axes Ox and Oy - by a and b.

The temperature dependence T with the components of deformations l_x, l_y, l_{xy} and stresses $\sigma_x, \sigma_y, \sigma_{xy}$ in the case of a flat stressed state has the form

$$\sigma_x = \frac{E_1}{1-\vartheta_1\vartheta_2}[(1-R^*_{11})l_x + \vartheta_2(1-R^*_{12})l_y - (a_1 + a_2\vartheta_2)(1-R^*_{13})T];$$

$$\sigma_y = \frac{E_2}{1-\vartheta_1\vartheta_2}[(1-R^*_{22})l_y + \vartheta_1(1-R^*_{21})l_x - (a_2 + a_1\vartheta_2)(1-R^*_{23})T];$$

$$\tau_{xy} = G(1-R^*_{33})l_{xy}$$

where E_1, E_2 - the elastic modulus of the material in the direction of the axes Ox and Oy, respectively; ϑ_1 - the coefficient of transverse compression in the direction Oy of tension in the direction Ox of tension in the direction Oy; $a_1, a_2 -$ coefficients of linear expansion in the direction of the axes Ox and Oy, respectively; between the characteristics $E_1, E_2, \vartheta_1, \vartheta_2$ there is a dependence $E_1\vartheta_2 = E_2\vartheta_1$; R^*_{ij} -integral operators with relaxation kernels $R_{ij}(t)$;

$$R^*_{ij}\,\varphi = \int_0^t R_{ij}(t-\tau)\varphi(\tau)d\tau, \quad i,\ j = 1,2,3.$$

For the strain component and changes in the curvature of the median surface of the shell and displacements of its median layer, the following relations take place [1-4];

$$\varepsilon_x = \frac{\partial U}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial W}{\partial x}\right)^2 - \left(\frac{\partial W_0}{\partial x}\right)^2\right] - k_1 W;$$

$$\varepsilon_y = \frac{\partial V}{\partial y} + \frac{1}{2}\left[\left(\frac{\partial W}{\partial y}\right)^2 - \left(\frac{\partial W_0}{\partial y}\right)^2\right] - k_2 W;$$

$$\gamma_{xy} = \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} + \frac{\partial W}{\partial x}\frac{\partial W}{\partial y} - \frac{\partial W_0}{\partial x}\frac{\partial W_0}{\partial y};$$

$$\chi_x = \frac{\partial^2 U}{\partial x^2}, \qquad \chi_y = \frac{\partial^2 W}{\partial y^2}, \qquad \chi_x = \frac{\partial^2 W}{\partial x \partial y},$$

where $W_0 = W(x,y)$ is the initial deflection.

Deformations l_x, l_y, l_{xy} for a layer that is separated from the median layer by a distance z, according to the hypothesis of direct normals, can be written

$$l_x = \varepsilon_x + z\chi_x, \qquad l_y = \varepsilon_y + z\chi_y, \qquad l_{xy} = \gamma_{xy} + 2z\chi_{xy}$$

Results and Discussion

Calculate N_x, N_y - normal, N_{xy} - tangential forces, M_x, M_y - bending moments. H -torque:

$$N_x = \int_{-h/2}^{h/2} \sigma_x dz = \frac{hE_1}{1-\vartheta_1\vartheta_2}\left\{(1-R^*_{11})\left(\frac{\partial U}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial W}{\partial x}\right)^2 - \left(\frac{\partial W_0}{\partial x}\right)^2\right] - k_1 W\right) + \right.$$

$$+\vartheta_2(1-R^*_{22})\left(\frac{\partial V}{\partial y} + \frac{1}{2}\left[\left(\frac{\partial W}{\partial y}\right)^2 - \left(\frac{\partial W_0}{\partial y}\right)^2\right] - k_2 W\right) -$$

$$\left. -(a_1 + \vartheta_2 a_2)(1-R^*_{13})T_N\right\};$$

$$N_y = \int_{-h/2}^{h/2} \sigma_y dz = \frac{hE_2}{1-\vartheta_1\vartheta_2}\left\{(1-R^*_{22})\left(\frac{\partial V}{\partial y} + \frac{1}{2}\left[\left(\frac{\partial W}{\partial y}\right)^2 - \left(\frac{\partial W_0}{\partial y}\right)^2\right] - k_2 W\right) + \right.$$

$$+\vartheta_1(1-R^*_{11})\left(\frac{\partial U}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial W}{\partial x}\right)^2 - \left(\frac{\partial W_0}{\partial x}\right)^2\right] - k_1 W\right) -$$

$$\left. -(a_2 + \vartheta_1 a_1)(1-R^*_{23})T_N\right\};$$

$$N_{xy} = \int_{-h/2}^{h/2} \tau_{xy} dz = Gh(1-R^*_{33})\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} + \frac{\partial W}{\partial x}\frac{\partial W}{\partial y} - \frac{\partial W_0}{\partial x}\frac{\partial W_0}{\partial y}\right):$$

$$M_x = \int_{-h/2}^{h/2} \sigma_x z dz = -\frac{E_1 h^3}{12(1-\vartheta_1\vartheta_2)}\left[(1-R^*_{11})\frac{\partial^2 W}{\partial x^2} + \vartheta_2(1-R^*_{22})\frac{\partial^2 W}{\partial y^2}\right] -$$

$$-\frac{E_1 h^3}{12(1-\vartheta_1\vartheta_2)}(a_1+\vartheta_2 a_2)(1-R^*_{11})T_M;$$

$$M_y = \int_{-h/2}^{h/2} \sigma_x z dz = -\frac{E_2 h^3}{12(1-\vartheta_1\vartheta_2)}\left[(1-R^*_{22})\frac{\partial^2 W}{\partial y} + \vartheta_1(1-R^*_{11})\frac{\partial^2 W}{\partial x^2}\right] -$$

$$-\frac{E_2 h^2}{1-\vartheta_1\vartheta_2}(a_2+\vartheta_1 a_1)(1-R^*_{22})T_M;$$

$$H = -\frac{Gh^3}{6}(1-R^*_{33})\frac{\partial^2 W}{\partial x \partial y},$$

and substituting them into the equations of motion [3-5, 8]

$$\frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} + p_x - ph\frac{\partial^2 U}{\partial t^2} = 0; \quad (1)$$

$$\frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} + p_x - ph\frac{\partial^2 V}{\partial t^2} = 0; \quad (2)$$

$$\frac{\partial^2 M_2}{\partial x^2} + 2\frac{\partial^2 H}{\partial x \partial y} + \frac{\partial^2 M_y}{\partial y^2} + k_1 N_x + k_2 N_y + \frac{\partial}{\partial x}\left(N_x\frac{\partial W}{\partial x} + N_{xy}\frac{\partial W}{\partial y}\right) +$$

$$\frac{\partial}{\partial y}\left(N_{xy}\frac{\partial W}{\partial x} + N_y\frac{\partial W}{\partial y}\right) + q - ph\frac{\partial^2 W}{dt^2} = 0 \quad (3)$$

we obtainthe following system of nonlinear integro-differential equations:

$$\frac{E_1}{1-\vartheta_1\vartheta_2}\left\{(1-R^*_{11})\left[\frac{\partial^2 U}{\partial x^2} + \left(\frac{\partial W}{\partial x}\frac{\partial^2 W}{\partial x^2} - \frac{\partial W_0}{\partial x}\frac{\partial^2 W_0}{\partial x^2}\right) - k_1\frac{\partial W}{\partial x}\right] +\right.$$

$$\left. +\vartheta_2(1-R^*_{22})\left[\frac{\partial^2 V}{\partial x \partial y} + \left(\frac{\partial W}{\partial y}\frac{\partial^2 W}{\partial x \partial y} - \frac{\partial W_0}{\partial y}\frac{\partial^2 W_0}{\partial x \partial y}\right) - k_2\frac{\partial W}{\partial x}\right]\right\} +$$

$$+G(1-R^*_{11})\left(\frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 V}{\partial x \partial y} + \frac{\partial^2 W}{\partial x \partial y}\frac{\partial W}{\partial y} + \frac{\partial W}{\partial x}\frac{\partial^2 W}{\partial y^2} - \frac{\partial^2 W_0}{\partial x \partial y}\frac{\partial W_0}{\partial y} -\right.$$

$$\left. -\frac{\partial^2 W_0}{\partial x}\frac{\partial^2 W_0}{\partial y^2}\right) - \frac{E_1}{1-\vartheta_1\vartheta_2}(a_1+a_2\vartheta_2)(1-R^*_{13})\frac{\partial T_N}{\partial x} + \frac{p_x}{h} - p\frac{\partial^2 U}{\partial t^2} = 0;$$

$$\frac{E_2}{1-\vartheta_1\vartheta_2}\left\{(1-R^*_{22})\left[\frac{\partial^2 V}{\partial y^2} + \left(\frac{\partial W}{\partial y}\frac{\partial^2 W}{\partial y^2} - \frac{\partial W_0}{\partial y}\frac{\partial^2 W_0}{\partial y^2}\right) - k_2\frac{\partial W}{\partial y}\right] +\right.$$

$$\left. +\vartheta_1(1-R^*_{11})\left[\frac{\partial^2 U}{\partial x \partial y} + \left(\frac{\partial W}{\partial x}\frac{\partial^2 W}{\partial x \partial y} - \frac{\partial W_0}{\partial x}\frac{\partial^2 W_0}{\partial x \partial y}\right) - k_1\frac{\partial W}{\partial y}\right]\right\} +$$

$$+G(1-R^*_{11})\left(\frac{\partial^2 U}{\partial x \partial y} + \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 W}{\partial x^2}\frac{\partial W}{\partial y} + \frac{\partial W}{\partial x}\frac{\partial^2 W}{\partial x \partial y} - \frac{\partial^2 W_0}{\partial x^2}\frac{\partial W_0}{\partial y} -\right.$$

$$-\frac{\partial W_0}{\partial x}\frac{\partial^2 W_0}{\partial x\partial y}\Bigg)-\frac{E_2}{1-\vartheta_1\vartheta_2}(a_2+a_1\vartheta_1)(1-R^*_{23})\frac{\partial T_N}{\partial y}+\frac{p_y}{h}-p\frac{\partial^2 V}{\partial t^2}=0;$$

$$\frac{1}{h}\Bigg\{D_1(1-R^*_{11})\frac{\partial^4 W}{\partial x^4}+[D_1\vartheta_2(1-R^*_{22})+D_2\vartheta_1(1-R^*_{11})+2D_G(1-$$

$$-R^*_{33})]\frac{\partial^4 W}{\partial x^2\partial y^2}+D_2(1-R^*_{22})\frac{\partial^4 W}{\partial y^4}\Bigg\}=\frac{\partial}{\partial x}\Bigg\{B_{11}\Bigg[(1-R^*_{11})\Bigg(\frac{\partial V}{\partial y}+$$

$$+\frac{1}{2}\Bigg[\Bigg(\frac{\partial W}{\partial x}\Bigg)^2-\Bigg(\frac{\partial W_0}{\partial x}\Bigg)^2\Bigg]-k_1W\Bigg)+\vartheta_2(1-R^*_{22})\Bigg(\frac{\partial V}{\partial y}+$$

$$+\frac{1}{2}\Bigg[\Bigg(\frac{\partial W}{\partial y}\Bigg)^2-\Bigg(\frac{\partial W_0}{\partial y}\Bigg)^2\Bigg]-k_2W)\Bigg]\frac{\partial W}{\partial x}+G(1-R^*_{33})\Bigg(\frac{\partial U}{\partial y}+$$

$$+\frac{\partial V}{\partial x}+\frac{\partial W}{\partial x}\frac{\partial W}{\partial y}-\frac{\partial W_0}{\partial x}\frac{\partial W_0}{\partial y}\Bigg)\frac{\partial W}{\partial y}\Bigg\}+\frac{\partial}{\partial y}\Bigg\{B_{22}\Bigg[(1-R^*_{22})\Bigg(\frac{\partial V}{\partial y}+$$

$$+\frac{1}{2}\Bigg[\Bigg(\frac{\partial W}{\partial y}\Bigg)^2-\Bigg(\frac{\partial W_0}{\partial y}\Bigg)^2\Bigg]-k_2W\Bigg)+\vartheta_1(1-R^*_{11})\Bigg(\frac{\partial U}{\partial x}+\frac{1}{2}\Bigg[\Bigg(\frac{\partial W}{\partial x}\Bigg)^2-$$

$$-\Bigg(\frac{\partial W_0}{\partial x}\Bigg)^2\Bigg]-k_1W\Bigg)\Bigg]\frac{\partial W}{\partial y}+G(1-R^*_{33})\Bigg(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}+\frac{\partial W}{\partial x}\frac{\partial W}{\partial y}-$$

$$-\frac{\partial W_0}{\partial x}\frac{\partial W_0}{\partial y}\Bigg)\frac{\partial W}{\partial x}\Bigg\}-B_{11}(a_1+\vartheta_2a_2)\frac{\partial}{\partial x}\Bigg[\frac{\partial W}{\partial x}(1-R^*_{11})T_N\Bigg]-$$

$$-B_{22}(a_2+\vartheta_1a_1)\frac{\partial}{\partial y}\Bigg[\frac{\partial W}{\partial y}(1-R^*_{23})T_N\Bigg]-B_{11}h(a_1+\vartheta_2a_2)(1-R^*_{11}\Bigg)\times$$

$$\times\frac{\partial^2 T_M}{\partial x^2}-B_{22}h(a_2+\vartheta_1a_1)(1-R^*_{22})\frac{\partial^2 T_M}{\partial y^2}+\frac{q}{h}-p\frac{\partial^2 W}{\partial t^2},\qquad(4)$$

where

$$B_{11}=E_1/(1-\vartheta_1\vartheta_2);\quad B_{22}=E_2/(1-\vartheta_1\vartheta_2);\quad B_{12}=B_{21}=\vartheta_1B_{22}=\vartheta_2B_{11};$$

$$T_N=\frac{1}{h}\int_{-h/2}^{h/2}T(x,y,z,t)dz,\quad T_M=\frac{1}{h^2}\int_{-h/2}^{h/2}T(x,y,z,t)zdz,$$

$$D_1=\frac{B_{11}h^3}{12},\quad D_2=\frac{B_{22}h^3}{12},\quad D_G=\frac{Gh^3}{6},$$

The resulting system is fairlygeneral.

Let us turn to some special cases.

1. If the dynamic process can be considered without taking into account the inertial loadscorresponding to the displacements U and V, then equations (1)-(3) are simplified. To justify the accepted assumption, you can use the obtained result of the work [9]. The system of

equations obtained in this case will not be given here.

2. For $k_1 = 0,\ k_2 = 1/R$, where R is the radius of curvature of the median surface, we obtain a system of equations for a circular cylindrical shell.

3. When $k_1 = k_2 = 1/R,$ we have equations for the spherical shell.

Starting to work in the same way as in [5-7, 9, 11] to determine the temperature distribution, we obtain the associated heat conduction equation for orthotropic solids in the form

$$a_1\frac{\partial^2 T}{\partial x^2}+a_2\frac{\partial^2 T}{\partial y^2}+a_3\frac{\partial^2 T}{\partial z^2}-pc_T\frac{\partial T}{\partial t}=\frac{a_1+a_2\vartheta_2}{1-\vartheta_1\vartheta_2}\frac{\partial\sigma_x}{\partial t}+\frac{a_2+a_1\vartheta_1}{1-\vartheta_1\vartheta_2}\frac{\partial\sigma_y}{\partial t},$$

where a_1, a_2, a_3 are the coefficients of thermal conductivity in three mutually perpendicular directions, c_T and is the specific heat capacity.

If the right-hand side of this equation is written with respect to displacement, it takes the form

$$a_1\frac{\partial^2 T}{\partial x^2}+a_2\frac{\partial^2 T}{\partial y^2}+a_3\frac{\partial^2 T}{\partial z^2}-pc_T\frac{\partial T}{\partial t}=\frac{E_1(a_1+a_2\vartheta_2)}{(1-\vartheta_1\vartheta_2)^2}\frac{\partial}{\partial t}\{(1-R^*_{11})\times$$

$$\times\left(\frac{\partial U}{\partial x}+\frac{1}{2}\left[\left(\frac{\partial W}{\partial x}\right)^2-\left(\frac{\partial W_0}{\partial x}\right)^2\right]-k_1W\right)+\vartheta_2(1-R^*_{22})\left(\frac{\partial V}{\partial y}+\right.$$

$$\left.+\frac{1}{2}\left[\left(\frac{\partial W}{\partial y}\right)^2-\left(\frac{\partial W_0}{\partial y}\right)^2\right]-k_2W\right)-(a_1+\vartheta_2a_2)(1-R^*_{13})T\}+$$

$$+\frac{E_2(a_2+a_1\vartheta_1)}{(1-\vartheta_1\vartheta_2)^2}\frac{\partial}{\partial t}\{(1-R^*_{22})\left(\frac{\partial V}{\partial y}+\frac{1}{2}\left[\left(\frac{\partial W}{\partial y}\right)^2-\left(\frac{\partial W_0}{\partial y}\right)^2\right]-k_2W\right)+$$

$$+\vartheta_1(1-R^*_{11})\left(\frac{\partial U}{\partial x}+\frac{1}{2}\left[\left(\frac{\partial W}{\partial x}\right)^2-\left(\frac{\partial W_0}{\partial x}\right)^2\right]-k_1W\right)-$$

$$-(a_2+\vartheta_1a_1)(1-R^*_{22})T\}.$$

The obtained systems of equations (4) and (5) are interrelated.

Conclusion

Thus, this system of equations describes the deformation of a viscoelastic оротогorthotropicshell resulting from non-stationary mechanical and thermal effects, as well as the reverse effect – a change in its temperature field due to deformation. Such a problem is called the coupled dynamic thermoviscoelasticity problem.

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