

Smart Innovation, Systems and Technologies 220

Nikita Voinov
Tobias Schreck
Sanowar Khan *Editors*



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TELECCON 2019

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Smart Innovation, Systems and Technologies

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Nikita Voinov · Tobias Schreck · Sanowar Khan
Editors

Proceedings of International
Scientific Conference
on Telecommunications,
Computing and Control

TELECCON 2019

 Springer

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Preface

This volume contains the papers that were presented at the First International Scientific Conference on Telecommunications, Computing and Control (TELECCON-2019) organized by Peter the Great St. Petersburg Polytechnic University during November 18–19, 2019. It provided a great platform for researchers from across the world to report, deliberate, and review the latest progress in the cutting-edge research pertaining to telecommunications, signal processing, artificial intelligence, intelligent control systems, modeling, and simulation.

We would like to express our appreciation to the members of the program committee for their support and cooperation in this publication. We are also thankful to the team from Springer for providing a meticulous service for the timely production of this volume.

Special thanks to all the guests who have honored us in their presence at the conference. Our thanks are due to all session chairs, track managers, and reviewers for their excellent support. Last but not least, our special thanks go to all the authors who submitted papers and all the attendees for their contributions and fruitful discussions that made this conference a great success.

St. Petersburg, Russia
Graz, Austria
London, UK

Nikita Voinov
Tobias Schreck
Sanowar Khan

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About the Editors

Nikita Voinov has been Associate Professor of the Higher School of Software Engineering at the Institute of Computer Science and Technology of Peter the Great St. Petersburg Polytechnic University since 2012, becoming Deputy Director for Science and Research in 2018. Dr. Voinov’s research interests run a gamut of topics including the technologies for developing mobile applications, information management and data storage, cloud infrastructure and services, and data science and analysis of big data. The current research projects he is participating in are “Technologies and toolset for reliable control of production areas of Internet of Things” (joint project with the Indian Institute of Technology Bombay, Mumbai, India) and “Methods and technologies for verification and development of software for modeling and calculations using HPC platform with extramassive parallelism.

Tobias Schreck has been Professor at the Institute of Computer Graphics and Knowledge Visualization at the Faculty for Computer Science and Biomedical Engineering of Graz University of Technology since 2015. His research interests concern visual data analysis and applied 3D object retrieval. Professor Schreck has acted as a principal investigator in several funded research projects, describing how large collections of data can be visually explored and analyzed for data understanding and decision-making. Another focus of research is how users can interactively search for visual patterns in data, assisted by similarity functions, visual quality measures, and novel search interfaces, including approaches based on user sketching and eye tracking, and how to interactively visualize and steer machine learning approaches like clustering and regression analysis by users, supporting effective and scalable data exploration. Potential applications include, among others, data exploration for engineering and industrial applications, in research data repositories, and digital libraries. Professor Schreck has served as a program co-chair for the IEEE Conference on Visual Analytics Science and Technology in 2017 and 2018, and is currently Associate Editor for IEEE Transactions on Visualization and Computer Graphics.

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computational electromagnetics, magnetic shape memory smart materials, finite element modeling and numerical methods, and forward and inverse problems in tomographic imaging. Professor Khan is Honorary Professor of SPPU, Fellow of the Institution of Engineering and Technology, the Institute of Measurement and Control, and a member of the IEEE, IEEE Magnetics, Engineering in Medicine and Biology, and Instrumentation and Measurement societies. He is also a founder member of the International Compumag Society and a member of the Journal Editorial Committee of Measurement and Control. Professor Khan is Editor-in-Chief of the journal *Sensor Review*. He has been Associate Editor of the journal *Measurement*, and the *International Journal on Measurement Technologies and Instrumentation Engineering*.

Parametric Oscillations of Viscoelastic Orthotropic Rectangular Plates of Variable Thickness



Rustamkhan Abdikarimov , Bakhodir Normuminov ,
Dadakhon Khodzhaev , and Davron Yulchiyev 

Abstract A mathematical model of the problem of parametric vibrations of viscoelastic rectangular orthotropic plates of variable thickness under periodic load is given in the paper on the basis of the Kirchhoff–Love hypothesis in a geometrically nonlinear statement. The mathematical model of this problem is constructed taking into account the propagation of elastic waves. Using the Bubnov–Galerkin method, based on a polynomial approximation of deflection and displacements, the problem is reduced to solving systems of nonlinear integro-differential equations with variable coefficients. The effects of viscoelastic properties of the material and changes in thickness on the oscillation process are studied.

Keywords Rectangular plate · Variable thickness · Viscoelasticity · Orthotropy · Parametric vibrations · Mathematical model · Relaxation kernel · Integro-differential equation · Numerical method

1 Introduction

Plates and shells of variable thickness are widely introduced in various fields of technology. This is primarily due to the requirements for strength, durability, and design of thin-walled elements of modern structures. Along with thin-walled structural elements from traditional metal materials, structures made of composite materials are widely used; this leads to the need to consider structures with homogeneous and inhomogeneous material properties. The study of problems for plates and shells of variable thickness is a very difficult task and sometimes faces insurmountable difficulties. On the one hand, this is connected with the solution of rather cumbersome equations, which are obtained in mathematical modeling, to reflect the real

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mechanical essence of the process of this problem. And on the other hand, it is connected with certain computational difficulties, i.e., the lack of suitable universal numerical methods for solving the obtained equations, and as a result, unified computational algorithms. The widespread use of personal computers and software products for solving similar problems of the theory of plates and shells of variable rigidity contributes to the increasing use of numerical analysis methods.

A number of papers [1, 2] are devoted to studying the behavior of plates and shells of constant thickness under dynamic loads in an elastic statement, and there a detailed review of the results of these studies can be found.

In [3] derives accurately, for the first time, the nonlinear damping from a fractional viscoelastic standard solid model by introducing geometric nonlinearity in it.

Theoretical and experimental nonlinear vibrations of thin rectangular plates and curved panels subjected to out-of-plane harmonic excitation are investigated in [4]. Experiments have been performed on isotropic and laminated sandwich plates and panels with supported and free boundary conditions.

Nonlinear vibrations of viscoelastic thin rectangular plates subjected to normal harmonic excitation in the spectral neighborhood of the lowest resonances are investigated in [5].

A review of publications devoted to the study of the behavior of plates and shells of smoothly variable thickness shows that at present, the behavior of such structural elements is insufficiently studied taking into account all the noted significant factors [6–11].

Studies of parametric vibrations of thin-walled structures have become a separate area of research in the mechanics of a deformable rigid body. They are widely applied to various mechanical systems, in particular to plates and shells.

In [12], a numerical–analytical method was proposed for studying parametric oscillations of plates under the action of static and periodic loads.

In [13–16], the results of a study of dynamic stability of various types of plates subjected to harmonic loading with and without nonlinearity are presented.

An analysis of the available literature showed [17–19] that there are almost no publications devoted to the study of nonlinear vibrations and dynamic stability of thin-walled structures such as viscoelastic plates and shells of variable thickness. In this paper, nonlinear parametric oscillations of viscoelastic orthotropic rectangular plates of variable thickness are numerically investigated. Based on the algorithm for the problem solution, a program was compiled in the Delphi programming environment.

2 Materials and Methods

Consider a viscoelastic orthotropic rectangular plate of variable thickness $h = h(x, y)$ with sides a and b under the action of axial dynamic loads. Let the plate undergo dynamic loading along side a with a periodic load $P(t) = P_0 + P_1 \cos(\Theta t)$ ($P_0, P_1 = \text{const}$, Θ is the frequency of external periodic load). A mathematical model

of the problem is constructed in a geometrically nonlinear statement according to the classical Kirchhoff–Love theory. We assume that the plate has initial deflections $w_0 = w_0(x, y)$.

In this case, physical dependence between stresses $\sigma_x, \sigma_y, \tau_{xy}$ and strains $\varepsilon_x, \varepsilon_y, \gamma_{xy}$ is taken in the form [2, 20]:

$$\begin{aligned}\sigma_x &= B_{11}(1 - \Gamma_{11}^*)\varepsilon_x + B_{12}(1 - \Gamma_{12}^*)\varepsilon_y, \quad (x \leftrightarrow y, 1 \leftrightarrow 2), \\ \tau_{xy} &= 2B(1 - \Gamma^*)\gamma_{xy},\end{aligned}\quad (1)$$

where Γ^*, Γ_{ij}^* are the integral operators with the relaxation kernels $\Gamma(t)$ and $\Gamma_{ij}(t)$, respectively:

$$\Gamma^*\phi = \int_0^t \Gamma(t - \tau)\phi(\tau)d\tau, \quad \Gamma_{ij}^*\phi = \int_0^t \Gamma_{ij}(t - \tau)\phi(\tau)d\tau, \quad i, j = 1, 2,$$

$$B_{11} = \frac{E_1}{1 - \mu_1\mu_2}, \quad B_{22} = \frac{E_2}{1 - \mu_1\mu_2}, \quad B_{12} = B_{21} = \mu_1 B_{22} = \mu_2 B_{11}, \quad B = \frac{G}{2},$$

E_1, E_2 are the elastic moduli in the direction of the axes x and y ; G is the shear modulus; μ_1, μ_2 are Poisson's ratios; here and hereafter, the symbol $(x \leftrightarrow y, 1 \leftrightarrow 2)$ indicates that the remaining relations are obtained by circular substitution of indices.

The relationship between strains in the middle surface $\varepsilon_x, \varepsilon_y, \gamma_{xy}$ and displacements u, v, w in x, y, z directions, taking into account initial irregularities, is taken in the form [2]:

$$\begin{aligned}\varepsilon_x &= \frac{\partial u}{\partial x} + \frac{1}{2} \left[\left(\frac{\partial w}{\partial x} \right)^2 - \left(\frac{\partial w_0}{\partial x} \right)^2 \right], \\ \varepsilon_y &= \frac{\partial v}{\partial y} + \frac{1}{2} \left[\left(\frac{\partial w}{\partial y} \right)^2 - \left(\frac{\partial w_0}{\partial y} \right)^2 \right], \\ \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \frac{\partial w}{\partial x} \frac{\partial w}{\partial y} - \frac{\partial w_0}{\partial x} \frac{\partial w_0}{\partial y}\end{aligned}\quad (2)$$

Bending M_x, M_y and torques H with (2) have the form [2, 20]:

$$\begin{aligned}M_x &= -\frac{h^3}{12} \left[B_{11}(1 - \Gamma_{11}^*) \frac{\partial^2(w - w_0)}{\partial x^2} + B_{12}(1 - \Gamma_{12}^*) \frac{\partial^2(w - w_0)}{\partial y^2} \right], \\ &\quad (x \leftrightarrow y, 1 \leftrightarrow 2), \\ H &= -\frac{Bh^3}{3} (1 - \Gamma^*) \frac{\partial^2(w - w_0)}{\partial x \partial y}.\end{aligned}\quad (3)$$

Substituting (1) and (3) into equation of motion [2]

$$\begin{aligned}
\frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} + p_x - \rho h \frac{\partial^2 u}{\partial t^2} &= 0, \quad \frac{\partial N_{xy}}{\partial x} + \frac{\partial N_y}{\partial y} + p_y - \rho h \frac{\partial^2 v}{\partial t^2} = 0 \\
\frac{\partial M_x}{\partial x^2} + \frac{\partial^2 M_y}{\partial y^2} + 2 \frac{\partial^2 H}{\partial x \partial y} + \frac{\partial}{\partial x} \left(N_x \frac{\partial w}{\partial x} + N_{xy} \frac{\partial w}{\partial y} \right) \\
+ \frac{\partial}{\partial y} \left(N_{xy} \frac{\partial w}{\partial x} + N_y \frac{\partial w}{\partial y} \right) + P_x(t) \frac{\partial^2 w}{\partial x^2} + q - \rho h \frac{\partial^2 w}{\partial t^2} &= 0
\end{aligned} \tag{4}$$

we get a system of integro-differential equations in partial derivatives of the form:

$$\begin{aligned}
&h \left[B_{11}(1 - \Gamma_{11}^*) \frac{\partial \varepsilon_x}{\partial x} + B_{12}(1 - \Gamma_{12}^*) \frac{\partial \varepsilon_y}{\partial x} + 2B(1 - \Gamma^*) \frac{\partial \varepsilon_{xy}}{\partial y} \right] \\
&+ \frac{\partial h}{\partial x} [B_{11}(1 - \Gamma_{11}^*) \varepsilon_x + B_{12}(1 - \Gamma_{12}^*) \varepsilon_y] + 2B \frac{\partial h}{\partial y} (1 - \Gamma^*) \varepsilon_{xy} - \rho h \frac{\partial^2 u}{\partial t^2} = 0, \\
&h \left[B_{22}(1 - \Gamma_{22}^*) \frac{\partial \varepsilon_y}{\partial y} + B_{21}(1 - \Gamma_{21}^*) \frac{\partial \varepsilon_x}{\partial y} + 2B(1 - \Gamma^*) \frac{\partial \varepsilon_{xy}}{\partial x} \right] \\
&+ 2B \frac{\partial h}{\partial x} (1 - \Gamma^*) \varepsilon_{xy} + \frac{\partial h}{\partial y} [B_{21}(1 - \Gamma_{21}^*) \varepsilon_x + B_{22}(1 - \Gamma_{22}^*) \varepsilon_y] - \rho h \frac{\partial^2 v}{\partial t^2} = 0, \\
&D \left[B_{11}(1 - \Gamma_{11}^*) \frac{\partial^4 (w - w_0)}{\partial x^4} + (8B(1 - \Gamma^*) + B_{12}(1 - \Gamma_{12}^*) + B_{21}(1 - \Gamma_{21}^*)) \right. \\
&\quad \left. \frac{\partial^4 (w - w_0)}{\partial x^2 \partial y^2} + B_{22}(1 - \Gamma_{22}^*) \frac{\partial^4 (w - w_0)}{\partial y^4} \right] \\
&+ \frac{\partial^2 D}{\partial x^2} \left(B_{11}(1 - \Gamma_{11}^*) \frac{\partial^2 (w - w_0)}{\partial x^2} + B_{12}(1 - \Gamma_{12}^*) \frac{\partial^2 (w - w_0)}{\partial y^2} \right) \\
&+ 2 \frac{\partial D}{\partial x} \left[B_{11}(1 - \Gamma_{11}^*) \frac{\partial^3 (w - w_0)}{\partial x^3} + (B_{12}(1 - \Gamma_{12}^*) + 4B(1 - \Gamma^*)) \frac{\partial^3 (w - w_0)}{\partial x \partial y^2} \right] \\
&+ 2 \frac{\partial D}{\partial y} \left[B_{22}(1 - \Gamma_{22}^*) \frac{\partial^3 (w - w_0)}{\partial y^3} + (B_{21}(1 - \Gamma_{21}^*) + 4B(1 - \Gamma^*)) \frac{\partial^3 (w - w_0)}{\partial x^2 \partial y} \right] \\
&+ \frac{\partial^2 D}{\partial y^2} \left(B_{22}(1 - \Gamma_{22}^*) \frac{\partial^2 (w - w_0)}{\partial y^2} + B_{21}(1 - \Gamma_{21}^*) \frac{\partial^2 (w - w_0)}{\partial x^2} \right) \\
&+ 8 \frac{\partial^2 D}{\partial x \partial y} B(1 - \Gamma^*) \frac{\partial^2 (w - w_0)}{\partial x \partial y} - \frac{\partial w}{\partial x} \left\{ h \left[B_{11}(1 - \Gamma_{11}^*) \frac{\partial \varepsilon_x}{\partial x} + B_{12}(1 - \Gamma_{12}^*) \frac{\partial \varepsilon_y}{\partial x} \right. \right. \\
&+ 2B(1 - \Gamma^*) \frac{\partial \varepsilon_{xy}}{\partial y} \left. \right] + \frac{\partial h}{\partial x} [B_{11}(1 - \Gamma_{11}^*) \varepsilon_x + B_{12}(1 - \Gamma_{12}^*) \varepsilon_y] + 2B \frac{\partial h}{\partial y} (1 - \Gamma^*) \varepsilon_{xy} \left. \right\} \\
&- h \frac{\partial^2 w}{\partial x^2} [B_{11}(1 - \Gamma_{11}^*) \varepsilon_x + B_{12}(1 - \Gamma_{12}^*) \varepsilon_y] - \frac{\partial w}{\partial y} \left\{ h \left[B_{22}(1 - \Gamma_{22}^*) \frac{\partial \varepsilon_y}{\partial y} \right. \right. \\
&+ B_{21}(1 - \Gamma_{21}^*) \frac{\partial \varepsilon_x}{\partial y} + 2B(1 - \Gamma^*) \frac{\partial \varepsilon_{xy}}{\partial x} \left. \right] + 2B \frac{\partial h}{\partial x} (1 - \Gamma^*) \varepsilon_{xy} \\
&+ \frac{\partial h}{\partial y} [B_{21}(1 - \Gamma_{21}^*) \varepsilon_x + B_{22}(1 - \Gamma_{22}^*) \varepsilon_y] \left. \right\} - h \frac{\partial^2 w}{\partial y^2} [B_{21}(1 - \Gamma_{21}^*) \varepsilon_x
\end{aligned}$$

$$+B_{22}(1 - \Gamma_{22}^*)\varepsilon_y] - 4h \frac{\partial^2 w}{\partial x \partial y} B(1 - \Gamma^*)\varepsilon_{xy} + P_x(t) \frac{\partial^2 w}{\partial x^2} + \rho h \frac{\partial^2 w}{\partial t^2} = q \tag{5}$$

The system of Eq. (5) with the corresponding boundary and initial conditions describes the motion of a viscoelastic orthotropic rectangular plate of variable thickness under the action of a periodic load $P(t) = P_0 + P_1 \cos(\Theta t)$ taking into account initial imperfections.

In calculations, the singular kernels of the Koltunov–Rzhanitsyn type [21] are used as relaxation kernels $\Gamma(t), \Gamma_{ij}(t), i, j = 1, 2$:

$$\Gamma(t) = Ae^{-\beta t} t^{\alpha-1}, (0 < \alpha < 1), \Gamma_{ij}(t) = A_{ij}e^{-\beta_{ij} t} t^{\alpha_{ij}-1}, (0 < \alpha_{ij} < 1) \tag{6}$$

Let the plate thickness change according to the following law $h(x) = \frac{1}{2}h_0(1 + \alpha * x)$; i.e., a linear increase in the plate thickness is observed (Fig. 1). Here, α^* is a parameter characterizing the variability of the thickness; h_0 is the plate thickness corresponding to $\alpha^* = 0$.

A solution to system (5) satisfying the boundary conditions of the problem is sought with respect to the displacements u and v , and deflection w in the form

$$u(x, y, t) = \sum_{n=1}^N \sum_{m=1}^M u_{nm}(t)\phi_{nm}(x, y), v(x, y, t) = \sum_{n=1}^N \sum_{m=1}^M v_{nm}(t)\phi_{nm}(x, y),$$

$$w(x, y, t) = \sum_{n=1}^N \sum_{m=1}^M w_{nm}(t)\psi_{nm}(x, y) \tag{7}$$

Substituting (7) into the system of Eq. (5) and performing the Bubnov–Galerkin procedure, taking into account dimensionless quantities

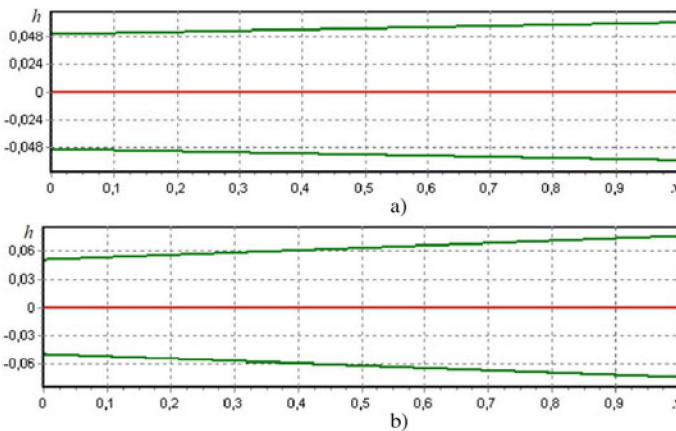


Fig. 1 Change in plate thickness depending on parameter α^* : **a** $\alpha^* = 0.2$; **b** $\alpha^* = 0.5$

$$\frac{u}{h_0}, \frac{v}{h_0}, \frac{w}{h_0}, \frac{w_0}{h_0}, \frac{x}{a}, \frac{y}{b}, \frac{h}{h_0}, \lambda = \frac{a}{b}, \delta = \frac{b}{h_0}, q^* = \frac{q}{E} \left(\frac{b}{h_0} \right)^4, \frac{\Theta}{\omega}, \omega t$$

and maintaining the previous notations, the following system of basic resolving nonlinear integro-differential equations is obtained

$$\begin{aligned} & \sum_{n=1}^N \sum_{m=1}^M a_{k \ln m} \ddot{u}_{nm} - \eta_1 \left\{ \sum_{n=1}^N \sum_{m=1}^M \{ [(1 - \Gamma_{11}^*) d_{1k \ln m} + (1 - \Gamma^*) d_{2k \ln m}] u_{nm} \right. \\ & + [(1 - \Gamma_{12}^*) d_{3k \ln m} + (1 - \Gamma^*) d_{4k \ln m}] v_{nm} \left. \right\} \\ & + \sum_{n,i=1}^N \sum_{m,j=1}^M \left[(1 - \Gamma_{11}^*) d_{7k \ln mij} + (1 - \Gamma_{12}^*) d_{8k \ln mij} + (1 - \Gamma^*) d_{9k \ln mij} \right] (w_{nm} w_{ij} - w_{0nm} w_{0ij}) \left. \right\} = 0, \\ & \sum_{n=1}^N \sum_{m=1}^M b_{k \ln m} \ddot{v}_{nm} - \eta_2 \left\{ \sum_{n=1}^N \sum_{m=1}^M \{ [(1 - \Gamma_{21}^*) e_{1k \ln m} + (1 - \Gamma^*) e_{2k \ln m}] u_{nm} \right. \\ & + [(1 - \Gamma_{22}^*) e_{3k \ln m} + (1 - \Gamma^*) e_{4k \ln m}] v_{nm} \left. \right\} \\ & + \sum_{n,i=1}^N \sum_{m,j=1}^M \left[(1 - \Gamma_{22}^*) e_{7k \ln mij} + (1 - \Gamma_{21}^*) e_{8k \ln mij} + (1 - \Gamma^*) e_{9k \ln mij} \right] (w_{nm} w_{ij} - w_{0nm} w_{0ij}) \left. \right\} = 0 \\ & \sum_{n=1}^N \sum_{m=1}^M c_{k \ln m} \ddot{w}_{nm} + \eta_3 \sum_{n=1}^N \sum_{m=1}^M p_{k \ln m}^2 (1 - 2\mu_{k \ln m} \cos \Theta t) w_{nm} \\ & - \eta_3 \left\{ \sum_{n=1}^N \sum_{m=1}^M \{ [\Gamma_{11}^* f_{5k \ln m} + \Gamma_{12}^* f_{6k \ln m} + \Gamma_{22}^* f_{7k \ln m} + \Gamma_{21}^* f_{8k \ln m} + \Gamma^* f_{9k \ln m}] w_{0nm} \right\} \\ & - \eta_3 \left\{ \sum_{n,i=1}^N \sum_{m,j=1}^M w_{nm} \left\{ [(1 - \Gamma_{11}^*) \xi_{1k \ln mij} + (1 - \Gamma_{21}^*) \xi_{2k \ln mij} \right. \right. \\ & + (1 - \Gamma^*) \xi_{3k \ln mij}] u_{ij} + [(1 - \Gamma_{22}^*) \xi_{4k \ln mij} + (1 - \Gamma_{12}^*) \xi_{5k \ln mij} + (1 - \Gamma^*) \xi_{6k \ln mij}] v_{ij} \left. \right\} \\ & + \sum_{n,i,r=1}^N \sum_{m,j,s=1}^M w_{nm} \left\{ (1 - \Gamma_{11}^*) g_{5k \ln mijrs} + (1 - \Gamma_{12}^*) g_{6k \ln mijrs} + (1 - \Gamma_{22}^*) g_{7k \ln mijrs} \right. \\ & \left. + (1 - \Gamma_{21}^*) g_{8k \ln mijrs} + (1 - \Gamma^*) g_{9k \ln mijrs} \right\} (w_{ij} w_{rs} - w_{0ij} w_{0rs}) \left. \right\} = 0 \\ & u_{nm}(0) = u_{0nm}, \dot{u}_{nm}(0) = \dot{u}_{0nm}, v_{nm}(0) = v_{0nm}, \dot{v}_{nm}(0) = \dot{v}_{0nm}, \\ & w_{nm}(0) = w_{0nm}, \dot{w}_{nm}(0) = \dot{w}_{0nm} \end{aligned} \quad (8)$$

where the constant coefficients entering this system are related to coordinate functions and their derivatives:

$$\begin{aligned} p_{k \ln m}^2 &= f_{5k \ln m} + f_{6k \ln m} + f_{7k \ln m} + f_{8k \ln m} + f_{9k \ln m} - 4\pi^2 \lambda^2 p_{k \ln m}^* \delta_0; \\ \mu_{k \ln m} &= \frac{2\pi^2 \lambda^2 p_{k \ln m}^*}{p_{k \ln m}^2} \delta_1. \end{aligned}$$

Based on the developed algorithm, a program in the Delphi algorithmic language was compiled.

3 Results and Discussion

Integration of system (8) was carried out using a numerical method based on the use of quadrature formulas [17]. The calculation results for various physical and geometric parameters are shown in graphs, Figs. 2 and 3. The dependence of the change in thickness has the following form: $h = 1 + \alpha^*x$, $h_0 = h(0) = const$, where α^* is the parameter of thickness change.

The effect of inhomogeneous material properties on the plate behavior was studied (Fig. 2).

As seen from the figure, an increase in parameter $\Delta = \sqrt{E_1/E_2}$ determining the degree of anisotropy (curve 1— $\Delta = 1$; curve 2— $\Delta = 1.5$, and curve 3— $\Delta = 2$) leads to a rapid increase in the amplitude of oscillations.

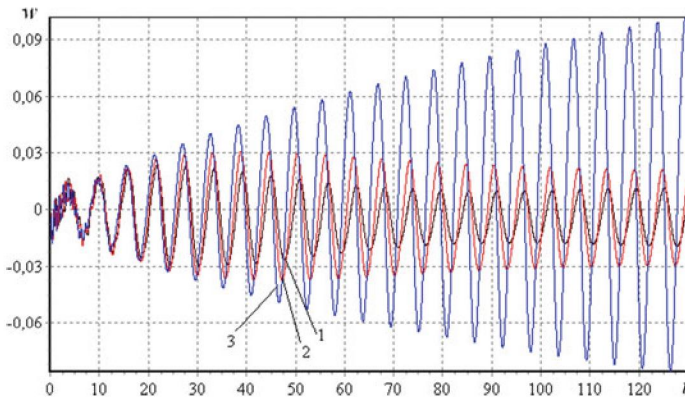


Fig. 2 Dependence of deflections on time at $\Delta = 1$ (1); 1.5 (2); 2 (3)

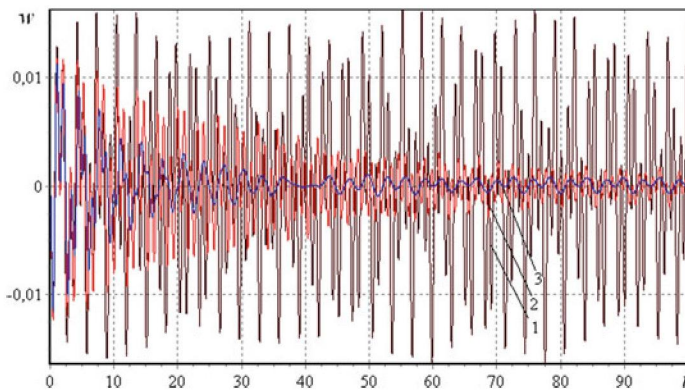


Fig. 3 Dependence of deflections on time

In Fig. 3, various curves correspond to the results obtained by various theories. Curve 1 corresponds to the elastic case, curve 2 to the results obtained taking viscosity into account in shear direction only ($A = 0.05$, $A_{ij} = 0$, $i, j = 1, 2$), and curve 3 to the case when viscosity is taken into account in all directions ($A = A_{ij} = 0.05$, $i, j = 1, 2$).

The results obtained confirm the need to take into account the viscoelastic properties of the material not only in shear direction, but in other directions as well.

4 Conclusion

A mathematical model, method, and computer program have been developed for evaluating the parametric vibrations of a viscoelastic orthotropic rectangular plate of variable thickness, taking into account geometric nonlinearity under the action of periodic loads.

The effect of the change in physico-mechanical and geometric parameters of the plate material on the amplitude–time characteristics and stress–strain state is estimated.

The method proposed in this work can be used for various types of thin-walled structures, such as plates, panels, and shells of variable thickness.

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