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Development of software that applies artificial intelligence methods to model and analyze vibrations and resonance effects in mechanical systems with changing boundaries

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This article presents the TB-ANALYSIS software package developed for intelligent analysis and control of resonance dynamics in one-dimensional systems with moving boundaries. Implemented in the MATLAB environment, the package combines classical methods for solving boundary value problems (analytical, asymptotic, and approximate) with artificial intelligence (AI) technologies to predict and prevent resonance phenomena. A key feature of the development is its hybrid architecture, which, along with numerical modeling and factor analysis modules, implements an intelligent module based on deep neural networks (DNNs). This module automatically predicts resonant frequencies based on model parameters and determines optimal values for damping, viscoelasticity, and stiffness coefficients to suppress resonance. Neural networks are trained using synthetic data generated by the package itself. The effectiveness and accuracy of the package have been confirmed by testing on model problems.

***Key words:* resonance, moving boundaries, boundary value problems, mathematical modeling, numerical methods, MATLAB, artificial intelligence, neural networks, parameter optimization**.

1. Introduction

Systems with moving boundaries find wide technical application in areas such as hoisting cables [1–5,7,8], flexible power transmission lines [6], and others. The mobility of the boundaries significantly complicates their mathematical description. Exact solution methods are generally limited to the wave equation and relatively simple boundary conditions [9]. Among approximate approaches, the most effective are the method based on constructing solutions of integro-differential equations [7,11,21–25], as well as the Kantorovich–Galerkin method [8–10,14]. This latter method has been extended to a broader class of model boundary value problems, which takes into account the bending rigidity of the object, the resistance of the external environment, and the rigidity of the foundation. The solution to the problems is implemented in dimensionless variables using the TB-ANALYSIS software package, developed in the MATLAB environment. This implementation allows the obtained results to be applied to calculations of a wide range of technical objects.

This paper presents a specialized software package, TB-ANALYSIS for intelligent modeling and analysis of the resonant dynamics of objects with moving boundaries. Developed in MATLAB, the package addresses the pressing problem of predicting and preventing destructive resonant phenomena in variable-length systems by combining classical numerical methods with artificial intelligence (AI) approaches. The primary goal of this work is to create a universal tool for studying the dynamics of variable-length systems, analyzing their resonant properties, and determining conditions for preventing resonant phenomena that pose a danger to structures.

The package features a modular architecture and includes functionality for: numerical solution of boundary value problems using intelligent method selection (analytical variable substitution, asymptotic method, and approximate analytical method); factor analysis of the influence of model parameters (drag coefficients, viscoelasticity, stiffness) on resonant modes; and parameter optimization to suppress resonance. Particular attention is paid to the built-in procedure for estimating and monitoring computational errors. The effectiveness and correctness of the package are confirmed by testing results on model problems. A practical application example is a study of transverse vibrations of a viscoelastic rope of variable length on an elastic foundation, with the amplitude dependences on time and the boundary velocity visualized. It is established that the amplitude at zero damping coefficients serves as an upper bound for other cases.

The key advantages of the package include its versatility, automated selection of solution methods, a user-friendly interface, and accuracy assessment tools. Future development prospects lie in expanding the class of problems solved, optimizing algorithms, and, most importantly, integrating artificial intelligence and machine learning methods. In particular, the use of deep neural networks trained on model data enables automated prediction of resonant frequencies and determination of optimal system parameters to prevent resonance. The use of deep neural networks (DNNs), Monte Carlo methods, and adaptive control significantly improves the accuracy of predictions and the efficiency of system control. The neural network is trained using data on system behavior at various frequencies and parameters. The network predicts resonant frequencies and suggests optimal parameters. The AI's results were validated using a mathematical model. Calculations confirmed that the parameters suggested by the artificial intelligence not only prevent resonance but also significantly reduce computation time.

2. Working with the software package

The TB-ANALYSIS software suite features a user interface built around four logically interconnected windows. The initial point of interaction with the environment is the start window, which serves as the central navigation hub. From here, the user can directly navigate to other functional blocks and use a universal menu system accessible in any open interface window. This approach ensures consistency across the various sections of the program.

Control of the system's main features is organized through a graphical main menu, featuring three buttons with intuitive icons. These correspond to the basic modules: "Study of Solutions to Model Boundary Value Problems," "Analysis of Resonance Properties of Models," and "Management of Resonance Phenomena." For increased convenience, all options accessible via these buttons are duplicated in the traditional menu bar, which is present in all working windows except the start window.

The menu bar consists of two main sections. The "File" section contains data management operations: loading initial model settings, saving results in various formats, and terminating a session. When saving, the user can choose to export numerical data in TXT or Excel spreadsheet formats for further processing, or save the generated graphs and visualizations as EPS or PNG files. The "Select Research Direction" section provides quick access to the same three key modules as the graphics menu.

The "Study of Solutions to Model Boundary Value Problems" module focuses on constructing solutions using asymptotic and approximate analytical approaches. It also allows for a comparative evaluation of the effectiveness of these methods and an analysis of the computational error for each. The "Analysis of Resonance Properties of Models" module is designed for factor analysis, which examines the influence of various parameters—such as boundary conditions, vibrational mode number, resonant velocity, damping characteristics, viscoelastic properties, and system stiffness parameters–on the amplitude of the resulting vibrations. The practical module "Resonance Phenomena Management" addresses engineering challenges in identifying zones of resonant instability and enables the identification of combinations of system parameters that reliably prevent the occurrence of dangerous resonant modes.

3. Study of solutions of model boundary value problems using software tools

Clicking the top button in this window takes you to a specialized interface for exploring solutions to boundary value problems, shown in Figure 1.

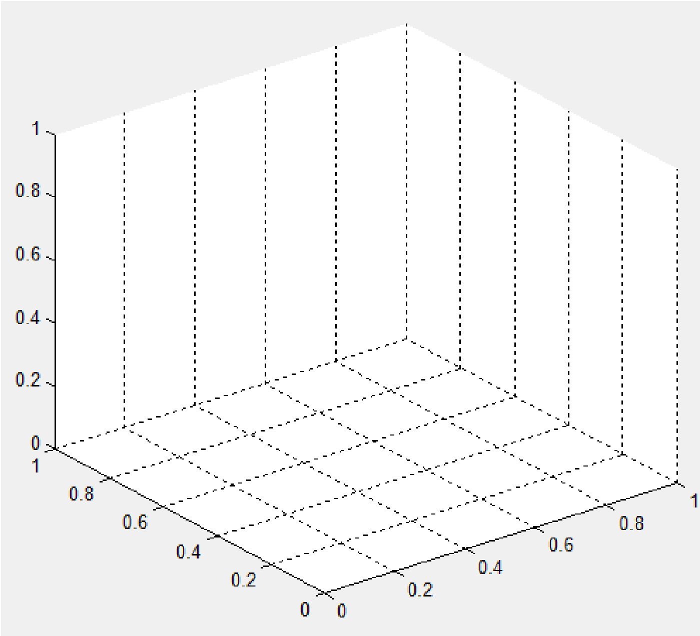

Fig. 1. Window for studying solutions of model boundary value problems

This interface retains the standard "File" and "Research Areas" menu items, making the program easy to use. Basic operations are available through the "File" section: "Import/Load" for batch loading source parameters from .xls/.xlsx and *.txt files, eliminating manual entry; "Export/Save" allows you to save numerical arrays in .xls/.xlsx and *.txt formats via the "Data" sub-item and export graphical results in *.eps and *.png formats via the "Graph" sub-item; and the "Exit" command allows you to completely terminate the application.

The "Research Areas" menu item contains a list of available program modules, including the subitems "Study of Solutions to Model Boundary Value Problems," "Analysis of Resonance Properties of Models," and "Comparison of Solution Methods." Each menu item corresponds to a separate functional block and is used to activate the corresponding software module.

Furthermore, the form contains two panels with radio buttons for "Study Object" and "Oscillation Type," an active "Calculate" button, and groups of windows for manual data entry: "Initial Model Parameters" (with the windows "Material Elastic Modulus (E)," "Initial Longitudinal Strain (epsilon0)," "Axial Moment of Inertia (I)," "Total Length of Undeformed Object (L0)," "Linear Density (r)," and "Cross-Sectional Area (S)"), "Initial Environmental Parameters" (with the "Environmental Drag Force (lambda)" window), and "Boundary Motion Parameters BsinW0(omega0t)." (with the windows “B=”, “W0=”, “omega0=”, “Linear velocity of movement (nu0)”), “Interval of change of coordinate (x)” (with the windows “start (x0)”, “step”, “end (xn)”), “Interval of change of time (t)” (with the windows “Start (t0)”, “Step” and “End (tn)”) and

“Calculation parameters” (with the windows “Accuracy of integral calculation” and “Number of terms of the solution function series”).

The software interface panel includes several key controls: the "Study Object" radio button allows you to select between two model objects—a rope and a beam—while the adjacent "Oscillation Type" panel allows you to specify the vibration type (longitudinal or transverse). The latter option is available exclusively for the "rope" object due to the physical properties of the model. The central control element is the "Calculate" button, which, when activated, initiates computational procedures and visualizes the results as graphical dependencies. A group of manual input fields is provided for setting the initial system parameters, where the names of each parameter clearly correspond to the text labels located to the left of the corresponding input elements.

The software implements three main methods for solving boundary value problems: an analytical method based on the substitution of variables in systems of differential-difference equations; an asymptotic approach for constructing solutions to homogeneous integro-differential equations and systems of ordinary differential equations modeling the dynamics of objects of variable length; As well as an approximate analytical method for solving integro-differential equations describing the motion of mechanical systems with moving boundaries.

The software package automatically selects a computational algorithm based on an analysis of the mathematical model type, the class of integro-differential equation, and the specified boundary conditions. For systems described by the wave equation, an analytical method with a change of variables in differential-difference equations is used; for models based on homogeneous integro-differential equations, an asymptotic method is applied; and for the analysis of complex non-homogeneous integro-differential equations, an approximate analytical method for constructing solutions is used. The algorithmic implementation of the computational methods is organized through a system of internal functions: the analytical method for solving boundary value problems is implemented in the "TBNumAnal" function, the asymptotic method is implemented in the "TBAsym" function, while the approximate analytical method for integro-differential equations is performed by the "TBNum" function. A visualization of the operation of this module is presented in Figure 2, which demonstrates typical calculation results.

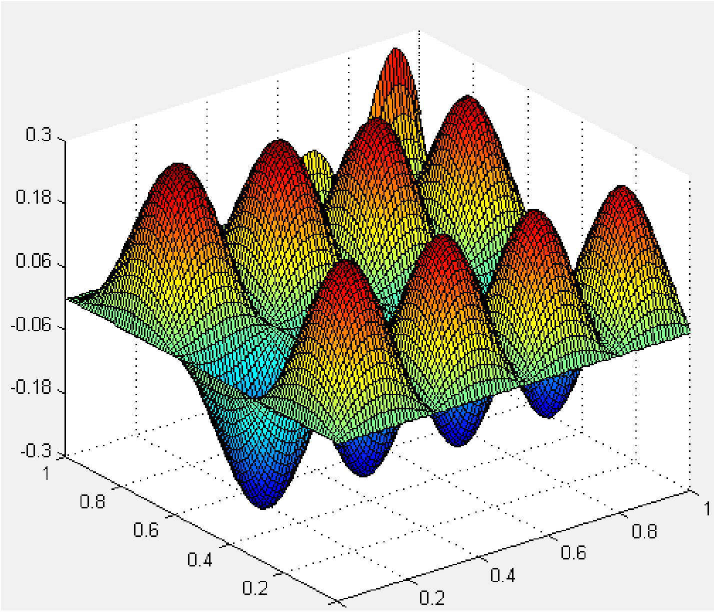

Fig. 2. Graph of the solution function of the boundary value problem for transverse vibrations of the rope

4. Analysis of resonance characteristics of models using a software package

Activating the "Analysis of Resonance Properties of Models" button in the start window takes the user to a specialized interface, the menu structure of which is identical to that of the module for studying boundary value problem solutions.

The resonance analysis module interface includes control panels for configuring study parameters. The "Study Object" radio button allows you to choose between rope and beam models, while the "Dependency Analysis" panel allows you to select the type of study: amplitude-time analysis or maximum amplitude-velocity analysis. Computational procedures are implemented through a system of built-in functions: the "met_ampl" function for calculating amplitude-time characteristics and the "met_ampl_max" function for analyzing the maximum amplitude-velocity dependence, which uses the first function as a subroutine.

This block also provides the ability to modify key model parameters, such as the mode number, damping coefficients, object stiffness, viscoelastic properties, and substrate stiffness, through the corresponding input fields. The interactive "Calculate" button is used to launch calculation procedures and subsequently display the resulting dependencies as graphs.

The dependence of maximum amplitude on speed is determined using an original method developed as part of this study. The method is based on an analytical expression for the oscillation amplitude, which is derived from the solution of integro-differential equations, taking into account the resonant characteristics of the modeled mechanical systems.

$$A_n^2(\tau) = E_n^2(\tau)\left\{\left[\int_0^{\tau} F_n(\zeta)\cos\Phi_n(\zeta)d\zeta\right]^2 + \left[\int_0^{\tau} F_n(\zeta)\sin\Phi_n(\zeta)d\zeta\right]^2\right\}. \quad (1)$$

The algorithm for numerically studying steady-state resonance and the phenomenon of passing through resonance is implemented in the "met_ampl_max" function. Figure 3 shows a graph of the dependence of the maximum amplitude of rope oscillations when passing through resonance on the boundary velocity for various values of the medium resistance coefficient (from top to bottom: $\lambda = 0$; $\lambda = 0,01$; $\lambda = 0,02$) with the following model parameters: mode number 1; object stiffness coefficient 0.01; viscoelasticity coefficient 0.01; substrate stiffness coefficient 0.02.

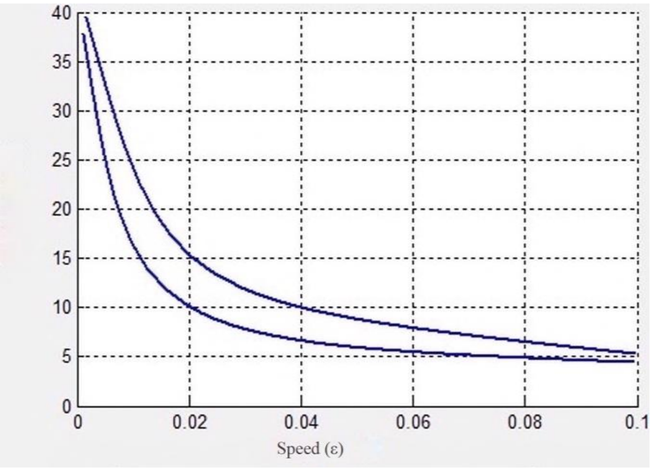

Fig. 3. Graph of the dependence of the maximum amplitude on the velocity of boundary movement for different values of the medium resistance coefficient

The calculation of the time dependence of the oscillation amplitude according to formula (1) is implemented in the internal function "met_ampl", which is used as a subroutine in the function "met_ampl_max". Figure 4 presents the results of test calculations demonstrating the change in the amplitude of transverse oscillations of a variable-length rope when passing through resonance in the first dynamic mode for a specific set of initial model parameters.

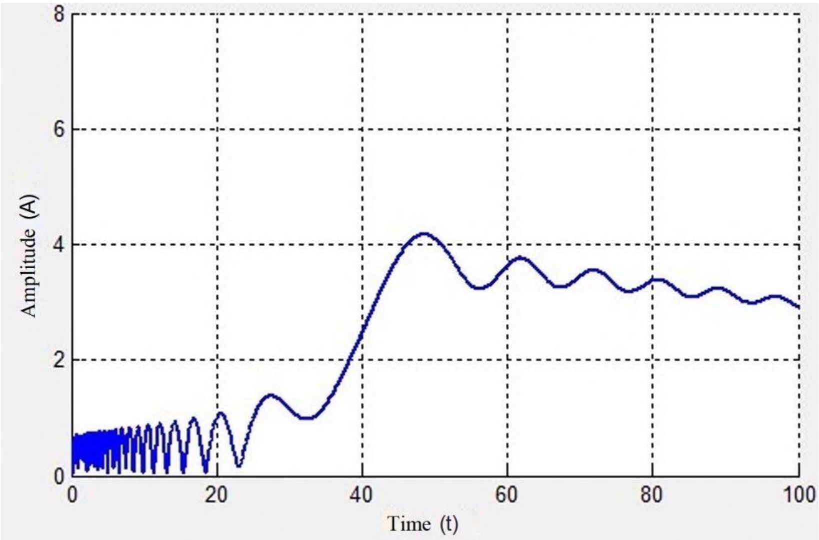

Fig. 4. Graph of amplitude versus time

5. Application of artificial intelligence to the example of vibrations of a variable-length rope

In addition to their direct functional role, the graphical dependencies shown in Figure 4 clearly demonstrate the characteristic features of the behavior of the oscillation amplitude, which form the basis of the method for determining the maximum amplitude.

Consider an example of using a neural network to predict resonant frequencies. Let the initial parameters of the system be given in dimensionless form:

-Rope stiffness: $k_0 = 100$,

-Damping: $c = 0.05$,

-Boundary velocity: $v_0 = 0.1$.

The neural network predicts a resonant frequency $\omega_n = 5$ and an amplitude $A_n = 0.2$. The allowable amplitude is $A_{allow} = 0.1$.

1. Calculate the loss function:

$$L_{res} = (0.2 - 0.1)^2 = 0.01.$$

2. Calculate the gradient:

$$\nabla_{\mathbf{p}} L_{res} = 2(0.2 - 0.1)\frac{\partial A_n}{\partial \mathbf{p}}.$$

3. Update the parameters:

$$\mathbf{p}_{new} = \mathbf{p}_{old} - \eta \nabla_{\mathbf{p}} L_{res}.$$

After several iterations, the system parameters are optimized, and the oscillation amplitude is reduced to the allowable level.

The developed software package TB-ANALYSIS is designed to solve a specific class of one-dimensional boundary value problems with moving boundaries, as well as for mathematical modeling and analysis of resonance properties of objects whose states are described by these boundary value problems. The package also enables the optimization of model parameters to prevent resonance phenomena using artificial intelligence (AI). The complex was developed in MATLAB as a standalone application. The results of this study have been incorporated into the package.

6. Conclusions

The TB-ANALYSIS software suite has proven itself as a versatile and reliable tool for mathematical modeling and analysis of the resonance characteristics of mechanical systems with moving boundaries. Testing has confirmed its high effectiveness in solving a wide range of boundary value problems.

Working with the suite is easy thanks to its intuitive interface, equipped with an intelligent system for selecting solution methods. The reliability of the obtained results is ensured by a built-in computational error assessment system. In this study, using the TB-ANALYSIS suite, enhanced with artificial intelligence technologies, we successfully determined the resonant frequencies of the system and developed conditions for resonance prevention. The initial system parameters were optimized to minimize the likelihood of resonance occurrence.

The study relied on collecting the system's amplitude-frequency characteristics, which allowed the identification of key parameters that have the greatest impact on resonance phenomena. A neural network capable of predicting resonant frequencies and suggesting optimal system settings was trained using this data. To address data limitations, the Monte Carlo method was extensively utilized. Machine learning methods were employed for an in-depth analysis of the parameters that contribute most to resonance.

All recommendations generated by artificial intelligence were thoroughly tested using a mathematical model. The calculations convincingly confirmed the high effectiveness of the proposed parameters in preventing resonance. Future development of TB-ANALYSIS lies in expanding its functionality and adapting it to solve more complex classes of problems, opening new horizons for research in the field of mechanical system dynamics. The approach presented in this paper, based on the integration of artificial intelligence and machine learning methods, not only improves calculation accuracy but also significantly reduces the time required to determine the optimal parameters for complex dynamic systems.

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