USING ARTIFICIAL INTELLIGENCE FOR MODELING VIBRATIONS OF A VARIABLE-LENGTH ROPE

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Relevance of the topic

Systems, the boundaries of which are moving, are widespread in technology (ropes of hoisting installations [1–5, 7, 8], flexible transmission links [6], etc.). The presence of moving boundaries causes significant difficulties in describing such systems.

The solution is implemented in dimensionless variables using the TB–Analysis software package developed in the Matlab, Python environment, which allows using the obtained results to calculate a wide range of technical objects. The TB–Analysis software package contains a module – resonance phenomena management. The "Resonance phenomena management" command is designed to determine the resonance region and identify resonance prevention conditions imposed on the model parameters using AI.

In addition, it is recognized that deterministic modeling of systems cannot be adequate for some types of problems, so it is necessary to move on to probabilistic–statistical, where random variables and stochastic oscillations are present.

Using artificial intelligence, the resonant frequencies of the system, as well as the conditions under which resonance can be prevented, were determined. The optimization of the system parameters under which the probability of resonance is minimal was carried out. Data was collected – amplitude–frequency characteristics of the system. Key parameters that affect resonance were determined. A neural network was trained on the data. In this case, the network predicts resonant frequencies and suggests optimal parameters. Nonlinear regression methods were used to determine the resonance conditions. In case of insufficient data, the data synthesis method – the Monte Carlo method – was used. ML methods were used to analyze which system parameters have the greatest influence on resonance. Clustering algorithms (k–means) were used to group frequencies at which the system is most vulnerable. Graphs of amplitude–frequency characteristics were constructed to clearly identify resonant areas. To prevent resonance, optimization of parameters was carried out using the gradient descent method to adjust system parameters, such as increasing damping and changing rigidity. Adaptive control methods and neural networks were used for dynamic adjustment of the system in real time.

The results of the AI work are tested on a mathematical model. Calculations confirmed that the proposed parameters really prevent resonance. This paper proposes an approach based on the application of artificial intelligence (AI) and machine learning (ML) methods, which not only improves the accuracy of calculations but also significantly reduces the time required to find optimal system parameters.

MATHEMATICAL STATEMENT OF THE PROBLEM (1)

The differential equation of motion of mechanical objects of variable length has the form

$$U_{\tau\tau}(\xi,\tau)+L[U(\xi,\tau)]=\varphi(\xi,\tau). \quad (1)$$

We write the boundary conditions in the following form

$$Y_{ji}\left[U\left(\ell_j(\varepsilon\tau),\tau\right)\right]=F_{ji}(\tau); \quad (2)$$

$$i=\overline{1,m};\ j=\overline{1,2}.$$

Here $U(\xi,\tau)$ – offset function; L – linear homogeneous differential operator with respect to ξ order $2m$ ($m\le 2$ – positive integer); Y_{ji} – linear homogeneous differential operators with respect to ξ; $\varphi(\xi,\tau), F_{ji}(\tau)$ – specified class functions C and C^2 respectively; $\ell_j(\varepsilon\tau)$ – boundary motion law; ε – small parameter ($\varepsilon=V/a$, V – border speed, a – vibration propagation speed).

The movement of the boundaries according to the law $\ell_j(\varepsilon\tau)$ corresponds to the slow movement mode.

When analyzing the resonance properties, the initial conditions are taken in the form $U(\xi,0)=U_\tau(\xi,0)=0$.

MATHEMATICAL STATEMENT OF THE PROBLEM (2)

Problem

$$U_{\tau\tau}(\xi,\tau)+L[U(\xi,\tau)]=\varphi(\xi,\tau) \tag{14}$$

Boundary conditions

$$Y_{ji}[U(\ell_j(\varepsilon\tau),\tau)]=F_{ji}(\tau);\ i=\overline{1,m};\ j=\overline{1,2} \tag{15}$$

Solution

$$U(\xi,\tau)=V(\xi,\tau)+H(\xi,\tau) \tag{16}$$

$$H(\xi,\tau)=\sum_{k=1}^{2}\sum_{r=1}^{m}D_{kr}(\xi,\varepsilon\tau)F_{kr}(\tau) \tag{17}$$

$$L[D_{kr}(\xi,\varepsilon\tau)]=0;\ Y_{ji}[D_{kr}(\ell_j(\varepsilon\tau),\tau)]=\begin{cases}1, k=j\wedge r=i;\\ 0, k\neq j\vee r\neq i.\end{cases} \tag{18}$$

Integro-differential equation of motion

$$V(\xi,\tau)=-\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}K(\xi,\zeta,\varepsilon\tau)\left[V_{\tau\tau}(\zeta,\tau)-\varphi(\zeta,\tau)+H_{\tau\tau}(\zeta,\tau)\right]d\zeta \tag{19}$$

$$Y_{ji}[V(\ell_j(\varepsilon\tau),\tau)]=0 \tag{20}$$

We seek the solution to problem (19) in the form of a series:

$$V(\xi,\tau)=\sum_{n=1}^{\infty}f_n(\tau)X_n(\xi,\varepsilon\tau). \tag{21}$$

MATHEMATICAL STATEMENT OF THE PROBLEM (3)

Own functions

$$X_n(\xi,\varepsilon\tau)=\omega_{0n}^2(\varepsilon\tau)\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}K(\xi,\zeta,\varepsilon\tau)X_n(\zeta,\varepsilon\tau)d\zeta \qquad (22)$$

$$f_n(\tau)=\mu_n(\tau)+\sum_{k=1}^{2}\sum_{r=1}^{m}Q_{n_{kr}}(\varepsilon\tau)F_{kr}(\tau);\quad Q_{n_{kr}}(\varepsilon\tau)=-\frac{\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}D_{kr}(\xi,\varepsilon\tau)X_n(\xi,\varepsilon\tau)g(\xi)d\xi}{\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}X_n^2(\xi,\varepsilon\tau)g(\xi)d\xi}. \qquad (23)$$

Let us expand the symmetric kernel into a series of eigenfunctions

$$K(\xi,\zeta,\varepsilon\tau)=\sum_{n=1}^{\infty}\frac{X_n(\xi,\varepsilon\tau)X_n(\zeta,\varepsilon\tau)}{\omega_{0n}^2(\varepsilon\tau)}, \qquad (24)$$

$$\frac{1}{\omega_{0n}^2(\varepsilon\tau)}=\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}K(\xi,\zeta,\varepsilon\tau)X_n(\xi,\varepsilon\tau)X_n(\zeta,\varepsilon\tau)d\xi d\zeta. \qquad (25)$$

System of ordinary with variable coefficients (order accuracy ε^2)

$$A_{1n}(\varepsilon\tau)\mu_n''(\tau)+2\varepsilon A_{2n}(\varepsilon\tau)\mu_n'(\tau)+A_{1n}(\varepsilon\tau)\omega_{0n}^2(\varepsilon\tau)\mu_n(\tau)=\theta_n(\tau), \qquad (26)$$

$$A_{1n}(\varepsilon\tau)=\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}X_n^2(\xi,\varepsilon\tau)g(\xi)d\xi;\ \varepsilon A_{2n}(\varepsilon\tau)=\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}X_{n_\tau}(\xi,\varepsilon\tau)X_n(\xi,\varepsilon\tau)g(\xi)d\xi; \qquad (27)$$

$$\theta_n(\tau)=\omega_{0n}^2(\varepsilon\tau)A_{1n}(\varepsilon\tau)\varphi_n(\tau)+E_n(\tau);\ E_n(\tau)=\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}\varphi(\xi,\tau)X_n(\xi,\varepsilon\tau)g(\xi)d\xi; \qquad (28)$$

$$\varphi_n(\tau)=\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}H(\xi,\tau)X_n(\xi,\varepsilon\tau)(\xi)d\xi\Big/\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}X_n^2(\xi,\varepsilon\tau)g(\xi)d\xi.$$

MATHEMATICAL STATEMENT OF THE PROBLEM (4)

Solution to problem (14) - (15)

$$U(\xi,\tau)=\sum_{n=1}^{\infty}\mu_n(\tau)X_n(\xi,\varepsilon\tau) \tag{29}$$

If we introduce a new function into (26)

$$\mu_n(\tau)=A_{0n}(\varepsilon\tau)y_n(\tau),\ \ A_{0n}(\varepsilon\tau)=\exp\left[-\int_0^{\tau}\frac{\varepsilon A_{2n}(\varepsilon\tau)}{A_{1n}(\varepsilon\tau)}d\tau\right] \tag{30}$$

then the system of d.e. (26) will not contain a memberc $y'(\tau)$:

$$y_n''(\tau)+\omega_n^2(\varepsilon\tau)y_n(\tau)=M_n(\varepsilon\tau)\cos W_n(\tau) \tag{31}$$

$$y_{1n}(\tau)=a_n(\varepsilon\tau)\cos w_n(\tau);\ \ y_{2n}(\tau)=a_n(\varepsilon\tau)\sin w_n(\tau) \tag{32}$$

$$a_n(\varepsilon\tau)=\frac{1}{\sqrt{\omega_n(\varepsilon\tau)}};\ \ w_n(\tau)=\int_0^{\tau}\omega_n(\varepsilon\tau)d\tau. \tag{33}$$

Expression for the amplitude of oscillations at $\varphi(\xi,\tau)=B_0(\xi)\cos W_0(\tau);F_{ji}(\tau)=B_{ji}\cos W_{ji}(\tau)$:

$$A_n^2(\tau)=\frac{1}{4}A_{0n}^2(\varepsilon\tau)a_n^2(\varepsilon\tau)\left\{\left[\int_0^{\tau}F_n(\varepsilon\zeta)\cos\Phi_n(\zeta)d\zeta\right]^2+\left[\int_0^{\tau}F_n(\varepsilon\zeta)\sin\Phi_n(\zeta)d\zeta\right]^2\right\}, \tag{34}$$

$$F_n(\varepsilon\zeta)=\frac{M_n(\varepsilon\zeta)}{a_n(\varepsilon\zeta)w_n'(\zeta)};\ \ \Phi_{n1}(\zeta)=w_n(\zeta)-W_n(\zeta);\ M_{n0}(\varepsilon\tau)=\int_{\ell_1(\varepsilon\tau)}^{\ell_2(\varepsilon\tau)}B_0(\xi)X_n(\xi,\varepsilon\tau)g(\xi)d\xi/[A_{0n}(\varepsilon\tau)A_{1n}(\varepsilon\tau)].$$

Methodology of analysis and numerical study of resonance properties

The expression for the amplitude of the system's oscillations in the n-th dynamic mode is:

$$A_n^2(\tau) = E_n^2(\tau)\left\{\left[\int_0^\tau F_n(\zeta)\cos\Phi_n(\zeta)d\zeta\right]^2 + \left[\int_0^\tau F_n(\zeta)\sin\Phi_n(\zeta)d\zeta\right]^2\right\}. \quad (35)$$

The phenomenon of steady-state resonance will be observed if the rate of change of the function $\Phi_n(\zeta)$ equals zero, i.e. $\Phi_n(\zeta) = \gamma,$ where $\gamma -$ constant value. In this case, the increase in amplitude is described by the following expression:

$$A_n(\tau) = E_n(\tau)\int_0^\tau F_n(\zeta)d\zeta. \quad (36)$$

The phenomenon of passing through resonance is observed in the time domain containing the point τ_0, where $\Phi_n'(\tau_0) = 0.$ If we take the amplitude at the beginning of the resonant region (point τ_1) to be equal to the amplitude of the external influence, then the amplitude at the end of the resonant region (point τ_2) is determined by the expression:

$$A_n^2(\tau_1,\tau_2) = E_n^2(\tau_2)\left\{\left[\int_{\tau_1}^{\tau_2} F_n(\zeta)\cos\Phi_n(\zeta)d\zeta\right]^2 + \left[\int_{\tau_1}^{\tau_2} F_n(\zeta)\sin\Phi_n(\zeta)d\zeta\right]^2\right\}. \quad (37)$$

STOCHASTIC OSCILLATIONS OF THE ROPE WITH MOVING BOUNDARIES (1)

The differential equation describing the longitudinal oscillations of the rope (viscoelasticity is taken into account based on the Voigt hypothesis) has the form [7, 10, 20]:

$$U_{tt}(x,t)+2\alpha U_t(x,t)-a^2\left[U_{xx}(x,t)-\int_0^t K(t-\nu)U_{xx}(x,\nu)d\nu+\mu U_{xxt}(x,t)\right]=f(x,t). \quad (42)$$

Border conditions

$$U(v_0t,t)=0;\ U(v_0t+l_0,t)=0. \quad (43)$$

Initial conditions

$$U(x,0)=U_1(x);\ U_t(x,0)=0. \quad (44)$$

In problem (42) – (44) it is indicated: $U(x,t)$ – longitudinal displacement of the rope point with coordinate x at time t; $a^2=E/\rho$ – velocity of wave propagation in the rope, E – modulus of elasticity of the rope material, ρ – linear mass density; α – resistance force of the medium acting per unit length of the rope, proportional to the speed of movement; μ – a small parameter that takes into account viscoelasticity; v_0t+l_0 – the law of motion of the rope boundary; $f(x,t)$ – a function that characterizes an external disturbance; $K(z)$ – relaxation core.

STOCHASTIC OSCILLATIONS OF THE ROPE WITH MOVING BOUNDARIES (2)

Let's introduce new variables that stop the bounds:

$$\xi = (x - v_0 t)/l_0; \quad \tau = at/l_0; \quad U(x,t) = V(\xi,\tau).$$

After transformations, we get:

$$V_{\tau\tau}(\xi,\tau) - 2vV_{\xi\tau}(\xi,\tau) - (1-v^2)V_{\xi\xi}(\xi,\tau) - 2k_0 V_{\xi}(\xi,\tau) + 2k_1 V_{\tau}(\xi,\tau) -$$
$$-d\int_{\xi}^{\xi+v\tau} K(-d(\xi-\eta))V_{\xi\xi}(\eta,\frac{1}{v}(\xi-\eta)+\tau)d\eta + \lambda\left(V_{\xi\xi\xi\xi}(\xi,\tau) - \frac{1}{v}V_{\xi\xi\tau}(\xi,\tau)\right) = F(\xi,\tau); \quad (45)$$

$$V(0,\tau) = 0;\ V(1,\tau) = 0; \quad (46)$$

$$V(\xi,0) = V_1(\xi);\ V_{\tau}(\xi,0) = 0. \quad (47)$$

Here $v = \frac{v_0}{a}; \quad d = \frac{l_0}{v_0}; \quad k_0 = \alpha v l_0; \quad k_1 = \alpha v d; \quad \lambda = \frac{\mu}{d}; \quad F(\xi,\tau) = v^2 d^2 f(x,t).$

The function $F(\xi,\tau)$ can be represented as

$$F(\xi,\tau) = \sum_{n=1}^{\infty} F_n(\tau)\sin(\omega_n \xi),\ \omega_n = \pi n. \quad (48)$$

Theorem 1. The solution to problem (45)–(47) can be given as a string

$$V(\xi,\tau) = \sum_{n=1}^{\infty} V_n(\tau)\sin(\omega_n \xi). \quad (49)$$

STOCHASTIC OSCILLATIONS OF THE ROPE WITH MOVING BOUNDARIES (3)

Substituting (48), (49) into (45), after transformations, we obtain the system of equations

$$V_{n_{\tau\tau}}(\tau)+\left(2k_1+\frac{\lambda}{\nu}\omega_n^2\right)V_{n_\tau}(\tau)+\omega_n^2(1-\nu^2)V_n(\tau)+$$
$$+\omega_n^2 d\int_{\xi}^{1}K(-d(\xi-\eta))V_n\left(\frac{1}{\nu}(\xi-\eta)+\tau\right)d\eta=F_n(\tau) \qquad (50)$$

with initial conditions

$$V_n(0)=2\int_0^1 V_1(\xi)\sin\left(\omega_n\xi\right)d\xi;\ V_{n_\tau}(0)=0. \qquad (51)$$

We accept the initial conditions and the external load as random, representing the sum of sinusoids with random amplitudes, denoting them $\tilde{V}(\xi)$ and $\tilde{F}(\xi,\tau)$ respectively. In this case, the oscillations will be random, and equations (50) form a system of random integro–differential equations

$$\tilde{V}_{n_{\tau\tau}}(\tau)+\left(2k_1+\frac{\lambda}{\nu}\omega_n^2\right)\tilde{V}_{n_\tau}(\tau)+\omega_n^2(1-\nu^2)\tilde{V}_n(\tau)+$$
$$+\omega_n^2 d\int_{\xi}^{1}K(-d(\xi-\eta))\tilde{V}_n\left(\frac{1}{\nu}(\xi-\eta)+\tau\right)d\eta=\tilde{F}_n(\tau); \qquad (52)$$

$$\tilde{V}_n(0)=2\int_0^1 \tilde{V}_1(\xi)\sin\left(\omega_n\xi\right)d\xi;\ \tilde{V}_{n_\tau}(0)=0. \qquad (53)$$

STOCHASTIC OSCILLATIONS OF THE ROPE WITH MOVING BOUNDARIES (4)

Characteristics of random variables – mathematical expectation, variance and covariance, have the following form:

$$M\left(\tilde{V}(\xi,\tau)\right)=\sum_{n=1}^{\infty}M\left(\tilde{V}_n(\tau)\right)\sin\left(\omega_n\xi\right); \tag{54}$$

$$D\left(\tilde{V}(\xi,\tau)\right)=\sum_{n,k=1}^{\infty}D_{n,k}(\tau)\sin\left(\omega_n\xi\right)\sin\left(\omega_k\xi\right); \tag{55}$$

$$C\left(\tilde{V}(\xi,\tau,\zeta,\upsilon)\right)=\sum_{n,k=1}^{\infty}C_{n,k}(\tau,\upsilon)\sin\left(\omega_n\xi\right)\sin\left(\omega_k\zeta\right). \tag{56}$$

To find the characteristics (54) – (56) of stochastic linear longitudinal oscillations of a viscoelastic rope, it is necessary to obtain statistical estimates for the solution of a system of random integro–differential equations (52). To do this, the relaxation kernel $K(z)$ can be taken in exponential form with a random component:

$$K(z,\overline{\beta})=K(z,\overline{b})\Big|_{\overline{b}=\overline{\beta}}=\sum_{j=1}^{N}c_j e^{-\beta_j z}, \tag{57}$$

where $c_j\in R_+$, β_j – is a possible value of a positive random variable b_j.

STOCHASTIC OSCILLATIONS OF THE ROPE WITH MOVING BOUNDARIES (5)

Denote the dependence of $\tilde{V}(\xi,\tau)$ and $\tilde{V}_n(\tau)$ on the random vector $\bar{b}$ as $\tilde{V}(\xi,\tau,\bar{b})$ and $\tilde{V}_n(\tau,\bar{b})$, respectively. By changing the variable

$$u_{\eta j}(\tau,\bar{b}) = \int_{\xi}^{1} e^{-\beta_j d\eta} \tilde{V}_n\left(\frac{1}{\nu}(\xi-\eta)+\tau\right),\bar{b})d\eta \tag{58}$$

the system of random integro–differential equations (52) is transformed into a system of random differential equations of the form

$$\begin{aligned} &\tilde{V}_{n_{\tau\tau}}(\tau,\bar{b}) + \left(2k_1 + \frac{\lambda}{\nu}\omega_n^2\right)\tilde{V}_{n_\tau}(\tau,\bar{b}) + \\ &+\omega_n^2(1-\nu^2)\tilde{V}_n(\tau,\bar{b}) + \omega_n^2 d\sum_{j=1}^{N} c_j e^{b_j d\tau}\, u_{\eta j}(\tau,\bar{b}) = \tilde{F}_n(\tau). \end{aligned} \tag{59}$$

The initial conditions will look like

$$\tilde{V}_n(0,\bar{b}) = 2\int_0^1 \tilde{V}_1(\xi)\sin\left(\omega_n\xi\right)d\xi;\ \tilde{V}_{n_\tau}(0,\bar{b}) = 0;\ u_{\eta j}(0,\bar{b}) = 0. \tag{60}$$

APPLICATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING (1)

4.1 Use of Deep Neural Networks (DNNs)

Deep neural networks (DNNs) are used to predict resonant frequencies and oscillation amplitudes. The network architecture includes several hidden layers with ReLU (Rectified Linear Unit) activation functions:

$$\mathrm{ReLU}(x) = \max(0, x). \tag{61}$$

The input data for the network includes system parameters:

- Rope stiffness k,
- Damping c,
- Boundary velocity v,
- External disturbances $f(x,t)$.

The output data are the resonant frequencies ω_n and amplitudes A_n. The network is trained using the backpropagation method and the Adam optimizer:

$$\theta_{new} = \theta_{old} - \eta \cdot \frac{\partial L}{\partial \theta}, \tag{62}$$

where θ are the network parameters, η is the learning rate, and L is the loss function.

APPLICATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING (2)

4.2 Monte Carlo Method for Estimating Stochastic Parameters

To account for random disturbances $\xi(x,t)$, the Monte Carlo method is used. Random variables are modeled using a normal distribution:

$$\xi(x,t) \sim N(0,\sigma^2), \tag{63}$$

where σ is the standard deviation. The Monte Carlo method allows estimating the expected mathematical expectation, variance and covariance of the oscillation amplitude:

$$M\left(\tilde{V}(\xi,\tau)\right) = \sum_{n=1}^{\infty} M\left(\tilde{V}_n(\tau)\right)\sin(\omega_n\xi);$$

$$D\left(\tilde{V}(\xi,\tau)\right) = \sum_{n,k=1}^{\infty} D_{n,k}(\tau)\sin(\omega_n\xi)\sin(\omega_k\xi);$$

$$C\left(\tilde{V}(\xi,\tau,\zeta,\upsilon)\right) = \sum_{n,k=1}^{\infty} C_{n,k}(\tau,\upsilon)\sin(\omega_n\xi)\sin(\omega_k\zeta).$$

APPLICATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING (3)

4.3 Adaptive Control Using AI

For real-time dynamic adjustment of system parameters, adaptive control based on neural networks is used. The control signal $u(t)$ is generated as:

$$u(t) = \mathrm{NN}_u\left(\mathbf{p}(t), \mathbf{y}(t)\right), \tag{64}$$

where $\mathbf{p}(t)$ are the current system parameters, and $\mathbf{y}(t)$ are the measured values of amplitude and oscillation frequency. The neural network NN_u is trained to minimize the loss function:

$$L_{control} = \sum_{t=1}^{T} \left(A_n(t) - A_{allow} \right)^2. \tag{65}$$

APPLICATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING (4)

4.4 Example of Using Neural Networks for Resonance Prediction

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:

$$L_{res} = (0.2 - 0.1)^2 = 0.01. \tag{66}$$

2. Calculate the gradient:

$$\nabla_{\mathbf{p}} L_{res} = 2(0.2 - 0.1)\frac{\partial A_n}{\partial \mathbf{p}}. \tag{67}$$

3. Update the parameters:

$$\mathbf{p}_{new} = \mathbf{p}_{old} - \eta \nabla_{\mathbf{p}} L_{res}. \tag{68}$$

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

APPLICATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING (5)

4.5 Use of Recurrent Neural Networks (RNNs)

For analyzing time series data, such as oscillation amplitude and frequency, recurrent neural networks (RNNs) are used. The RNN architecture includes hidden layers with long short-term memory (LSTM) units, which allow accounting for temporal dependencies in the data. The loss function for RNNs is:

$$L_{RNN} = \sum_{t=1}^{T} \left(y_t - \hat{y}_t \right)^2, \tag{69}$$

where y_t are the true values, and $\hat{y}_t$ are the predicted values.

APPLICATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING (6)

4.6 Clustering Methods for Analyzing Resonance Regions

To group frequencies at which the system is most vulnerable, clustering methods such as k-means are used. The k-means algorithm minimizes the loss function:

$$L_{cluster} = \sum_{i=1}^{k} \sum_{x \in C_i} \left\| x - \mu_i \right\|^2, \tag{70}$$

where C_i are the clusters, and μ_i are the cluster centers.

SOFTWARE PACKAGE TB–ANALYSIS

The developed software package "TB–Analysis" is designed to solve a certain class of one–dimensional boundary value problems with moving boundaries, as well as for mathematical modeling and analysis of the resonant properties of objects whose states are described by these boundary value problems. The software package also allows for the selection of model parameters to prevent resonance phenomena using artificial intelligence (AI). The software was developed in the Matlab, Python environment environment as a standalone application.

The user interface of the "TB–Analysis" software package consists of four windows, one of which is the startup window. This window appears when the program is launched, and the other windows can be accessed from the startup window. Additionally, these windows can be accessed from one another via a menu. The startup window of "TB–Analysis" contains three active buttons with schematic illustrations, which launch the following main modules of the software package:

1.Investigation of solutions to model boundary value problems;

2.Analysis of resonant properties of models;

3. Management of resonance phenomena.

An example of the module's operation

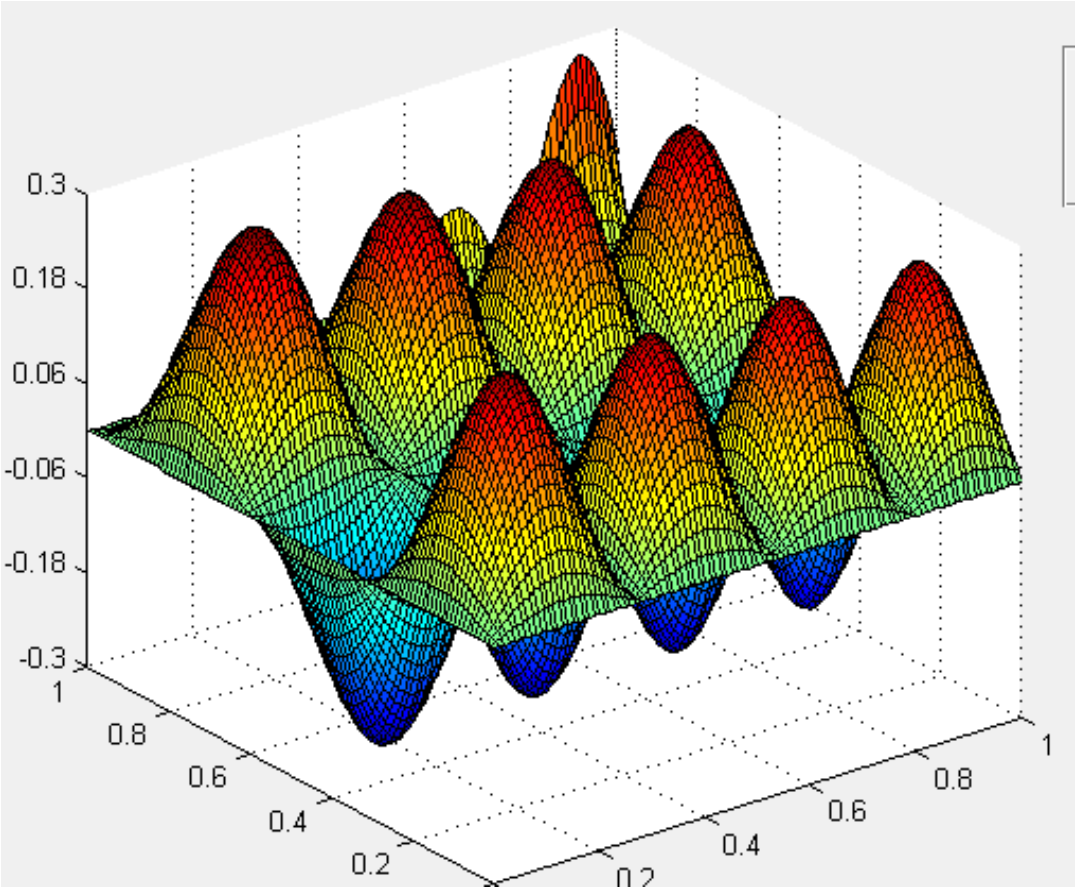


Fig. 1. Graph of the solution function for a boundary value problem of transverse vibrations of a cable.

An example of the module's operation

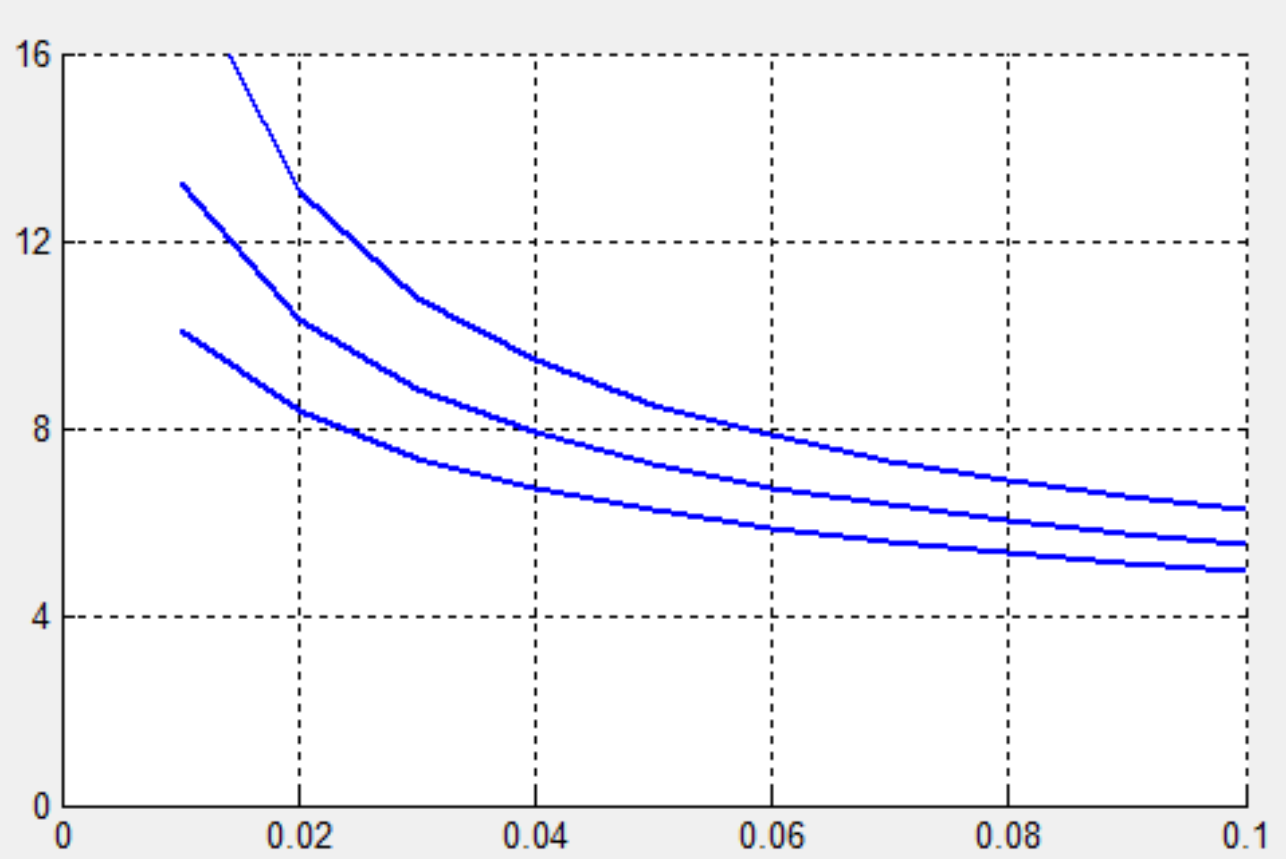


Fig. 2. Graph of the dependence of the maximum amplitude on the speed of boundary movement for various values of the environmental resistance coefficient.

An example of the module's operation

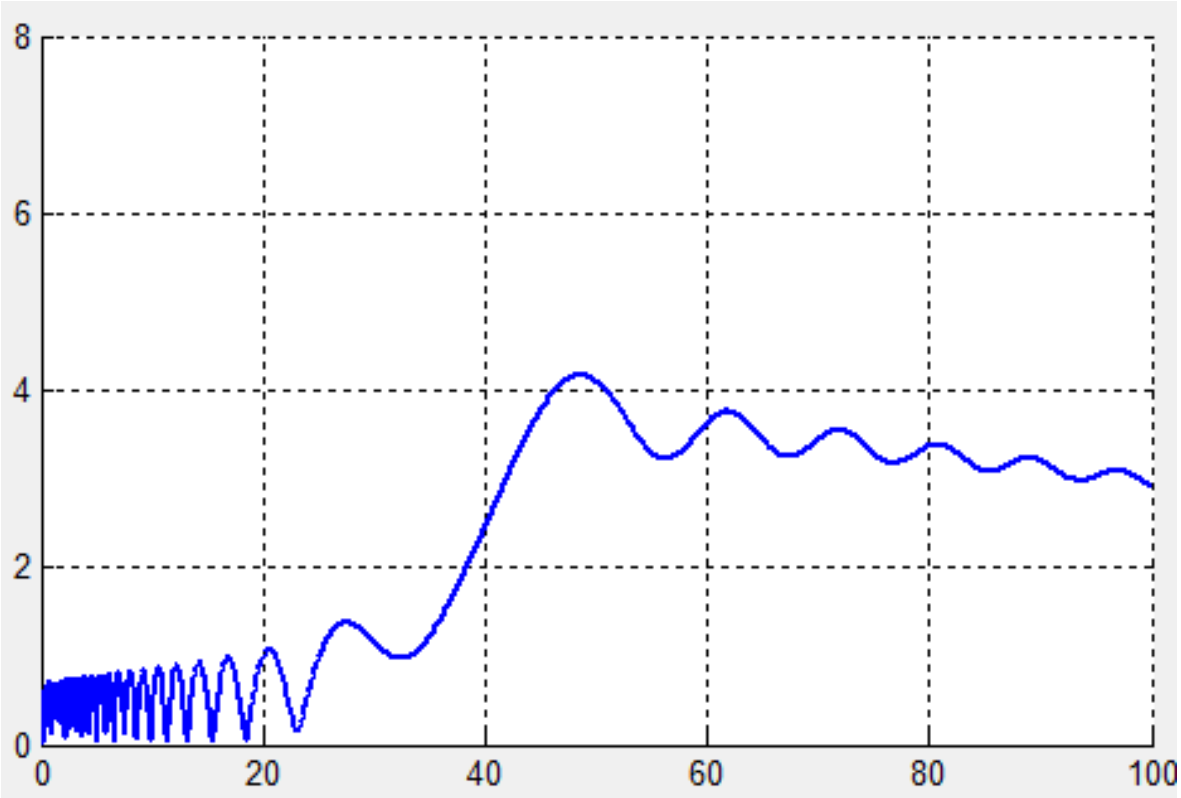


Fig. 3. Graph of the dependence of amplitude on time.

CONCLUSION

Thus, with the help of the software package “TB–Analysis” artificial intelligence was utilized to identify the resonant frequencies of the system and the conditions under which resonance could be avoided. The system's parameters were optimized to reduce the probability of resonance. Data on the system's amplitude–frequency characteristics were collected, and key parameters affecting resonance were determined. A neural network was trained on this data to predict resonant frequencies and amplitudes. Nonlinear regression methods were applied to define resonance conditions, and the Monte Carlo method was used for data synthesis when data was insufficient. Machine learning techniques were employed to analyze which system parameters most significantly influence resonance. Frequency analysis using the Fast Fourier Transform (FFT) was conducted to identify resonance regions, and clustering algorithms (k–means) were used to group frequencies where the system is most vulnerable. Amplitude–frequency characteristic graphs were plotted to clearly delineate resonance areas. To mitigate resonance, system parameters such as damping and stiffness were optimized using gradient descent. Adaptive control methods and neural networks were implemented for real–time system tuning. AI was also used to forecast conditions that could lead to resonance and to prevent it.

The problem of stochastic longitudinal vibrations in a viscoelastic cable with moving boundaries, considering damping forces, was formulated as a system of stochastic integro–differential equations. This system was simplified to a set of stochastic differential equations with random initial conditions. The Monte Carlo method was proposed for estimating expansion coefficients. The neural network was trained on data reflecting the system's behavior across various frequencies and parameters, enabling it to predict resonant frequencies and recommend optimal parameters. The AI's predictions were validated using a mathematical model, confirming that the suggested parameters effectively prevent resonance.

The use of deep neural networks, Monte Carlo methods and adaptive control not only improves the accuracy of forecasting, but also significantly reduces the time required to find the optimal system parameters.

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Thank you!