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DETERMINATION OF EQUIPMENT SHUTDOWN PREDICTION DURING OSCILLATORY PROCESSES

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Abstract. Free vibration problems of a flat element are investigated by all boundary value problems; generalization of the decomposition method in dynamics is given to solve boundary value problems, while it is shown that the decomposition method gives an exact solution obtained by the direct method, which in turn makes it possible to test the parts of production plants for wear leading to the shutdown of the equipment or the whole process. By checking the strength of the equipment parts, studying the degree of risk of possible breakdowns, emergency shutdowns can be predicted, and it is also possible to create controlled shutdowns.

Keywords: free vibration problems, oscillatory process, decomposition method, equipment shutdown prediction, elastic and viscoelastic media

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ТЕРБЕЛМЕЛІ ПРОЦЕСТЕР КЕЗІНДЕ ЖАБДЫҚТЫҢ СӨНУІН БОЛЖАУДЫ АНЫҚТАУ

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Аннотация. Тегіс элементтің еркін тербеліс есептері барлық басқа шеткі есептерді зерттейді, шеткі есептерді шешу үшін динамикадағы ыдырау әдісін жалпылау берілген, ал ыдырау әдісі тікелей әдіспен алынған нақты шешімді беретіндігі көрсетілген, бұл өз кезегінде өндірістік қондырғылардың бөлшектерін тозу ықтималдылығын сынауға мүмкіндік береді. Жабдықтың бөлшектерін беріктікке тексеріп, ықтимал сыну қаупінің дәрежесін зерттей отырып, апаттық тоқтауларды болжауға болады, сонымен қатар бақыланатын тоқтаулар кестесін құру мүмкіндігі бар.

Түйін сөздер: еркін тербеліс тапсырмалары, тербеліс процесі, ыдырау әдісі, жабдықтың тоқтауын болжау, серпімді және тұтқыр серпімді орта

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Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

ОПРЕДЕЛЕНИЕ ПРОГНОЗИРОВАНИЕ ОТКЛЮЧЕНИЯ ОБОРУДОВАНИЯ ПРИ КОЛЕБАТЕЛЬНЫХ ПРОЦЕССАХ

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Аннотация. Задачи свободного колебания плоского элемента исследуют все остальные краевые задачи, для решения краевых задач дано обобщение метода декомпозиции в динамике, при этом показано, что метод декомпозиции даёт точное решение, полученное прямым методом, это в свою очередь дает возможность тестировать детали производственных установок на предмет износа приводящей к останове отдельного оборудования или целого технологического процесса. Проверяя детали оборудования на прочность, изучая степени риска возможных поломок, можно прогнозировать авариные остановы, также появляется возможность создания контролируемых останов.

Ключевые слова: задачи свободных колебаний, процесс колебаний, метод разложения, прогноз останова оборудования, упругая и вязкоупругая среда

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Introduction

The development of science and technology, the creation of new structures, and the use of high-quality materials and advanced technologies have placed increasing demands on research in the field of deformable media dynamics. In recent decades, there has been growing interest in both theoretical and applied studies of oscillatory processes in elastic and viscoelastic bodies. This trend is driven by the increasing complexity of equipment designs and the need to enhance reliability and durability.

The choice of this research topic is motivated by a problematic situation: despite substantial progress in solid mechanics, many classes of boundary value problems associated with non-stationary oscillations and interactions of structural elements with deformable media remain insufficiently studied. Specifically, issues related to the consideration of rheological properties, material anisotropy, thermal effects, geometric features, and complex boundary and operating conditions are of particular concern.

The relevance of this research is determined by its practical significance. Understanding oscillatory processes in planar and spatial elements of elastic and viscoelastic materials allows predicting equipment reliability, monitoring wear, preventing emergency situations, and optimizing operational performance. This is crucial in mechanical engineering, shipbuilding, nuclear and hydroelectric power, space technology, as well as in seismology, geophysics, and acoustic flaw detection.

The object of this study comprises elastic and viscoelastic planar and spatial structural elements interacting with deformable media. The subject of research is the processes of non-stationary oscillations and wave propagation in these elements.

The purpose of the study is to develop effective mathematical methods for analyzing oscillatory processes in elastic and viscoelastic materials, taking into account rheological properties, and to apply these methods for predicting equipment reliability.

To achieve this goal, the following tasks were set:

- Conduct a theoretical analysis of oscillations and wave processes in elastic and viscoelastic media.
- Develop and adapt approximate methods for solving boundary value problems, particularly the decomposition method proposed by G. Pshenichny.
- Perform numerical modeling of oscillatory processes in planar elements with various boundary conditions.
- Investigate the effects of viscoelastic parameters, boundary constraints, geometry, and other factors on natural frequency characteristics.
- Justify the practical application of these methods for monitoring wear and preventing equipment failure.

The research methods include mathematical modeling, approximate analytical methods (decomposition method), numerical calculations, and the use of specialized software such as Trace Mode for industrial system analysis and monitoring.

The research hypothesis posits that the decomposition method provides accurate solutions for boundary value problems in elastic and viscoelastic elements, and the results of numerical analysis can serve as a foundation for predicting equipment conditions and optimizing operational processes.

Materials and methods.

Despite the extensive body of theoretical and applied research in this field, many significant classes of boundary value problems and their analysis remain largely unresolved or necessitate further refinement. These encompass problems related to unsteady oscillations of roads, plates, and shells while considering rheology.

To solve such problems, approximate oscillation equations derived from three-dimensional equations of motion in the theory of elasticity are commonly employed, using different hypotheses

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and assumptions of mechanical or geometric nature to simplify the problem-solving process. Additionally, the original three-dimensional problem in elasticity theory is often reduced to two-dimensional or one-dimensional formulations through various mathematical techniques, including variational and asymptotic methods, power series methods, and more.

Numerous studies have been conducted to reduce three-dimensional problems to two-dimensional engineering and mathematical methods. However, these studies do not provide a complete solution. Consequently, further investigation is required to examine the dynamic behavior of circular rods interacting with a deformable medium based on vibration equations derived using rigorous mathematical techniques. This research is of significant scope, as circular rods are integral elements of various engineering structures, ranging from simple machinery, instruments, and structures to complex space technology, nuclear and hydroelectric power plants, shipbuilding, and more.

The consideration of rheological properties, material anisotropy, the shell of the interacting medium, temperature changes, varying thickness, and other factors leads to considerable complexity in studying these problems. However, accurately accounting for these factors is crucial for ensuring the strength, reliability, and durability of structures, which can result in substantial savings in material resources and minimize equipment wear (Mailybayev et al., 2019: 100–104).

Wear is a gradual deterioration of material surfaces, accompanied by changes in geometric shapes and surface layer properties of parts. Wear can be categorized as normal or abnormal, depending on the underlying causes. Chemical wear involves the formation of thin oxide layers on parts, which subsequently exfoliate from the surface, often accompanied by rust and metal corrosion. Physical wear occurs due to excessive loads, surface friction, abrasion, and mechanical stress. It can result in the development of microcracks, cracks, or roughening of the metal surface. Normal wear is associated with short-term dimensional changes due to improper installation, operation, and maintenance practices.

In summary, addressing these wear-related factors and studying the dynamic behavior of viscoelastic bodies, especially in the context of circular rods interacting with deformable media, presents complex challenges that require further investigation to ensure structural strength, reliability, and durability.

Physical wear can manifest in various forms, including confluent pitting, fatigue, abrasive erosion, and erosion. Thermal wear, on the other hand, occurs when molecular bonds within the metal appear and subsequently deteriorate due to temperature fluctuations. Several factors influence wear, which are as follows:

Material quality of the parts:

The wear resistance of parts is generally higher when the surface hardness is greater, although this relationship is not always linear.

Materials with high hardness exhibit higher wear resistance, but there is an increased risk of particle detachment. To mitigate this, parts require high viscosity to prevent particle separation.

When two parts made of homogeneous materials undergo friction, an increase in the friction coefficient leads to accelerated wear. Therefore, more expensive and complex parts should be made from harder and better-quality materials, while simpler and cheaper parts can be made from materials with lower friction coefficients.

Surface treatment quality:

Wear of a part occurs in three stages: initial wear, steady wear, and rapid-increasing wear. Optimizing the first stage through precise and clean part processing, maximizing the second stage, and preventing the third stage helps to increase the service life of parts.

Lubrication:

Introducing a layer of grease between rubbing parts fills surface roughness and unevenness, significantly reducing friction and wear.

Speed of movement and specific pressure:

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Experimental data suggests that within certain specific loads and speeds (0.05 to 0.7), the oil layer remains intact, allowing parts to operate for extended periods. Increasing the load drastically increases part wear (Bondareva, 2010: 242).

Rigidity infringement in motionless parts.

Violation of fit.

Violation of relative part positions in joints.

Currently, most industrial equipment is equipped with automated control systems for monitoring process parameters. These systems collect data on equipment operating modes, store process parameters, and provide notifications for emergencies and malfunctions. The development of methods to determine equipment conditions based on process parameters is crucial for modern equipment assessment (Bondareva, 2010: 242).

Results and discussion

During operation, automated control systems may encounter various incidents such as sensor malfunctions, communication line breakdowns, controller/computer failures, or process parameter deviations beyond established boundaries. To ensure process continuity, the control system must include means for detecting and handling such emergency situations. Tracemode6 provides tools for this purpose, such as:

Automatic identification of hardware failures or data exchange issues by setting an unreliability sign for a channel associated with Input/Output equipment.

Automatic identification of program unreliability when channel values exceed set limits.

Monitoring FLOAT channels (analog alarms) by setting boundaries to detect abnormal process states.

Monitoring events and accidents using event class channels.

Trace Mode 6 also offers actions to prevent or mitigate accidents during ASM operation, such as alarms, operator recommendations, and blocking mechanisms. Process status information can be stored in archives and alarm reports.

To numerically analyze oscillatory processes in elastic and viscoelastic media, an effective approach is to apply the approximate method based on the decomposition method developed by Professor G. Pshenichny (Pshenichnov, 1985: 792–794; Pshenichnov, 1986:12–17) for static problems. In this context, we focus on examining the oscillation problems of flat rectangular elements under arbitrary boundary conditions along the element edges to determine the natural frequencies using the decomposition method. Initially, we present the method's formulation for the case of an elastic flat element, with future applications planned for viscoelastic materials. Figure 1 illustrates the frequency variations of natural vibrations for a viscoelastic plate.

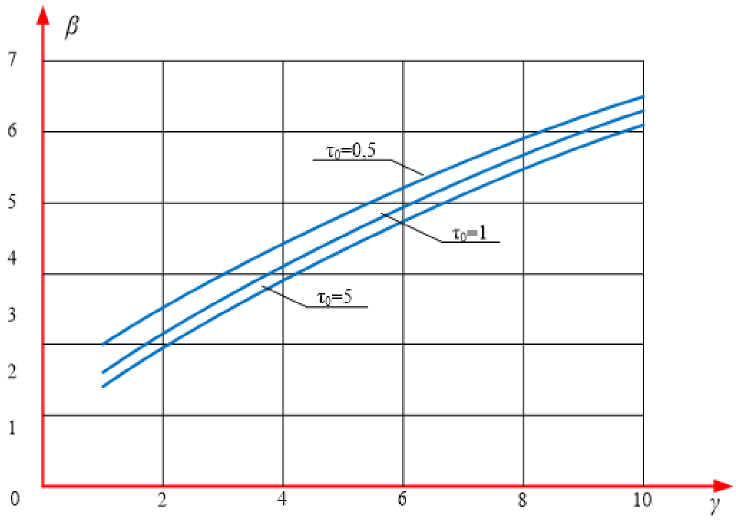

Fig. 1. Curves of changes in the frequencies of natural vibrations for a viscoelastic plate at $\tau0 = 0.5$, $\tau0 = 1.0$, $\tau0 = 5.0$, $v1 = 0.34$, $v2 = 0.3$

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For a flat element made of elastic material, we express the approximate equation of transverse vibration as a fourth-order equation in the form

$$\Delta^2 W - D_0 \frac{\partial^2}{\partial t^2}\Delta W + D_1 \frac{\partial^4 W}{\partial t^4} + D_2 \frac{\partial^2 W}{\partial t^2} = 0, \tag{1}$$

where the coefficients D_0, D_1, D_2 are determined by the geometry and material properties of the flat element. Seeking a solution to the equation in the form (1), we introduce the equation

$$W = \exp\left(i\frac{b}{h}\right) W_0(x, y) \tag{2}$$

by substituting (2) for W_0, yielding equation (3):

$$\Delta^2 W_0 + D_0\left(\frac{b}{h}\right)^2 \xi^2 \Delta W_0 + \xi^2\left(\frac{b}{h}\right)^2\left[D_1\left(\frac{b}{h}\right)^2 \xi^2 - D_2\right] W_0 = 0 \tag{3}$$

To facilitate the decomposition method, it is advantageous to introduce new independent and dependent variables as follows:

$$\begin{gathered}\alpha = \frac{\pi}{l_1}x; \qquad \beta = \frac{\pi}{l_2}y; \qquad W_0 = \frac{l_1^4}{\pi^4}v; \\ \lambda = \frac{l_1}{l_2}; \qquad \lambda_1 = \frac{l_1}{\pi h}\end{gathered} \tag{4}$$

Expressed in these variables (4), equation (3) takes the form:

$$\begin{gathered}\left[\frac{\partial^4 v}{\partial \alpha^4} + 2\lambda^2 \frac{\partial^4 v}{\partial \alpha^2 \partial \beta^2} + \lambda^4 \frac{\partial^4 v}{\partial \beta^4}\right] + \lambda_1^2 D_0 \left(\frac{b}{h}\right)^2 \xi^2 \times \\ \times \left[\frac{\partial^2 v}{\partial \alpha^2} + \lambda^2 \frac{\partial^2 v}{\partial \beta^2}\right] + \lambda_1^4 \left(\frac{b}{h}\right)^2 \xi^2 \left[D_1 \left(\frac{b}{h}\right)^2 \xi^2 - D_2\right] v = 0\end{gathered} \tag{5}$$

The decomposition method in the theory of oscillations follows a general procedure (7). We state the auxiliary problems as follows:

Problem 1: Determine a solution to the equation

$$\frac{\partial^4 v_1}{\partial \alpha^4} = f^{(1)}(\alpha, \beta) \tag{6}$$

subject to boundary conditions

$$L_1(\alpha, \beta) = 0; \qquad L_2(\alpha, \beta) = 0; \qquad (\alpha = 0; \pi) \tag{7}$$

Problem 2: Determine a solution to the equation

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$$\lambda^4 \frac{\partial^4 v_2}{\partial \beta^4} = f^{(2)}(\alpha,\beta) \tag{8}$$

subject to boundary conditions

$$L_3(\alpha,\beta)=0; \qquad L_4(\alpha,\beta)=0; \qquad (\beta=0;\pi) \tag{9}$$

The specific boundary conditions at the plate edges depend on the fixation conditions or the presence of free edges, which may involve stresses.

The remaining part of equation (5) is denoted as

$$\begin{gathered} 2\lambda \frac{\partial^4 v_3}{\partial \alpha^2 \partial \beta^2} + \lambda D_0 \left(\frac{b}{h}\right)^2 \xi^2 \left(\frac{\partial^2 v_3}{\partial \alpha^2} + \lambda^2 \frac{\partial^2 v_3}{\partial \beta^2}\right) + \lambda_1^4 D_0 \left(\frac{b}{h}\right)^2 \times \\ \times \xi^2 \left[D_1 \left(\frac{b}{h}\right)^2 \xi^2 - D_2\right] v_3 + f^{(1)}(\alpha,\beta) + f^{(2)}(\alpha,\beta) = 0, \end{gathered} \tag{10}$$

where $f^{(j)}(\alpha,\beta)$ represents arbitrary functions whose specific form depends on the boundary value problems being solved. Following the decomposition method, we assume that

$$v_3 = \frac{1}{2}\left[v_1 + v_2\right] \tag{11}$$

must also satisfy certain conditions at designated points of the plane element. The general solutions of the auxiliary problems' equations (6) and (8) can be expressed as

$$\begin{gathered} v_1 = f_1(\alpha,\beta) + \frac{\alpha^3}{6}\varphi_1(\beta) + \frac{\alpha^2}{2}\varphi_2(\beta) + \alpha\varphi_3(\beta) + \varphi_4(\beta); \\ v_1 = f_1(\alpha,\beta) + \frac{\beta^3}{6}\psi_1(\alpha) + \frac{\beta^2}{2}\psi_2(\alpha) + \beta\psi_3(\alpha) + \psi_4(\alpha); \end{gathered} \tag{12}$$

where φ_j, ψ_j represents arbitrary functions of the arguments determined by the boundary conditions (7) and (9). We then represent the arbitrary functions in a general form as

$$f^{(j)}(\alpha,\beta) = \sum_{n=1}^{\infty}\sum_{j=1}^{\infty} a_{n,m}^{(j)} \sin(\alpha n)\sin(\beta m), \tag{13}$$

where $a_{n,m}^{(j)}$ represents arbitrary constants, and the functions $f_j(\alpha,\beta)$ in the general solutions (12) are equal to

$$f_1(\alpha,\beta) = \sum_{n=1}^{\infty}\sum_{j=1}^{\infty} \frac{a_{n,m}^{(j)}}{n^4} \sin(\alpha n)\sin(\beta m);$$

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$$f_2(\alpha, \beta) = \sum_{n=1}^{\infty} \sum_{j=1}^{\infty} \frac{a_{n,m}^{(2)}}{m^4} \sin(\alpha n) \sin(\beta m). \qquad (14)$$

By using particular solutions to problems under given boundary conditions and employing the approximate representations (Morokina et al., 2018: 6566–6570) to determine the unknowns $a_{n,m}^{(j)}$, we obtain a homogeneous linear system of algebraic equations. A nontrivial solution of this system leads to a frequency equation, enabling us to determine the natural frequencies of flat elements. The problems related to viscoelastic materials in flat elements are solved in a similar manner.

The concept of a software and hardware complex forms the basis of automated systems for monitoring the state of equipment. This concept has emerged relatively recently in the field of computer technology and fiscal devices. One popular example of a software and hardware complex is "Cruise" with Trace Mode software. "Cruise" is an automated process control system that combines hardware and software components and is designed to implement automatic, automated, and remote control of industrial facilities. The structure of the "Cruise" software and hardware complex is depicted in Figure 2.

The main objectives of creating an automated process control system are as follows:

Ensuring the management of technological processes in normal, emergency, and post-emergency conditions.

Providing operational personnel with sufficient, reliable, and timely information about operating modes, the course of technological processes, equipment conditions, and technical controls.

Optimization of technical and economic indicators.

Increasing the reliability of equipment.

Improving working conditions for operating personnel.

Working with the software and hardware complex involves addressing various tasks such as:

Collecting and primary processing of information.

Monitoring the reliability of received information.

Receiving and storing retrospective information.

Creating process equipment monitoring teams and presenting information to operational and engineering personnel through mnemonic representations, diagrams, graphs, and histograms.

Logging and documentation.

Registering emergency events and analyzing protection actions.

Monitoring and displaying the state of the hardware and software complex.

The complex operates as a distributed control system with a two-level organization, utilizing the standard Ethernet protocol for communication between different system levels. This approach allows for the incorporation of extensive experience in building fault-tolerant systems and leveraging the latest advancements in distributed computing and redundancy.

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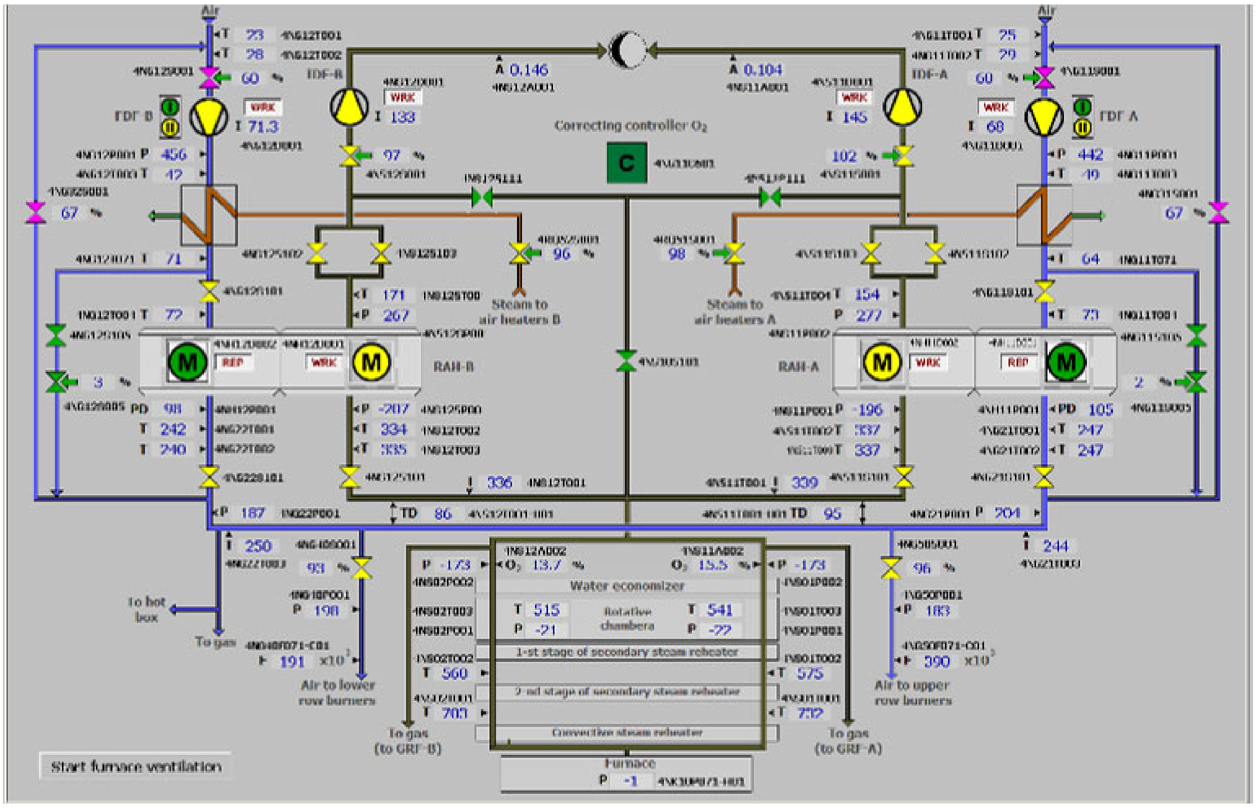

Fig. 2. DCS «Cruise» structure.

Overall, the automated control system represents a decentralized human-machine system in which control tasks are partly performed automatically and partly through remote automated control with human involvement. In urgent cases, emergency tools and individual control keys installed on the backup control system's remote controls can be used for process control. Individual control and monitoring tools are employed to ensure a safe shutdown of equipment in the event of a functional failure of the software and hardware complex. Each level of the process control systems is equipped with corresponding control posts where operational personnel are stationed. Information is generated and displayed automatically by the technical means of the software and hardware complex, while management decisions are made and implemented by the operator. The operator interacts with the control system through the information presentation subsystem (DCS «Круиз». Full description of the system [electronic resource] http://pikzebra.ru/ptk/doc/index.php).

In Trace Mode 6, the automatic creation and configuration of the channel base for controllers is accompanied by the automatic construction of the operator's graphical interface using monitors. Equipment control algorithms are also selected. Figure 3 illustrates the recording of emergency stops based on technical parameters in Trace Mode. Monitors within the system can generate messages in various situations during the operation of an automated control system. For instance, when a channel value of the FLOAT class exceeds a set limit or when there are changes in employee status. These messages are logged in a dedicated text file called the alarm report (AR), which is configured for each node. AR messages are logged on channels for which the corresponding flag is set. The configuration of the AR allows monitors to generate messages. Message texts for events can be defined in dictionaries. If a channel is linked to a dictionary, messages from the dictionary will be generated; otherwise, monitors will generate default messages. For some channels, the criteria for generating messages are dependent on specific channel parameters. The dictionary can also be configured to transmit messages through additional means, such as SMS messages to a specified mobile phone number via a console network. Graphic

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elements used in the development of graphical screens allow operators to input arbitrary messages into the alarm report and view all AR messages, as well as acknowledge them (Gerasimov, 2011: 128).

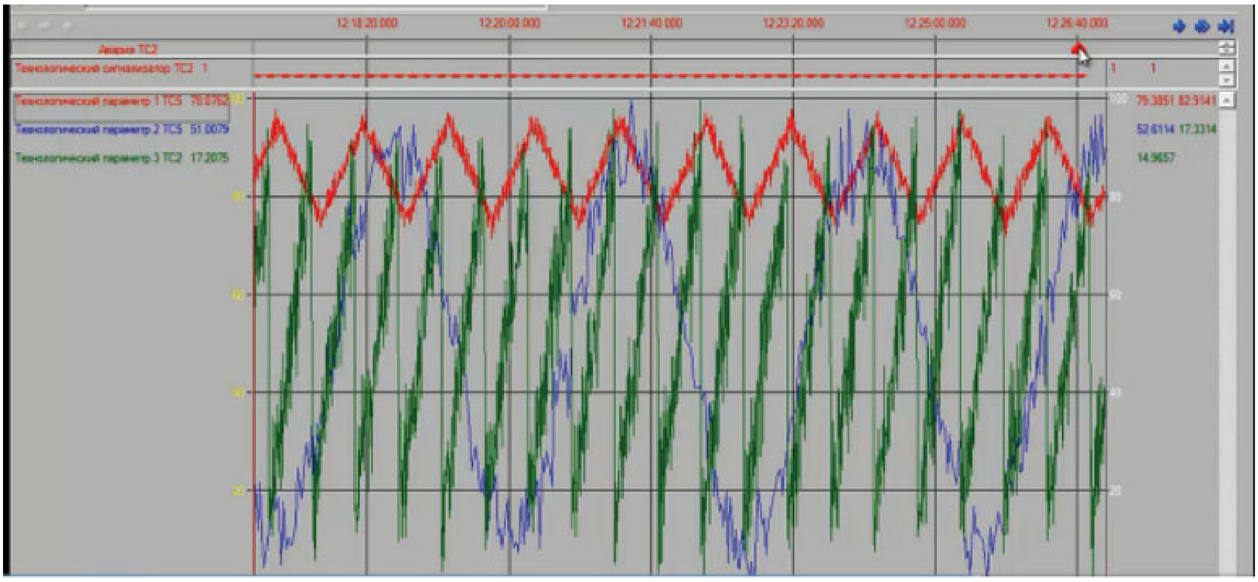

Fig. 3. Registration of emergency stops based on technical parameters in the Trace Mode

To exit the alarm state for a variable, its value must decrease by an amount known as the deadband, such that it falls below the threshold. Similar interpretations apply for lower pre-alarm and emergency alarms. These conditions hold for alarms of the deviation type. The set value of a variable can be modified by either the operator or the program. The alarm is triggered when the variable value exceeds the tolerance limit. Alarms determined by the rate of change of a parameter occur if it exceeds the maximum permissible value or falls below it. The concept of a «deadband» does not apply to alarms of this type (Anokhina, 2004).

Conclusion

The present study provides a comprehensive analysis of the natural oscillations of planar rectangular elements and the propagation of harmonic waves in both elastic and viscoelastic media, demonstrating the effectiveness of the decomposition method for solving complex boundary value problems. By employing this method, a wide range of free vibration problems were addressed, covering different boundary conditions along element edges and varying material properties. The results highlight the significant influence of viscoelastic parameters, boundary constraints, geometric characteristics, and rheological properties on the dynamic behavior of structural elements.

The objectives and research methods were successfully implemented, leading to several key outcomes. First, the approximate equations of transverse vibrations for planar elastic elements were derived and solved using the decomposition method. This approach provided a systematic framework to decompose the governing fourth-order differential equations into auxiliary problems, allowing the precise determination of natural frequencies. Second, the method was extended to viscoelastic materials, revealing the effect of relaxation times and damping parameters on oscillatory behavior. The obtained frequency curves demonstrate the critical role of viscoelasticity in both stabilizing vibrations and affecting energy dissipation, which is essential for accurate modeling of real-life engineering structures.

Third, the practical applicability of the theoretical framework was demonstrated through the use of the Trace Mode 6 software, which allows automated monitoring of industrial equipment. Numerical simulations performed in this software provide valuable insights into the operational behavior of structural elements, enabling early detection of abnormal conditions, wear, or potential equipment failure. The

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integration of theoretical modeling and software-based monitoring illustrates the effectiveness of combining mathematical analysis with practical industrial applications.

The study confirms the initial hypothesis that the decomposition method is a robust and reliable tool for analyzing oscillatory processes in both elastic and viscoelastic media. It enables precise determination of natural frequencies and mode shapes, which are critical for predicting equipment behavior, preventing premature wear, and ensuring operational safety. Furthermore, the results provide a foundation for optimizing design parameters, such as material selection, geometric configuration, and boundary conditions, thereby enhancing durability and reliability while reducing maintenance costs.

This research has significant implications for a broad range of engineering fields, including mechanical engineering, nuclear and hydroelectric power, shipbuilding, aerospace technology, and materials science. The theoretical findings can be applied to improve predictive maintenance strategies, develop automated control systems for monitoring equipment state, and optimize structural design to withstand dynamic loads. Moreover, understanding the interaction of viscoelastic elements with surrounding deformable media has potential applications in geophysics, seismology, and acoustic defect detection, where accurate modeling of wave propagation and energy dissipation is critical.

Future research directions include the extension of the decomposition method to three-dimensional elements and complex structural assemblies under combined thermal, mechanical, and electromagnetic effects. The development of integrated computational models that couple oscillation analysis with real-time monitoring data will enhance predictive maintenance capabilities and industrial process optimization. Additionally, further investigation into nonlinear behavior, multi-scale effects, and advanced viscoelastic material models will contribute to a deeper understanding of structural dynamics under operational conditions.

In conclusion, the present study successfully demonstrates that rigorous mathematical methods, such as the decomposition method, combined with numerical and software-based tools, provide an effective and practical approach to analyzing oscillatory processes in elastic and viscoelastic elements. The results not only confirm theoretical expectations but also offer practical guidelines for improving equipment reliability, prolonging service life, and optimizing industrial operations. This work represents a significant contribution to the field of deformable media dynamics and provides a foundation for further scientific exploration and technological advancement.

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