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LABORATORY STUDIES OF WAVE PROCESSES FOR THE PROBLEMS OF PROCESSING DATA FROM VIBROACOUSTIC SAFETY CONTROL OF STRUCTURES AND TECHNICAL SYSTEMS

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Abstract. The article is devoted to improving automation systems for vibroacoustic monitoring of the stability and safety of structures. The aim of the study is to develop and experimentally validate digital models of wave processes for data processing tasks in vibroacoustic monitoring used in the practical assessment of the state and safety of engineering structures. Methods: analysis of experimental data; software-based construction of digital models; laboratory experiments; and modeling of transverse wave propagation. The analysis demonstrated the relevance of conducting laboratory studies of wave processes to verify theoretical models and to identify characteristic features and hidden patterns in the dynamics of wave propagation in various media. A functional scheme of a laboratory plant for generating vibroacoustic oscillations was developed and tested at the authorized training center of the French electromechanical corporation Schneider Electric at Dnipro University of Technology. Algorithms and software were created for modeling the propagation of excitation and reflected transverse waves. Monochromatic harmonic oscillations were generated with subsequent frequency increase, and pulse excitation and switching waves were simulated. Experimental results showed that when interacting with an absorbing boundary, the amplitude of the transverse wave decreases while the waveform and main characteristics of the wave process remain stable during further propagation. A significant pattern for vibroacoustics was observed: wave propagation has a deterministic nature with superimposed stochastic components caused by complex reflection conditions. A new approach to vibroacoustic data analysis was developed, involving the construction of digital vibration excitation models to create digital twins of real wave processes through frame-by-frame temporal visualization and color mapping of time intervals. This enables comprehensive analysis of oscillations and wave propagation processes in complex structures. The results obtained can be used for practical interpretation of vibroacoustic signals and for monitoring the safety of engineering structures.

Keywords: safety of structure operation, automation of vibroacoustic control, wave process models, data processing, digital filters.

1. Introduction

Non-destructive vibroacoustic testing is one of the most promising methods for ensuring the safe operation and structural stability of buildings and constructions [1, 2]. This method is based on recording and analyzing the resonant responses of structures to impact chaotic excitations. The high sensitivity of the vibroacoustic method to internal defects and cracks makes it effective for inspecting buildings, underground, and buried structures. However, vibroacoustic testing always involves recording of large volumes of data that contain not only useful information about the structure state but also noise of various origins. Manual processing of such data increases labor intensity, reduces the response speed to changes in the structure state (which are often critical), and makes the results largely dependent on the researcher's subjectivity [3, 4].

Automated vibroacoustic monitoring addresses two major challenges: regulating the amplitude and other parameters of impact excitations, and converting heterogeneous measurement data into results suitable for analysis. Solving the first challenge requires developing software models and algorithms for generating an electrical control signal that excites mechanical vibroimpact oscillations. Several issues remain unresolved, including limitations in the impact mechanism's drive power, which hinder

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deep-level monitoring, and system inertia, which leads to insufficient acceleration and deceleration of the vibroimpact device.

The second challenge involves the automatic detection of anomalies and resonant modes in the received signal [5]. This calls for the development of universal signal processing methods and algorithms capable of effectively interpreting resonant characteristics under noisy conditions and within complex geometries of the surveyed objects.

Overcoming these scientific challenges is a prerequisite for transitioning from semi-manual systems to fully automated next-generation vibroacoustic systems. Such systems will significantly improve diagnostic accuracy, broaden the applicability of the method, and ensure timely detection of hazardous defects during the operation and safety monitoring of underground workings, deep structures, and technical systems.

Vibroacoustic data processing is most often based on theoretical principles of shear wave propagation in various media, their reflection from crack boundaries, and their absorption [6, 7]. However, laboratory studies of wave processes play a crucial role in accurately interpreting theoretical models. Such experiments allow verification and refinement of process mechanisms and help identify characteristic features and hidden patterns in the dynamics of wave propagation in different media

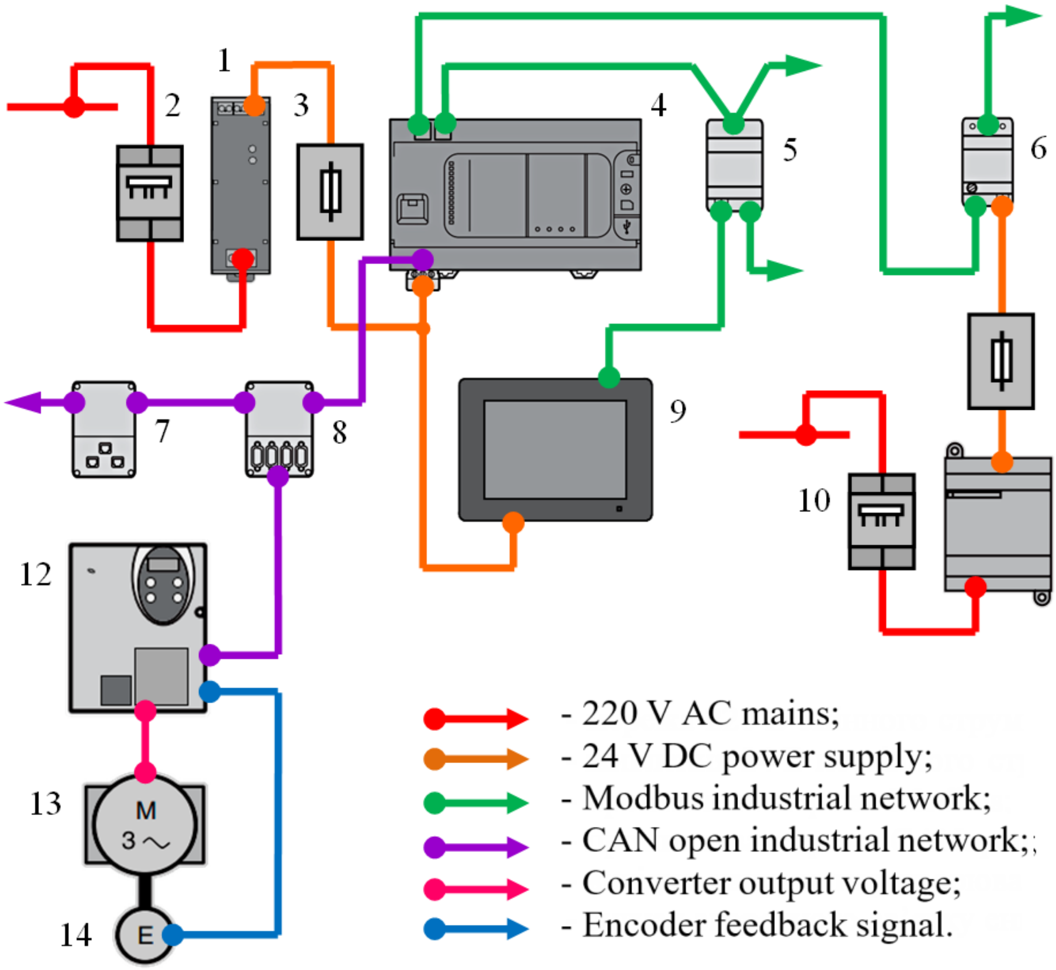
The aim of the study is to develop and experimentally validate digital models of wave processes for data processing tasks in vibroacoustic monitoring used in the practical assessment of the state and safety of engineering structures.

2. Methods

Laboratory experiments, software-based methods for constructing digital models of vibration excitation, and techniques for simulating the propagation of shear waves were used in the study.

To conduct laboratory experiments on the propagation of excitation and reflected shear waves, a functional scheme of the laboratory plant was developed (Fig. 1), a test bench with the necessary equipment was assembled, and the required software was created. It consists of a Schneider Electric programmable logic controller (PLC) designed for controlling industrial equipment, automating machinery, and building distributed control systems (Fig. 1, pos. 4). The controller is connected to the Schneider Electric “Lexium LXM05AD10M2” servo drive and serves as the central control unit, ensuring real-time system coordination (Fig. 1, pos. 12). It processes signals according to a predefined program, generates control pulses and commands for the servo drive, and sets the required position, speed, or torque. Thanks to its high-speed outputs and CANopen support, the controller provides precise motion synchronization and ensures smooth and reliable drive operation. Within the study in the laboratory plant, it is used for developing algorithms to control vibroacoustic oscillations and to adjust the positioning system.

The laboratory plant incorporates a BSH0701P01A2A electric motor (Fig. 1, pos. 13), which is fitted with an encoder. The encoder is a sensor used to determine the position, speed, and direction of the motor shaft's rotation (Fig. 1, pos. 14). The encoder enables precise motion reproduction with position, speed, and acceleration feedback, allowing for the simulation and development of high-precision control systems. It is mounted on the motor shaft and provides feedback to the controller to compensate for deviations and mechanical errors in the operation of the laboratory plant. A Magelis XBTGT2120 touch panel (Fig. 1, pos. 9) serves as the operator interface providing visualization of operating parameters, input of control commands, and interactive configuration of the plant.



1, 11 – power supplies; 2, 10 – circuit breakers; 3 – fuse; 4 – programmable logic controller (PLC); 5 – Modbus industrial bus splitter without optical isolator; 6 – Modbus industrial bus splitter with optical isolator and separate power supply; 7, 8 – CANopen industrial network splitters; 9 – touch panel; 12 – servo drive; 13 – electric motor; 14 – encoder

Figure 1 – Functional diagram of the laboratory plant

Algorithms for conducting experiments and analyzing data were developed, and digital models were created to study wave processes. Modeling was performed on a flexible element representing a mechanical system approximated by a chain of discrete masses connected by flexible, massless links. This discrete approximation made it possible to accurately reproduce the dynamics of the distributed system and to investigate the propagation of shear waves along the flexible element.

Within the modeling framework, variations in wave shape and wavelength were studied under different tension values, and the influence of joint backlash on the chaotic behavior of the oscillatory process was analyzed.

The upper end of the flexible element (the first link) was rigidly fixed to the rim of a disk mounted directly on the motor shaft, which eliminated slippage. The boundary conditions of the lower end (the last link) were varied between experimental series: free condition, fixed condition, and immersion in a viscous medium.

The oscillations were recorded using a video capture method, which allowed tracking of the instantaneous positions of points along the flexible element. The resulting video sequence was processed frame-by-frame: each frame was converted into a separate layer; each layer number corresponds to a specific moment in time. For further visual analysis and identification of waves resulting from different excitations, each time layer was assigned a unique color tone.

The laboratory plant for generating vibroacoustic oscillations was tested at the authorized training center of the French energy and engineering corporation Schneider Electric (Dnipro University of Technology). During testing, the laboratory plant demonstrated full operational capability and complete compliance with the declared technical specifications.

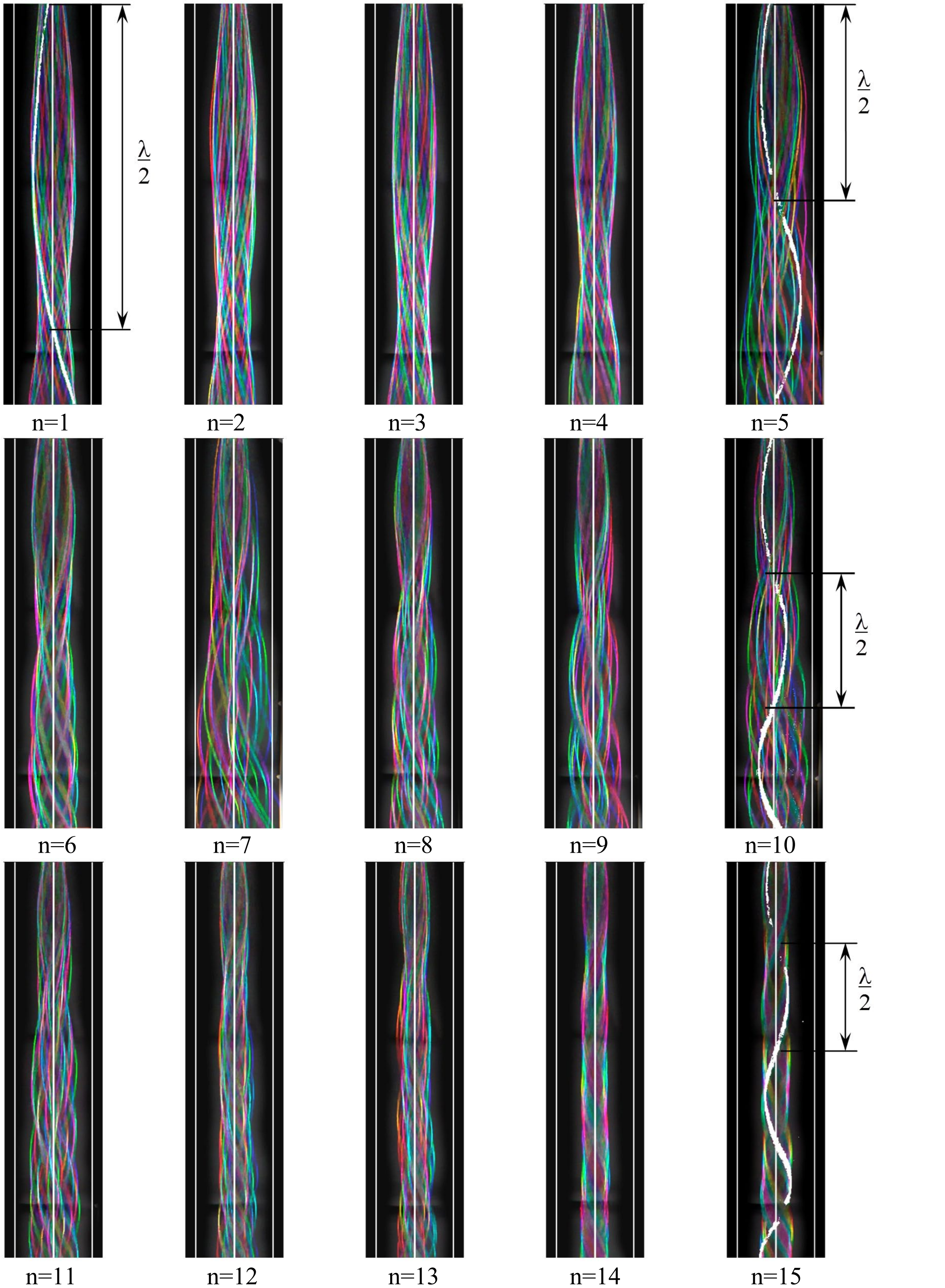
3. Results and Discussion

The study focused on investigating the propagation of shear waves along a freely suspended vertical flexible element, modeled as a system of interacting mass pairs. In particular, monochromatic harmonic oscillations with sequentially increasing frequency were generated. Pulse excitation waves and switching waves were also simulated.

Visual analysis of the photo prints of the monochromatic oscillations (Fig. 2) showed that the upper part of the flexible element model performed ordered oscillations, since its top end was rigidly fixed to the disk and the motor shaft. The motions of the lower part of the flexible element exhibit chaotic oscillations, which are particularly pronounced at certain frequencies (the 5th, 7th, and 10th sinusoidal components show the strongest chaotic behavior, Fig. 2). This is a manifestation of the edge effect of the model, which introduces a slight nonlinearity into the system due to the varying conditions of wave reflection at different positions along the lower part of the flexible element. The initial wavelength, λ_0, is determined by the oscillation frequency of the motor shaft (excitation frequency) and the propagation velocity of the transverse wave along the flexible element of the model [8]:

$$\lambda_0 = \frac{v}{f} \text{ m}, \tag{1}$$

where λ_0 is the initial wavelength, m; v is the propagation velocity of the transverse wave along the flexible element, m/s; f is the oscillation frequency of the motor shaft, Hz.



 – color designation of the moment of time; *n* – the number of the harmonic wave (experiment number); *λ*/2 – half the length of the transverse wave

Figure 2 – Modeling the propagation of ordered and chaotic transverse waves during monochromatic free oscillations of pairwise-interacting masses

However, the wavelength of the transverse wave gradually decreases with increasing distance from the excitation source due to changes in the conditions of wave propagation (for the 5th, 10th, and 15th sinusoidal components, Fig. 2). Near the source of oscillations, the amplitude and energy of the wave are higher, and the tension in the flexible element modeling the wave is more significant. As the distance from the exciter increases, the tension in the flexible element gradually decreases, and the external excitation weakens, leading to a reduction in the propagation velocity of the oscillations. Since the wavelength is directly related to the propagation velocity at a constant frequency, the decrease in velocity caused by damping results in a reduction of the wavelength. This relationship can be described by the following analytical expression:

$$\lambda(r) = \frac{1}{f}\sqrt{\frac{T(r)}{\mu}e^{-ar}} \text{ m,} \tag{2}$$

where $T(r)$ is the tension of the element at a distance r, N; μ is the linear density of the flexible element, kg/m; α is the damping coefficient, 1/m; $e^{-\alpha r}$ is the exponential decrease in amplitude and velocity due to losses associated with damping.

Since the actual tension of the flexible element contains a random component, the function $T(r)$, accounting for weight, backlash in the links, and inevitable chaotic effects, is represented as:

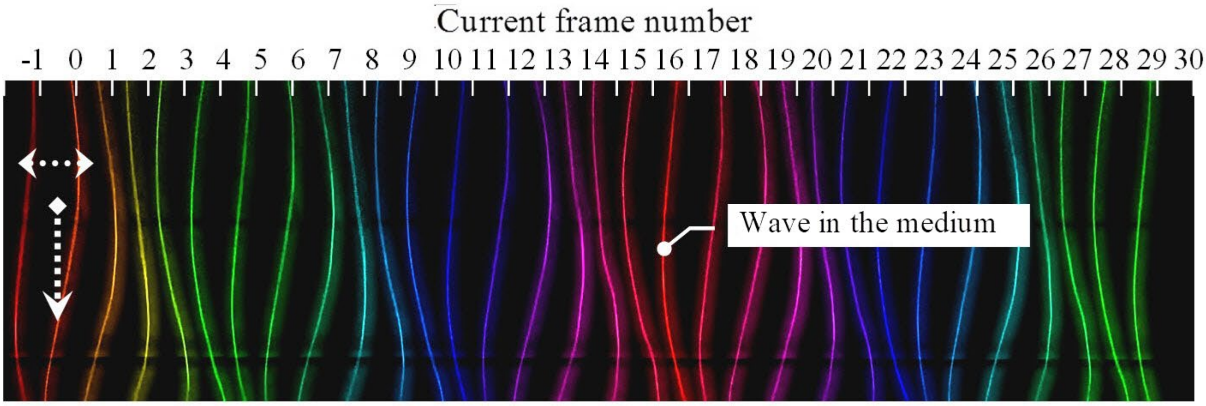
$$T(r) = T_0 - k(r) + \xi(r) \text{ N,} \tag{3}$$

where T_0 is the deterministic component under the ideal tension of the flexible element; k is the linear decrease in tension along the length of the flexible element, $k \geq 0$, N; $\xi(r)$ is the random component with zero mean and variance $\sigma^2(r)$.

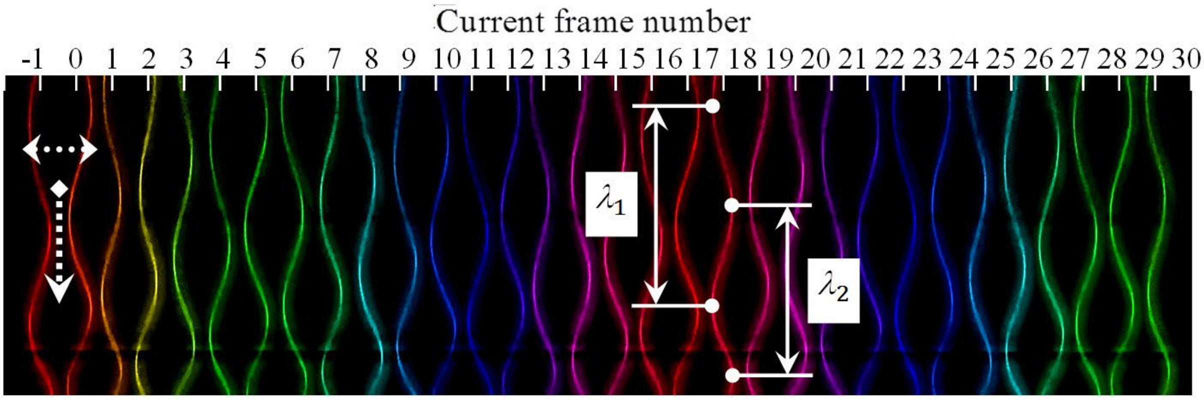
The application of equation (2) with the factors considered in relation (3) has the following limitations: the behavior of the element is described by linear elasticity; transverse bending angles are small; the element is homogeneous in mass per unit length; and there are no bad local defects that could lead to rupture.

Thus, the flexible element of the laboratory model can be regarded as a cellular automaton, where each link (individual mass) acts as a cell interacting with neighboring links, with the interaction strength increasing with proximity and the tension of the flexible element. Two fundamental properties of the cellular automaton are observed: the new states of system elements depend solely on their immediate neighborhood, and complex structures spontaneously emerge from simple initial conditions. Energy inputs applied to an individual link primarily affect this link and its nearest neighbors, creating a “spike” or zone of anomalous excitation.

The effect of wavelength reduction can also be observed in Fig. 3, which shows undamped transverse waves interacting in pairs, with frame-by-frame time unfolding under a constant, long-duration harmonic excitation. The wavelength λ_2, measured between two wave maxima within a specific frame at time t corresponding to frame number n, is smaller than the wavelength λ_1, which is measured between two maxima of opposite sign at the same moment in time in the same frame at a higher geometric position with a displacement ≈π.



a) Wave with frequency $3 \cdot f$



b) Wave with frequency $7 \cdot f$

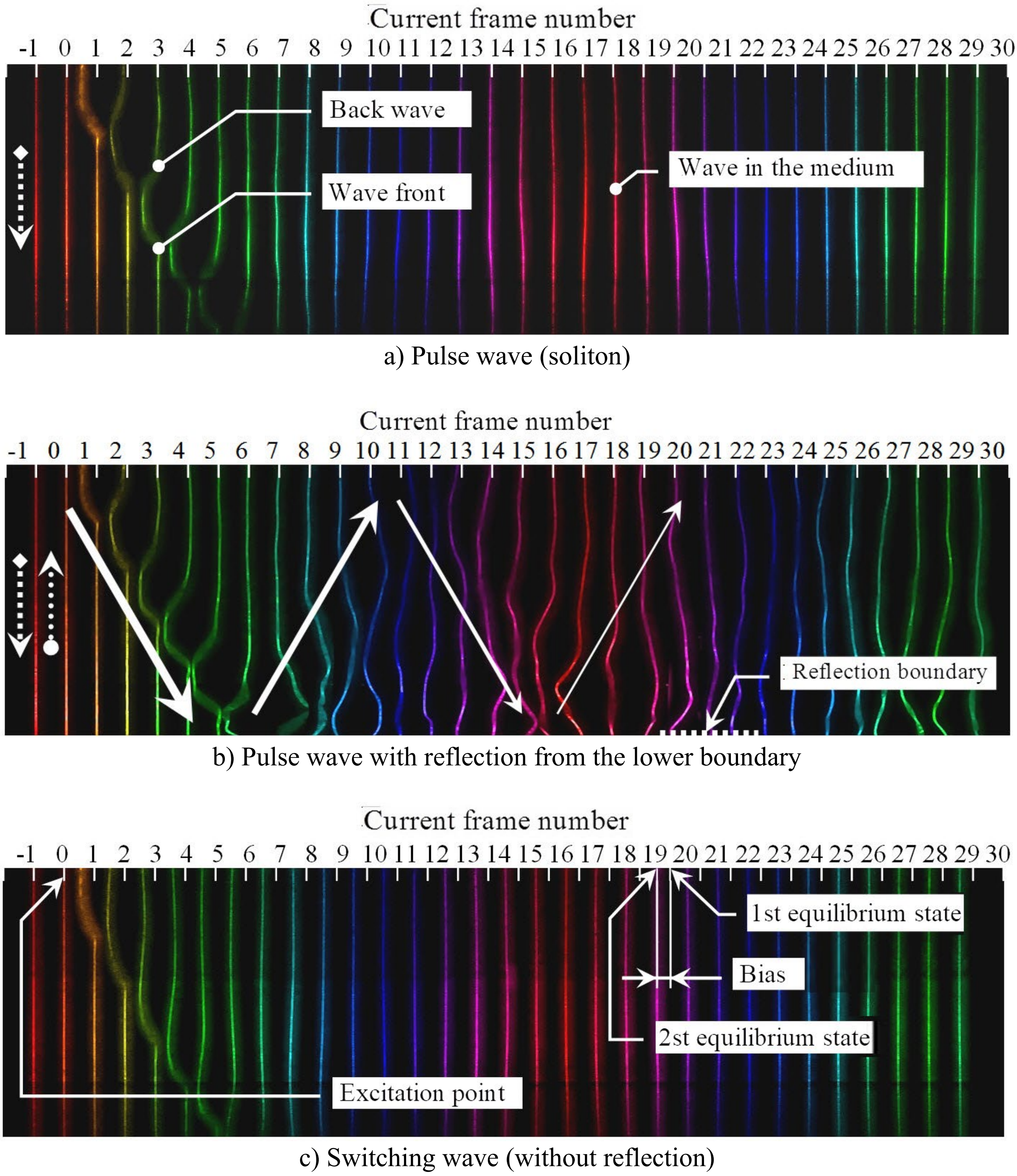
– color designation of the moment of time; – direction of propagation of the transverse wave (behind the first front); – direction of movement of masses (direction of oscillations)

Figure 3 – Result of a laboratory experiment on the propagation of transverse waves interacting pairwise in time under constant harmonic disturbance

A series of experiments similar to those shown in Fig. 3 demonstrates that the ratio of wavelengths arising in the flexible element across different experiments is determined by the ratio of harmonic numbers. To control the motor generating the wave oscillations, a cyclic scanning of harmonics is organized. At each iteration of the cycle, the corresponding amplitude and initial phase are selected. These parameters are then used to compute the sinusoidal component of the harmonic.

Experiments were conducted on the propagation of a single wave generated by a short excitation on the motor shaft, both without reflection from the lower boundary and with reflection under the condition that the lower link of the flexible element model is fixed (Fig. 4a, b), as well as on the propagation of the switching wave from the first stable state to the second stable state with a displacement Δ (Fig. 4c).

Experiments showed that a single transverse wave, generated by a short-duration disturbance such as a vibrational impact, possesses stable properties and propagates through the medium without distorting its shape. Unlike conventional waves that gradually dissipate, this wave maintains its amplitude and structure. Its velocity is directly related to its amplitude: the higher is the amplitude, the faster the wave propagates.



a) Pulse wave (soliton)

b) Pulse wave with reflection from the lower boundary

c) Switching wave (without reflection)

– frame number color coding; – direction of propagation of the first excitation wave; – direction of propagation of the first reflected wave

Figure 4 – Result of a laboratory experiment on the propagation of solitary perturbation waves interacting in pairs with a frame-by-frame time sweep

If the medium is unbounded, the wave travels uniformly in one direction. When reflected from a nearly ideal boundary with minimal energy absorption, the wave returns in the opposite direction, retaining its stable shape and structure. Depending on the boundary's properties, this reflection is accompanied by a phase change (inversion) or occurs without alteration. Upon encountering an energy-absorbing boundary, the wave's amplitude decreases; however, a pattern significant for vibroacoustics is observed: the waveform and characteristics of the wave process remain stable during further propagation.

In the experimental plant, to prevent rupture of the flexible element model, the bottom mass (link) was elastically attached to the base. The presence of backlash in the mounts led to partial chaotic behavior of the oscillations, which increased waveform distortion and caused wave splitting (Fig. 4, b). In real systems, additional nonlinear effects during wave propagation and reflection further reduce the stability and integrity of the solitary wave.

The developed visualization method, which employs frame-by-frame temporal unfolding and color mapping of time intervals, enables the analysis of oscillations and wave propagation in various complex objects with distributed and point masses. This opens prospects for its application in processing and interpreting vibroacoustic data by creating digital twins of real processes, making it an effective tool for technical system diagnostics, structure state monitoring, and studying distributed oscillatory processes in engineering practice.

The research results hold promise for application in the vibroacoustic monitoring of structures and technical systems, leading to: improved accuracy of structure diagnostics; identification of local and distributed defects; enhanced interpretation of vibroacoustic signals for structure state monitoring.

4. Conclusions

1. A functional schematic of a laboratory plant was developed to create and experimentally validate digital models of wave processes for vibroacoustic data processing tasks. A test bench was assembled, comprising the necessary equipment and software. A series of laboratory experiments was conducted to study the propagation of excitation transverse waves and reflected waves. The experiments involved generating monochromatic harmonic oscillations with sequential frequency increases, as well as simulating impulse excitation waves and switching waves.

2. The experiments established that upon interaction with an absorbing boundary, the amplitude of the transverse wave decreases; however, the waveform and the fundamental characteristics of the wave process remain stable during subsequent propagation. Under real conditions, the propagation of transverse waves exhibits both deterministic and stochastic nature due to complex reflection conditions. In a dispersive medium, where damping is accompanied by a decrease in phase velocity, a corresponding reduction in wavelength is observed. These findings can enhance the practical assessment of the engineering structure safety.

3. An enhanced approach to vibroacoustic analysis is proposed, based on creating digital twins of wave processes. Its foundation comprises digital models of oscillation

excitation and a visualization method that combines frame-by-frame temporal unfolding with color mapping of time intervals. This enables qualitative and, upon further refinement, quantitative analysis of wave propagation in complex objects with distributed and point masses. The developed methodology shows good potential for practical application in diagnosing and monitoring the structure state and safety.

Conflict of interest

Authors state no conflict of interest.

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ЛАБОРАТОРНІ ДОСЛІДЖЕННЯ ХВИЛЕВИХ ПРОЦЕСІВ ДЛЯ ЗАДАЧ ОБРОБКИ ДАНИХ ВІБРОАКУСТИЧНОГО КОНТРОЛЮ БЕЗПЕКИ СПОРУД ТА ТЕХНІЧНИХ СИСТЕМ

Яланський О., Слащова О., Селезньов А., Бріженюк В., Дігтяр К., Іконніков М.

Анотація. Стаття присвячена вдосконаленню систем автоматизації віброакустичного контролю стійкості та безпеки споруд. Мета роботи полягає в побудові та лабораторній апробації цифрових моделей хвилевих процесів для задач обробки даних віброакустичного контролю та практичної оцінки стану безпеки інженерних споруд. Методи дослідження: аналіз експериментальних даних; програмні методи побудови цифрових моделей; лабораторні експерименти; моделювання поширення поперечних хвиль. Аналіз показав доцільність проведення лабораторних досліджень хвильових процесів для верифікації теоретичних моделей, виявлення характерних ознак та прихованих закономірностей динаміки поширення хвиль у різних середовищах. Створено функціональну схему лабораторної установки для збудження віброакустичних коливань, яка реалізована та апробована на базі авторизованого навчального центру французької енергомашинобудівної корпорації «Schneider Electric» в Дніпровському університеті технологій. Розроблено алгоритми та програмне забезпечення для моделювання поширення збуджувальних та відбитих поперечних хвиль. Згенеровано монохромні гармонійні коливання з послідовним підвищенням частоти, змодельовано хвилі імпульсного збудження та перемикання. Експериментально встановлено, що при взаємодії з поглинаючою границею амплітуда поперечної хвилі зменшується, однак зберігається форма та основні характеристики хвильового процесу при подальшому поширенні. Спостерігається суттєва для віброакустики закономірність: поширення хвиль має детермінований характер з накладенням стохастичних компонентів, зумовлених складними умовами відбиття. Розвинено підхід до аналізу даних віброакустичного контролю, що передбачає побудову цифрових моделей збудження коливань для створення цифрових двійників реальних хвильових процесів шляхом візуалізації коливань з покадровою часовою розгорткою та колоризацією часових інтервалів. Це дозволяє проводити комплексний аналіз коливань і процесів поширення хвиль у складних об'єктах. Отримані результати можуть бути використані для практичної інтерпретації віброакустичних сигналів та моніторингу безпеки інженерних споруд.

Ключові слова: безпека експлуатації споруд, автоматизація віброакустичного контролю, моделі хвилевих процесів, обробка даних.