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DEVELOPMENT AND TESTING OF DIGITAL FILTER MODELS FOR AUTOMATION OF A STRUCTURE VIBROACOUSTIC MONITORING AND ITS SAFETY ASSESSMENT

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Abstract. The article is devoted to the improvement of data processing and analysis methods in automated vibroacoustic diagnostic systems for structures. The aim of the study is to develop and test digital data processing models for automating vibroacoustic damage diagnostics and safety assessment of structures. Methods: analysis of scientific sources on vibroacoustic data processing; laboratory studies of signal filtering; modeling of digital filters; software-based data processing methods. The analysis showed that methods and algorithms for automatic processing of vibroacoustic signals are still underdeveloped, particularly those capable of effectively interpreting resonance characteristics under conditions of noise and complex geometry of inspected objects. Structures and Mathcad models of low- and high-pass digital filters of the second, third, and fourth degrees were developed. The response of the proposed models to typical inputs—step, sinusoidal, triangular, and "sawtooth" signals—was determined. The functionality of the developed models was confirmed, including the behavior of transient processes and the phase shift depending on the filter degree. It was established that the application of the proposed digital filter models ensures: suppression of noise generated by acoustic wave reflections from randomly distributed crack systems; extraction of the useful frequency range; smoothing of signals for identifying dominant and most hazardous cracks. The novelty of applying the developed models with filters of various degrees for vibroacoustic damage detection and safety assessment of structures lies in the fact that the filter degree can automatically adapt to a specific task or change dynamically. During data processing, filters of different degrees are combined to eliminate non-informative noise without introducing significant distortions into the instrumental control data of the object. The developed models can be applied in practical research for processing vibroacoustic diagnostic signals of structure damage and its safety assessment using computers in automated systems and digital instruments for real-time monitoring.

Keywords: structure safety, vibroacoustic control, automation, data processing, digital filters.

1. Introduction

The problem of ensuring the reliability and safety of structures is particularly important. A significant part of the infrastructure has been in operation for decades, experiencing natural wear, temperature fluctuations, flooding, as well as additional loads and damage caused by dynamic impacts from earthquakes and explosions. Many defects in the form of microcracks or hidden damage cannot be visually detected, but they may pose a serious threat to the stability of structures and the safety of people. Under such conditions, there arises the need to apply control methods that allow the assessment of structure condition without its destruction or dismantling. Vibroacoustic diagnostics occupy a special place among such methods. This approach is based on the registration and analysis of acoustic and vibration signals that occur during the operation of a structure or under its purposeful excitation by impact loads. Such an approach makes possible to detect even small defects due to its high sensitivity to crack growth processes and local failures [1, 2]. An important advantage of the method is the possibility of continuous non-destructive monitoring of structure conditions in real time, which is especially relevant for high-risk objects (tunnels, dams, industrial and energy facilities).

The relevance of applying vibroacoustic diagnostics is determined by a combination of factors. First, there is the need to ensure control of damaged infrastructure,

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where traditional inspection methods may be insufficient [3]. Second, there is a high level of development of the national scientific school in the field of acoustic emission and vibroacoustic monitoring [4–6], confirmed by the development of standards and specialized instruments. However, the effectiveness of the vibroacoustic method depends on the degree of its automation. Currently, methods and algorithms for signal processing that are able to effectively interpret resonance characteristics under conditions of noise and complex geometry of inspected objects remain underdeveloped [7–10]. At the same time, the development of digital technologies allows significant improvement in noise filtering, extraction of useful frequency ranges, and automatic data interpretation, which provides more accurate and reliable determination of structure damage. Therefore, one of the main tasks is the automatic detection of anomalies and resonance modes in the received signal, which requires further scientific research and appropriate engineering implementation.

The aim of this study is to develop and test digital data processing models for the automation of vibroacoustic diagnostic systems for damage detection and safety assessment of structures.

2. Methods

The research methods cover the analysis of scientific sources, laboratory studies, digital filter modeling and software methods for processing vibroacoustic monitoring data.

For digital processing of vibroacoustic monitoring data, the analog continuous response signal recorded by the instrument's receiver must be converted into a sequence of discrete samples of the current signal levels {x(tμ)} using an analog-to-digital converter. As a result, a digital sequence of numbers is obtained, which describes the instantaneous values of the output signal in time. These samples are fed into a filter, where digital data processing (filtering) is performed. In this case, the filter implements a given digital transfer function. The transfer function of a low-pass filter, in the general case, can be written as

$$W(p) = A(P) = \frac{A_0}{1 + c_1 P + c_2 P^2 + \ldots + c_i P^i + \ldots + c_n P^n} = \frac{A_0}{1 + \sum_{i=1}^{n} c_i P^i} \quad , \qquad (1)$$

where A_0 - is the filter amplification coefficient; c_1, c_2, … , c_i, … c_n – are positive real coefficients.

As a result, at the output a new sequence of samples {y(tμ)}is formed, which possesses the necessary frequency properties for processing the vibroacoustic signal. The most important processing tasks for vibroacoustic monitoring data are: suppression of noise arising from reflections of acoustic waves from randomly distributed crack systems; extraction of the useful frequency range for the most effective monitoring; smoothing of the signal, which is necessary for identifying dominant and most hazardous cracks. During further processing, the sequence {y(tμ)}is used in digital form for data analysis and interpretation.

The type of filter is determined for a specific diagnostic task. Specifically, the Butterworth filter provides minimal amplitude distortion in the passband, while the Bessel filter provides minimal phase distortion. The criteria of optimality assume minimizing the root-mean-square or phase errors. Digital filters are implemented in accordance with developed Mathcad models based on general-purpose microcontrollers with the 8-bit MCS 51 architecture and the 32-bit ARM STM32 architecture. Modeling of certain specific filter implementations is performed using the Filter Design Toolbox and Simulink extensions for the Matlab mathematical package. These technical tools make it possible to implement filters with the parameters required for solving vibroacoustic diagnostic tasks.

3. Results and discussion

In the course of the research, digital filter structures were obtained, and Mathcad models of low- and high-pass filters of the second, third, and fourth degrees were developed in order to preliminary verify their performance and compliance of their characteristics with analog prototypes.

The software blocks of the models are presented in Fig. 1 (the vertical line denotes the body of an integral program unit, such as a module or loop). The figure shows: ↓k – the operator of filter transformation of degree k; X – the formal parameter of the program block used to transmit the vector of current input signal values; Nel – the formal parameter of the program block used to transmit the number of elements in the input signal vector; i – the integer index variable; R10, R10 ,…, Rk0 – the initial values of the corresponding internal coordinates R1i, R1i ,…, Rki , which are the input signals for the delay elements of the digital filter structural scheme; Y0– the initial value of the output signal Yi of the filter; Y – the formal parameter of the program block used to transmit the vector of current output signal values.

```
↓3(X,Nel) := | i ← 1
             | (R1₀ ← 0  R2₀ ← 0  R3₀ ← 0)
             | Y₀ ← 0
             | while  i < Nel
             |    | Yi ← D3·Xi + R3i−1
             |    | R1i ← D0·Xi − C0·Yi
             |    | R2i ← D1·Xi − C1·Yi + R1i−1
             |    | R3i ← D2·Xi − C2·Yi + R2i−1
             |    | i ← i + 1
             | Y
```

a)

```
↓4(X,Nel) := | i ← 1
             | (R1₀←0  R2₀←0  R3₀←0  R4₀←0)
             | Y₀ ← 0
             | while  i < Nel
             |    | Yi ← D4·Xi + R4i−1
             |    | R1i ← D0·Xi − C0·Yi
             |    | R2i ← D1·Xi − C1·Yi + R1i−1
             |    | R3i ← D2·Xi − C2·Yi + R2i−1
             |    | R4i ← D3·Xi − C3·Yi + R3i−1
             |    | i ← i + 1
             | Y
```

б)

Figure 1 – Software models of third-degree (a) and fourth-degree (b) low-pass filters

Inside the program block model, a “while” loop with the index variable i is organized, in which the vector of current input signal values is scanned, and new current values of the output signal Yi and internal coordinates R1i, R1i,…, Rki are calculated.

Testing showed that the digital implementation of the developed Mathcad models based on microcontrollers ensures the required calculation accuracy depending on the bit depth of the data representation and the calculated frequency characteristics depending on the ratio of the microcontroller clock frequency to the selected filter degree.

The response of the developed models to typical input signals - step, sinusoidal, triangular, and sawtooth signals (Fig. 2) - was determined with different values of coefficients of the analog prototype filters, in particular for filters with critical damping, Bessel, Butterworth, and Chebyshev type I with ripple characteristics of 0.5 dB and 1 dB. Figure 2 presents the graphs of the transient function (a) and the response to a sawtooth input signal (b) of low-pass filters (left) and high-pass filters (right) with critical damping of 2nd, 3rd, and 4th degrees, for which the coefficients were chosen according to [11].

The analysis of the oscillograms of the filter responses to typical inputs confirms the operability of the developed Mathcad models: the nature of transient processes, the phase shift depending on the filter degree, and the steady-state values of the output signal correspond to their analog prototypes. In particular, for a linearly increasing input signal, we observe a linear increase of the low-pass output signal with the same rate, while for the high-pass filter the output signal stabilizes and is maintained at a level corresponding to the rate of change of the input signal (Fig. 2). In the steady-state mode, the low-pass output signal stabilizes at the level of the input signal (in relative units normalized to the unity gain coefficient A0=1), while the high-pass output signal decays to zero and remains stabilized at that level.

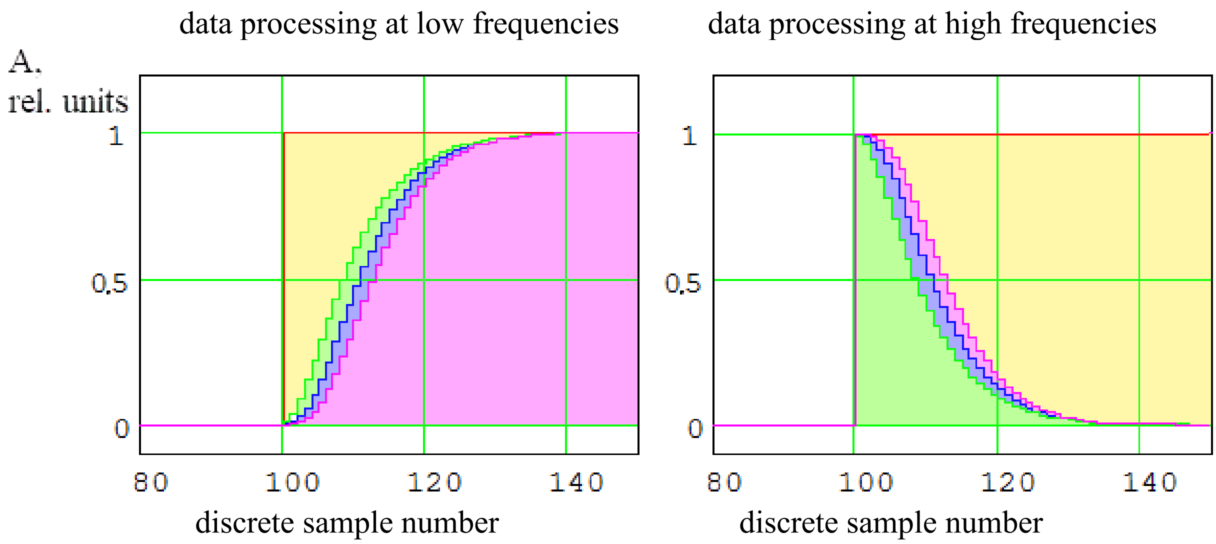

Figure 2 – Simulation of the response of developed digital filters to a step change of the input signal

Using a test harmonic signal with linearly increasing frequency, amplitude-frequency characteristics were constructed for the obtained filter models, where amplitude is plotted as a function of the normalized current frequency relative to the sampling frequency (Fig. 3). The figure shows the corresponding graphs for low-pass and high-pass filters with critical damping, within the frequency range from 1 rel. units (LF) to the frequency at which the effect of input signal distortion (aliasing) begins to manifest significantly. For better visualization and simplification of analysis, the graphs are plotted in logarithmic scale. The obtained characteristics qualitatively and quantitatively correspond to the characteristics of analog prototypes, which confirms the functionality of the developed digital filter models.

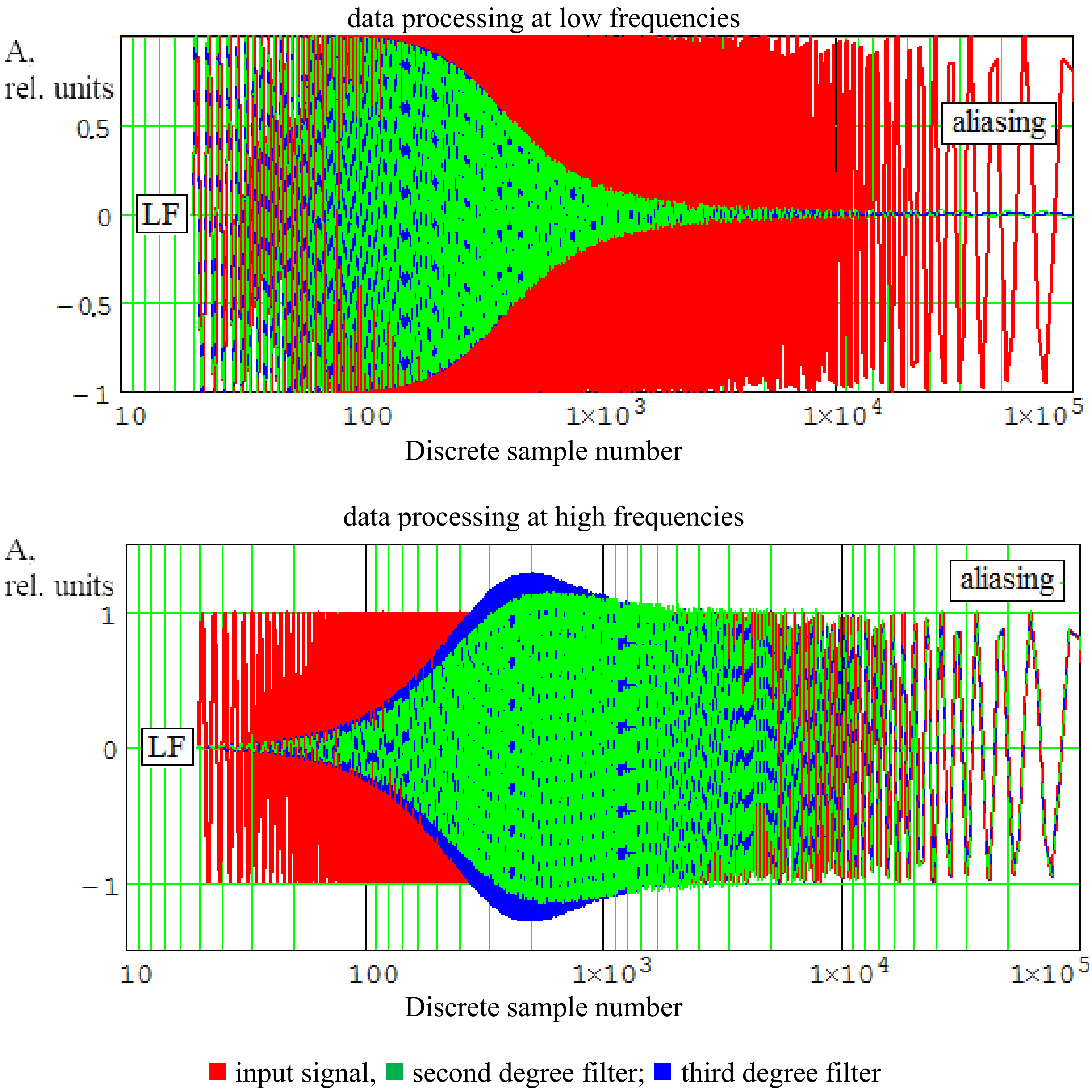

Figure 3 – Amplitude-frequency characteristics of filters in logarithmic scale

The difference between filters of various degrees is one of the key aspects of digital data filtering. The degree of a filter determines the number of coefficients in the digital transformation. The higher is the degree, the more strongly the filter “cuts off” frequencies outside the working band. A first-degree filter produces a gradual spectrum roll-off, a second-degree filter produces a steeper roll-off, and so on. Thus, the use of filters of different degrees allows selecting a compromise between the quality of acoustic data filtering and the complexity of implementation (flexibility). In particular, in simple sensors, a first- or second-degree filter is sufficient to suppress noise. A low-degree filter performs fewer operations and conserves microcontroller resources. A high-degree filter performs more operations but provides greater accuracy. Figure 4 illustrates the influence of filter degree on the shape of the amplitude-frequency characteristic. The parameters and transient characteristics of the developed models also correspond to the prototypes, whose characteristics are presented in [11].

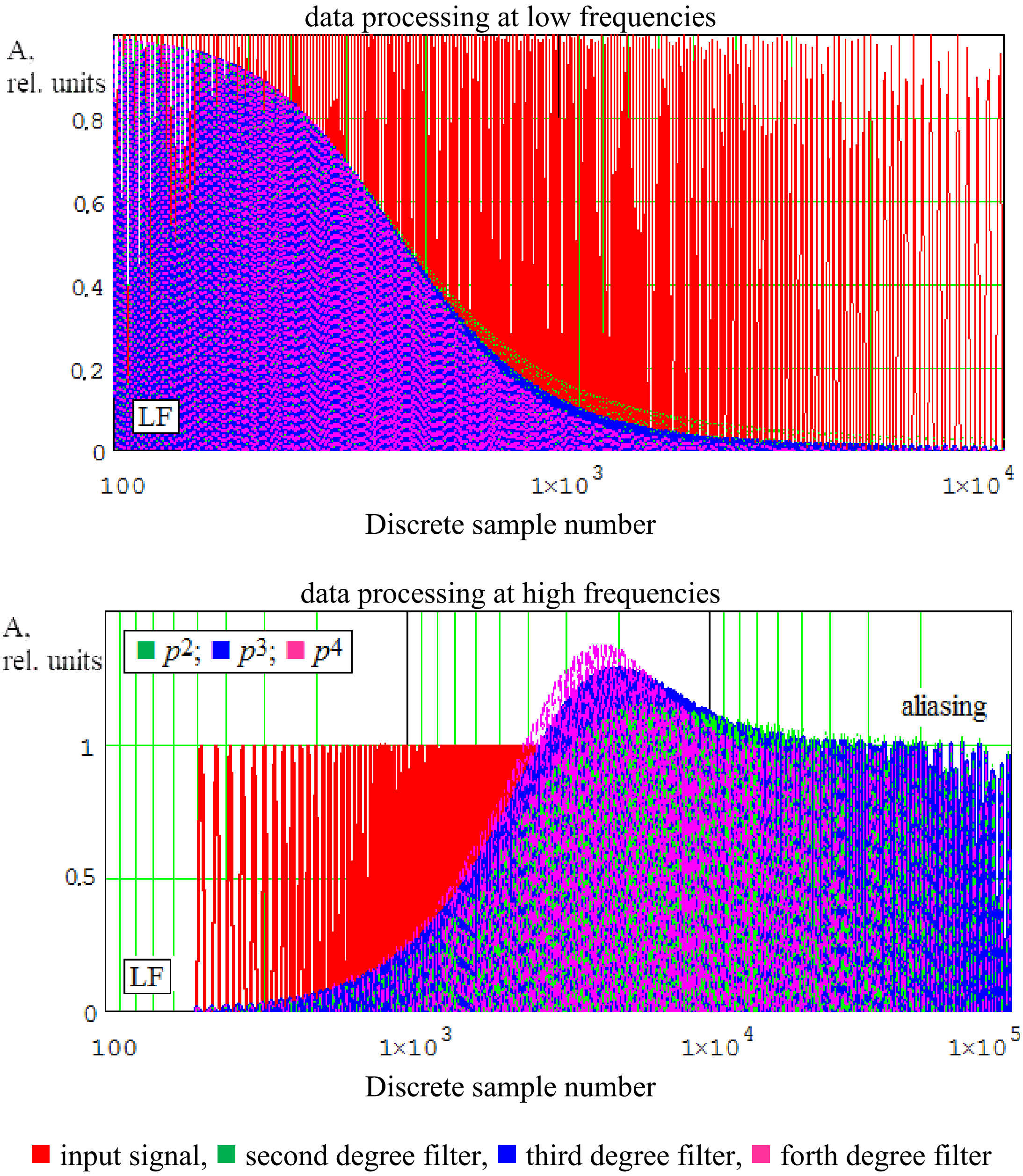

Figure 4 – Amplitude-frequency characteristics of digital filters of different degrees in logarithmic scale within a narrowed frequency range

In a short fragment of the oscillogram with an expanded discrete-time axis (Fig. 5), the input signal and the signal after processing by digital filters are presented. The performed processing of vibroacoustic monitoring data demonstrated that the use of digital filters ensures effective suppression of noise generated by the reflection of acoustic waves from randomly distributed crack systems. The useful frequency range is extracted, which improves the efficiency of diagnostic monitoring, and the signal is smoothed, enabling the identification of dominant and most hazardous cracks.

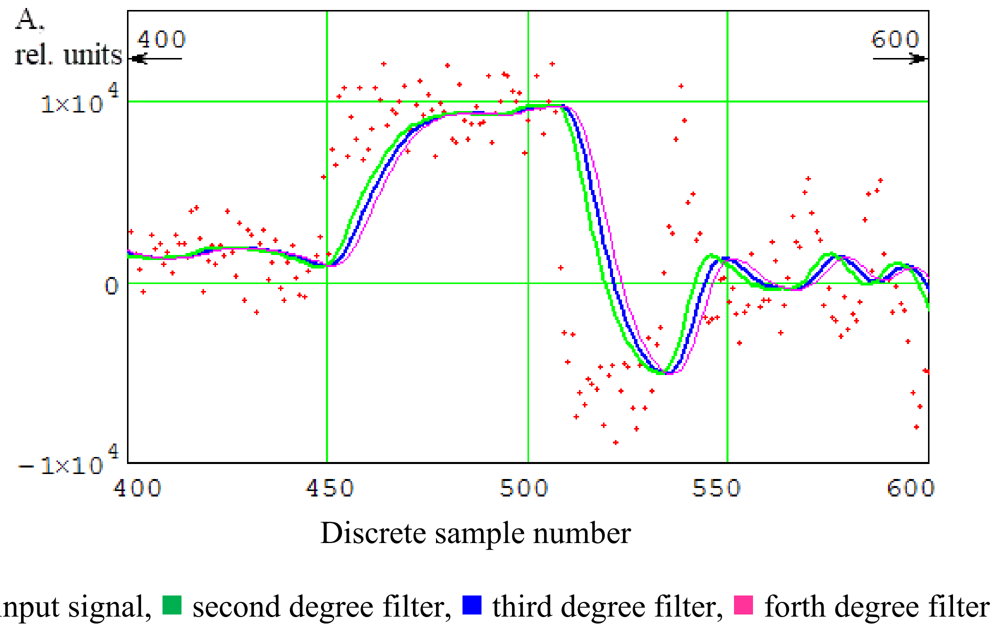

Figure 5 – Result of processing vibroacoustic diagnostic data
(input and digitally filtered signals on a short fragment of the oscillogram with an expanded discrete-time axis are shown)

The novelty of applying methods with filters of different degrees for vibroacoustic monitoring of structure damage and safety lies in the fact that the filter degree can be adapted to a specific task or dynamically adjusted. In adaptive filters, the degree may change depending on the spectrum of the input signal, data transmission conditions, or quality requirements. During data processing, filters of different degrees can be combined in order to, on the one hand, eliminate non-informative noise, and on the other hand, avoid significant distortions of instrumental monitoring data of the object.

So, the developed models meet the adequacy criteria and can be used in practical researches for processing vibroacoustic diagnostic signals – both using computers in automated systems and digital instruments for real-time monitoring. Thus, the application of the developed models and implementations of digital filter provides broad opportunities for controlling frequency response and eliminating distortions during response processing at automated vibroacoustic monitoring of structure damage and safety. Moreover, modern software methods make possible dynamic or combined use of filters to achieve reliable monitoring results.

4. Conclusions

1. Processing of vibroacoustic monitoring data showed that the use of the developed digital filter models ensures effective suppression of noise generated by the reflection of acoustic waves from randomly distributed crack systems. At the same time, the useful frequency range is extracted, which improves monitoring efficiency, and the signal is smoothed to identify dominant and most dangerous cracks.

2. As a result of the research, structures and Mathcad models of low-pass and high-pass digital filters of the second, third, and fourth degrees were obtained. The response of the developed models to typical inputs—step, sinusoidal, triangular, and sawtooth signals—with different values of analog prototype filter coefficients was determined. Analysis of the filter responses to typical inputs confirmed the operability of the developed models: the nature of transient processes and phase shifts depending on filter degree. The steady-state values of the output signals correspond to their analog prototypes.

3. The scientific novelty of this study lies in the possibility to adapt the filter degree to specific vibroacoustic damage and safety monitoring tasks, or to change it in dynamics. In adaptive filters, the degree can be changed depending on the input signal spectrum, data transmission conditions, or quality requirements. During data processing, a combination of filters of different degrees is used, allowing, on the one hand, to eliminate uninformative noise and, on the other, to avoid significant distortions in the instrumental monitoring data of the object.

4. The developed models can be applied in practical studies for processing vibroacoustic diagnostic signals of structure damage and assessing its safety using computers in automated systems as well as digital instruments for real-time monitoring.

Conflict of interest

Authors state no conflict of interest.

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РОЗРОБКА ТА АПРОБАЦІЯ МОДЕЛЕЙ ЦИФРОВИХ ФІЛЬТРІВ ДЛЯ АВТОМАТИЗАЦІЇ ВІБРОАКУСТИЧНОГО КОНТРОЛЯ І ОЦІНКИ БЕЗПЕКИ СПОРУД

Слащов І.М, Беліков А., Дегтярь К., Яланський О., Харченко В., Іконніков М.

Анотація. Стаття присвячена вдосконаленню методів обробки і аналізу даних в системах автоматизації віброакустичної діагностики споруд. Мета роботи полягає в розробці та апробації моделей цифрової обробки даних для автоматизації систем віброакустичної діагностики пошкодженості і оцінки безпеки споруд. Методи: аналіз наукових джерел щодо обробки даних віброакустичного контролю; лабораторні дослідження фільтрації сигналів; моделювання цифрових фільтрів; програмні методи обробки даних. Аналіз показав, що недостатньо розвинуто методи та алгоритми автоматичної обробки віброакустичних сигналів, які здатні ефективно інтерпретувати резонансні характеристики в умовах шумів та складної геометрії обстежуваних об'єктів. Розроблено структури і Mathcad-моделі цифрових фільтрів низьких та високих частот другого, третього та четвертого порядків. Визначено реакцію розроблених моделей на типові впливи: ступінчастий, синусоїдальний, трикутний сигнали та сигнал типу «пила». Підтверджена працездатність розроблених моделей: характер перехідних процесів, фазовий зсув в залежності від порядку фільтра. Встановлено, що застосування розроблених моделей цифрових фільтрів забезпечує: придушення шумів, які виникають при відбитті акустичної хвилі від хаотично розташованих систем тріщин; виділення корисного діапазону частот; згладжування сигналу для пошуку домінуючих і найбільш небезпечних тріщин. Новизна застосування розроблених моделей з фільтрами різного порядку для віброакустичного контролю пошкоджень та безпеки споруд полягає в тому, що порядок фільтра може автоматично адаптуватися під конкретне завдання або динамічно змінюватися. При обробці даних комбінуються фільтри різних порядків, щоб усунути неінформативні шуми, але і не вносити суттєвих викривлень в інструментальні дані контролю об'єкта. Розроблені моделі можуть застосовуватися в практичних дослідженнях для обробки сигналів віброакустичної діагностики пошкодженості і оцінки безпеки споруд за допомогою комп'ютерів в автоматизованих системах і в цифрових приладах оперативного контролю.

Ключові слова: безпека експлуатації споруд, віброакустичний контроль, автоматизація, обробка даних, цифрові фільтри.