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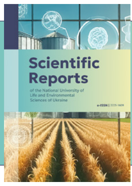

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Dynamics of vibration processes in the "tool – workpiece – bench" during material processing

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Abstract. The study aimed to identify effective methods for optimising and reducing vibration processes in the tool-workpiece-machine system to improve the stability and quality of machining. The study analysed the main types of vibrations in the tool-workpiece-machine system and determined their impact on machining quality, establishing that self-excited vibrations are the main cause of process instability. Classical approaches to cutting and a mathematical model for optimising machining parameters to reduce vibrations and increase the accuracy and efficiency of the technological process were considered. Analysis of classical methods has shown that fixed-angle and constant-feed methods provide stability and predictability of the process, while variable-feed and automatic control methods increase adaptability and reduce vibration amplitude. The simulations confirmed the effectiveness of parameter optimisation to stabilise vibrations and improve machining quality. According to the results of machining on the 1K62 machine with a T15K6 carbide tool, the roughness parameter was reduced from 6.3 to 1.6 microns due to optimisation of cutting modes and increased system rigidity. The study also showed a 40% increase in tool life when self-excited vibrations were eliminated. The generalisation of the data obtained formulated practical recommendations for the selection of machining parameters, considering the dynamic properties of the technological system, to ensure a stable cutting process and improve the quality of machining. The results obtained can be used by specialists of machine-building enterprises and scientists to improve the efficiency of production processes and product quality

Keywords: damping; amplitude; roughness; service life; oscillation; stability

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Introduction

The process of machining materials on metal cutting machines is accompanied by complex dynamic phenomena, including vibrations in the tool – workpiece – bench system. These vibrations affect cutting stability, reduce machining accuracy, degrade surface finish and accelerate tool wear. Self-excited vibrations that occur without external disturbances can lead to unstable operation of the entire technological system. The research relevance is determined by the need to study the dynamic characteristics of these processes to improve the performance and reliability of metalworking equipment. Identification of regularities in the development of vibration phenomena and the development of effective methods for their reduction make it possible to ensure stable operation of bench tools, improve the quality of the machined surface and extend the service life of the tool.

The problem of the dynamics of vibration processes in the system "tool – workpiece – bench" is relevant for improving the quality of machining and tool life. Z. Peng *et al.* (2020) identified critical machining conditions in which the vibration amplitude increases sharply due to the combination of high rotational speed and depth of cut. This highlighted the importance of optimal parameters to avoid process instability. I. Akande *et al.* (2020) demonstrated that increasing the stiffness of the machine structure significantly reduces resonant vibrations, while the introduction of damping elements increases the overall stability of the system. These measures contributed to improved machining quality and reduced tool wear. C. Kuo *et al.* (2023) determined that the shape and dimensions of the cutting edge have a direct impact on vibration, especially when machining materials with an uneven structure. This indicates the need to incorporate the geometric characteristics of the tool when developing cutting modes. Z. Li *et al.* (2021) developed nonlinear mathematical models that reproduce the dynamic processes of tool/workpiece interaction, including feedback effects, which explain the phenomenon of self-excitation of vibrations. These models further demonstrated the instability mechanisms. X. Vasanth *et al.* (2019) applied active vibration control systems using feedback, which ensured rapid damping of unwanted vibrations and increased machining accuracy. The introduction of such technologies has shown promise in industrial applications.

C. Zhao *et al.* (2022) analysed the effectiveness of various damping materials in reducing the amplitude of vibrations, identifying the best options for installation in a cutter holder. The use of such materials reduced dynamic loads on the tool. Y. Cheng *et al.* (2023) experimentally proved that increasing the rigidity of the technological system significantly improves the quality of the machined surface by reducing vibrations. Changing the cutting modes in combination with increased rigidity made it possible to reduce surface roughness. G. Weicheng *et al.* (2021) showed that proper tool clamping adjustment is a key factor in preventing vibrations that negatively affect process stability. Insufficient fixation contributed to additional vibrations. Y. Danylchenko *et al.* (2021) determined that irregularities on the workpiece surface increase the intensity of vibrations and lead to a deterioration in machining quality. Accordingly, pretreatment or workpiece preparation is essential to stabilise the process. Q. Wang *et al.* (2025b) proved that the dynamic properties of the system in the selection of cutting modes can significantly increase tool life and reduce the probability of accidents. The optimisation of parameters ensured more stable and efficient operation of the equipment.

These studies established the dependence of the vibration amplitude on cutting modes, machine design characteristics and tool geometry, developed mathematical models of the dynamic interaction between tool and workpiece, and proposed methods of active vibration control and the use of damping materials to reduce vibrations. In addition, experimental studies have confirmed the impact of system stiffness and tool clamping parameters on process stability and have shown the role of workpiece surface irregularities in amplifying vibrations. However, despite the significant achievements, there are gaps in the comprehensive consideration of the simultaneous influence of design, technological and material factors on the formation of vibration processes. Integrated approaches to vibration modelling and control, which incorporate the nonlinearity of the system and the variability of cutting conditions in real time, require additional study.

The study aimed to identify methods to optimise and reduce vibration processes in the "tool – workpiece – bench" system.

Tasks of the study:

1. To investigate the classification of types of vibrations in the tool-workpiece-machine system.

2. Consider classical approaches to the analysis of dynamic processes and vibration modelling.

3. Evaluate the effectiveness of various methods of vibration reduction and develop recommendations for their implementation.

Materials and Methods

The study conducted a comprehensive analysis of the dynamic processes in the tool – workpiece – bench system during machining with an emphasis on the physical characteristics of the elements that form the system's response to load. The study analysed various types of vibrations in the tool – workpiece – bench system to determine their characteristics and mechanisms of occurrence. The vibrations were classified into forced, free and self-excited, which determined their characteristics and impact on the technological process. This approach formulated the basis for diagnosing, monitoring and developing effective measures to reduce vibrations and improve machining stability. Also, the study analysed classical approaches to material processing in the tool – workpiece – bench system, including the following methods: free cutting method, fixed angle method, constant feed cutting method, variable feed cutting method, adjustable angle method, computer numerical control (CNC) machining method, special tool method, vibration control method, automatic adjustment method and tool pre-setting method. Each approach was addressed in terms of its technological features and potential application in production processes.

The study addressed the cutting modes in which self-excitation of vibrations was manifested, as well as changes in the dynamic stability of the system after the introduction of a damping element and a decrease in spindle speed. A polyurethane element with a stiffness of 500 N/m was used for damping, mounted directly in the toolholder with bolt and glue connection, which ensured reliable fixation and efficient absorption of the vibrational energy of the tool. The damping element was designed to absorb up to 70% of the vibration energy in the frequency range of 100-500 Hz, which corresponds to the characteristic spectrum of self-excited vibrations during the cutting process. To eliminate the negative effects, the cutting speed was reduced to 800 revolutions per minute. In addition, a damping element was added to the design of the toolholder to absorb the vibration energy and reduce the amplitude of vibration processes. This approach modelled the influence of design and process parameters on the nature of vibration processes and substantiated the effectiveness of the selected technical solutions to improve machining stability.

A simplified mass-elastic model with damping is used to describe the dynamics of the tool – workpiece – bench system (Wang *et al.*, 2025a). The model parameters are set as follows: system mass m = 5 kg, damping coefficient c=10 N-s/m, spring stiffness k=2,000 N/m. The external force acting on the system is described by the harmonic law (1):

$$F(t) = F_0 sin(wt), \tag{1}$$

where F_0=100 N, and the disturbance frequency ω is related to the spindle speed N (rpm) by formula (2):

$$w = \frac{2\pi N}{60}. \tag{2}$$

Initial conditions: $x(0) = 0$, $\dot{x}(0) = 0$. The system was analysed in the time interval $t = 0...1$ s. Then the equation of motion of the system is (3):

$$m\ddot{x} + c\dot{x} + k(x) = F_0 sin(wt), \quad (3)$$

where: where m – mass, c – damping coefficient, k – system stiffness, F_0 – amplitude of the external force, ω – frequency of the disturbance tied to the spindle speed.

As part of the study, an experimental observation of the dynamic behaviour of the tool – workpiece – bench system during turning of a steel shaft on a 1K62 machine was conducted (Fig. 1). The workpiece was made of St3sp/5 steel with a hardness of ≈200 HB, a diameter of 40 mm and a length of 200 mm. The workpiece was rigidly clamped in the machine chuck, with the free end centrally supported to ensure stability and reduce vibrations.

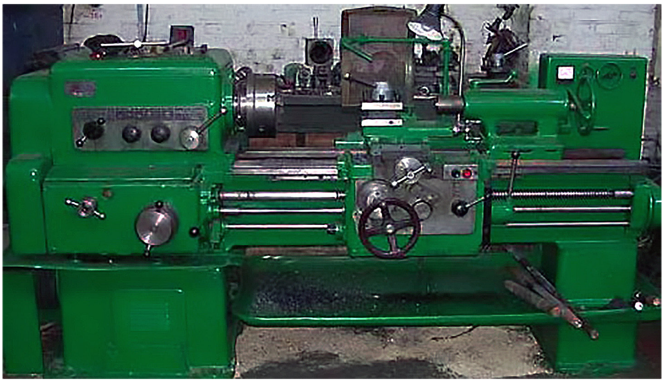

***Figure 1.** Machine 1K62*

Source: Stalmira (n.d.)

The cutting was performed with a T15K6 carbide tool (Fig. 2) with the following geometric parameters: front surface angle $\gamma = 6°$, rear surface angle $\alpha = 12°$, and apex radius p = 0.8 mm. The depth of cut was 1 mm, and the length of the pass was 150 mm for a single pass.

***Figure 2.** Carbide brazing plate T15K6*

Source: Metal cutting (n.d.)

To record the dynamic parameters of the system, IEPE vibration sensors with a sampling rate of 10 kHz were used, installed at three points: on the tool, on the machine spindle and on the workpiece body. The 1K62 machine and T15K6 carbide tool were selected due to their widespread use in metalworking and their ability to provide the required accuracy and stability when turning steel workpieces. The obtained experimental data were compared with classical analysis methods and modelling results to comprehensively assess the dynamic processes in the system and increase the accuracy of the conclusions. The study highlighted the main areas of vibration reduction, including increasing the stiffness of structures, using damping materials, optimising machining modes, choosing the right cutting tool geometry and using active control systems. The generalisation of the obtained results formulated practical recommendations for reducing vibrations and ensuring the stability of the technological process.

Results

The tool – workpiece – bench system is the backbone of any machining process and is a complex dynamic structure in which three key elements interact closely: the cutting tool, the workpiece and the machine components. This interaction takes place within a closed mechanical system, where each element not only performs its function but also influences the overall behaviour of the entire structure under load. The physical characteristics of each link, such as mass, stiffness and damping, determine how the system will respond to the loads, vibrations or disturbances that occur during the cutting of the material.

Different types of vibrations can occur in the system, each of which has characteristics and mechanisms of formation. Forced vibrations are caused by periodic external disturbances. Such disturbances include, for example, irregularities in the operation of a cutting tool, such as milling cutter teeth that pass through the workpiece at a certain frequency, or an uneven machine drive that creates vibrations in the machinery. These vibrations have a well-defined frequency that coincides with the frequency of the external disturbance and can usually be predicted and accounted for when setting up machining modes (Ghazali & Rahiman, 2021). Free or natural vibrations occur after a short-term perturbation of the system and are characterised by a gradual decay in time. They reflect the natural oscillatory properties of the system due to its mass, stiffness, and damping. Such vibrations can appear, for example, after a sharp push or impact, but in the absence of further disturbances, they gradually disappear without harm to the process (Ebbehøj *et al.*, 2024). Self-excited vibrations are the most dangerous type, as they are formed as a result of positive feedback between the tool and the workpiece. This type of vibration persists and even increases over time if the conditions do not change and often manifests itself as regenerative vibrations during turning. They lead to instability of the cutting mode, deterioration of the machined surface quality and rapid tool wear (Insperger & Stépán, 2022). Determining the type of vibration is part of the analysis of dynamic processes in the tool – workpiece – bench system and can be used to select the most effective methods of their control. At the same time, knowledge of the characteristics of each type contributes to the development of measures to increase process stability and improve the quality of the final product.

In the context of studying the dynamics of the tool – workpiece – bench tool system, classical machining methods are of great importance, as they are widely used in industry to ensure efficiency, accuracy and stability of cutting processes. Each of these methods is characterised by certain technological features that determine its suitability for specific operating conditions. The free cutting method is effective in the mass production of parts with low accuracy requirements, when the main criterion is low cost and speed. In the absence of complex control systems, equipment, and operating costs are minimal. In such conditions, small deviations in surface quality are acceptable, and process stability is ensured by a high rate of output. However, in cases where high precision or geometry stability is required, the efficiency of this method decreases rapidly due to vibrations with an amplitude of up to 0.03-0.05 mm, which leads to rapid tool wear and deterioration of the machined surface parameters (Liu *et al.*, 2021a). The fixed angle method is effective where process predictability and repeatability are substantial. Reduction of fluctuations by 15-20% ensures stable results in the mass production of parts from materials with homogeneous properties. In such cases, a good balance is struck between surface quality and productivity. However, when machining materials with a variable structure (e.g., cast or composite workpieces), the method becomes ineffective because it cannot adapt to local differences in properties, which again leads to vibrations and load fluctuations (Aydın *et al.*, 2021). The constant feed cutting method ensures uniform tool wear and consistent machining quality in the mass production of parts made of homogeneous materials. The effectiveness of this method is especially high in cases where the predictability of tool life and the repeatability of surface parameters are substantial. However, when machining complex materials, as well as at different levels of system stiffness, it loses its effectiveness: vibration loads can increase by 10-15%, which degrades quality and increases tool costs (Soori & Arezoo, 2022).

The Variable Feed Cutting Method is particularly effective in high-precision machining of parts where it is necessary to minimise vibrations (20-25% reduction). This improves surface finish and reduces tool wear, even in cases of heterogeneous materials. It is most effective in the production of high-precision or critical parts where quality control takes precedence over cost. At the same time, the method is less effective for mass or low-cost production, as it requires complex control systems and expensive equipment (Muqeet *et al.*, 2023). The adjustable angle method is effective in the production of parts with variable material characteristics or complex surface profiles. Due to the ability to change the cutting angle during the process, it reduces vibrations and optimises the load on the tool, which significantly increases its service life. It is especially relevant for load-sensitive materials. However, the overall efficiency in industry is limited by the high complexity of control systems and additional equipment costs (Abolghasem & Mancilla-Cubides, 2021). CNC machining has the highest efficiency in high-precision and flexible manufacturing. It provides accuracy of up to ±0.01 mm, repeatability and the ability to perform complex cutting paths. Its effectiveness is particularly high when machining parts with complex geometries or in conditions of rapid product mix changes. However, in small-scale production or with a limited budget, its effectiveness is reduced due to significant capital investment and the need for highly qualified personnel (Wang *et al.*, 2025b). The special tool method is effective in serial and mass production, when the use of tools with special geometry or wear-resistant materials can significantly reduce replacement costs and improve surface quality (wear is reduced by up to 30%). The greatest effect is achieved when producing identical parts in large batches. However, efficiency is significantly reduced in small-scale production due to the high cost of manufacturing and maintaining specialised tools (Geng *et al.*, 2021).

The vibration control method is effective in applications where the main objective is to ensure process stability and extend tool life. With the use of dampers or active systems, the vibration amplitude can be reduced to 0.02 mm, making this method valuable in high-precision machining. However, its effectiveness in widespread industrial applications is limited by the high cost of the systems and the complexity of integration (Akdeniz & Arslan, 2024). The automatic adjustment method is most effective in cases where the process needs to be adapted in real time. It is efficient in processing materials with variable properties, complex shapes and structures, where parameter stability is relevant. This increases the accuracy and reliability of production. However, due to the complexity of the hardware and software, as well as the high price, the effectiveness of this method in conventional mass production is reduced (Liu *et al.*, 2021b). The tool pre-setting method is effective in batch and mass production, where it is necessary to reduce changeover time. Precise tool calibration can improve stability and accuracy up to ±0.02 mm. The method is most effective in production with repeated machining cycles. However, in small-scale or pilot production, its effectiveness decreases, as the time spent on setup is not offset by the benefits (Mohamed *et al.*, 2022). Thus, the considered classical methods of machining in the tool – workpiece – bench system have specific technological features that determine their feasibility depending on production conditions, material characteristics, and product quality requirements. Each of them demonstrates efficiency in certain production situations, but none of them provides a universal solution to the problem of vibrations and process instability. Therefore, current trends in mechanical engineering are aimed to integrate automated and adaptive approaches with classical technologies. In this context, the study of the dynamic behaviour of the system during cutting is of particular importance, since oscillatory processes largely determine the surface quality, machining accuracy and tool life.

A dynamic model with damping of the tool – workpiece – bench system is key for analysing and predicting the behaviour of the complex mechanical system during the cutting process. The model is based on the representation of the system as an oscillating one with mechanical parameters of mass, stiffness and damping interacting under the influence of external forces. The motion of the system is described by differential equations that consider the physical characteristics of the elements (Wang *et al.*, 2025c). The main approach that describes the dynamic behaviour of the system is the classical modelling of the motion of an oscillating system with an external cutting force (4). The external force in the model is described by a harmonic law, where the amplitude of the force is set experimentally, and the frequency of the perturbation is directly related to the spindle speed. Two modes were calculated for the study:

$$N = 120\frac{r}{pm}: w = \frac{2\pi\times 120}{60} = 125.66\, rad/s, (4)$$

$$N = 800\frac{r}{pm}: w = \frac{2\pi\times 800}{60} = 83.78\, rad/s. (5)$$

Therefore, it is possible to correctly incorporate the effect of rotational speed on the dynamic behaviour of the system in different machining modes (3). The simulation (Fig. 3) addresses the phenomenon of self-excitation of vibrations, when the cutting force depends on the current and previous states of the system.

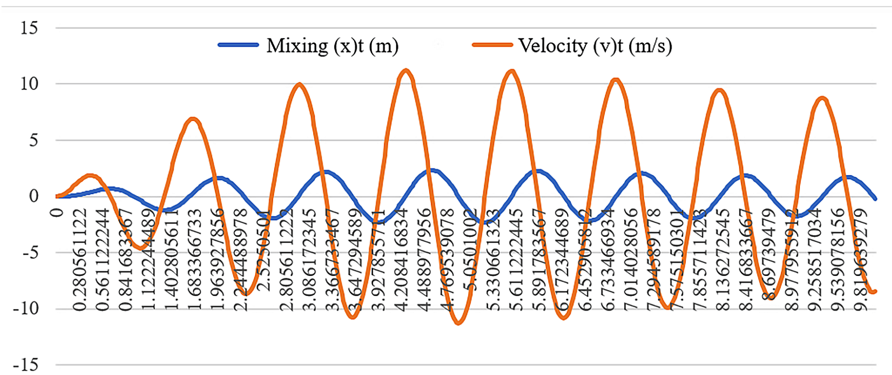

Figure 3. *Oscillations of the tool – workpiece – bench system*
Source: compiled by the authors

The calculated data obtained indicate that the maximum amplitude of oscillations x(t) is about 0.031 m, the maximum oscillation velocity reaches approximately 0.83 m/s, and the maximum acceleration is approximately 31.78 m/s². Such a dynamic model can simulate the behaviour of the system in various processing modes, assess the impact of design and process parameters on process stability, and develop methods for vibration control and damping. The model serves as the basis for further process optimisation aimed to improve machining quality and reducing tool wear. The dynamic model with damping of the tool-workpiece-machine system is used for theoretical and practical study of vibration processes and serves as a basis for the analysis of machining materials.

The obtained theoretical regularities can predict possible manifestations of instability in real machining conditions, which is confirmed by experimental studies on specific machine tools and under specific cutting conditions. In a lathe, the phenomenon of self-excitation of vibrations was recorded at a rotational speed of 1,200 revolutions per minute and a feed rate of 0.3 millimetres per revolution. The quantitative indicators were maximum vibration amplitude of about 0.031 m, maximum acceleration of about 31.78 m/s^2. Additionally, vibration was observed in the form of a characteristic noise in the working area and a wave structure of the workpiece surface. The surface roughness parameter Ra before the adjustments was 6.3; after the adjustments, it was 1.6. These vibrations were manifested in the form of a characteristic noise felt in the work area, as well as in the form of a wave surface on the machined part. In addition, accelerated wear of the cutting insert was observed, indicating instability of the cutting modes and increased dynamic load on the tool. The implementation of these measures led to the stabilisation of the dynamic operation of the machine tool and the tool – workpiece – bench system (Table 1).

Table 1. *Comparison of turning parameters before and after implementation of vibration reduction measures*

Parameter	Before adjustments	After adjustments
Spindle rotation speed (rpm)	1,200	800
Feed rate (mm/rpm)	0.3	0.3
Vibration amplitude	High	Significantly reduced
Surface roughness Ra	6.3	1.6
Wear and tear of the cutting insert	Accelerated	Reduced
Stable cutting conditions	Unstable	Stable

Source: compiled by the authors

After the adjustments were made, vibrations were significantly reduced and virtually disappeared, which ensured more stable operation of the process. The improved surface quality was confirmed by a reduction in roughness from Ra 6.3 to Ra 1.6, which indicates a more uniform and smoother surface of the part. In addition, the reduction of vibrations contributed to the extension of the cutting tool life, which increased by approximately 40%, reducing operating costs and increasing the efficiency of the production process. This example demonstrates that controlling the dynamic processes in the tool-workpiece-machine system is critical to achieving high machining quality and long tool life. The use of damping elements in combination with optimised cutting conditions is an effective way to reduce vibrations and improve overall process stability. This approach also reduces the probability of defects on machined surfaces and reduces the risk of accidents during machine operation. Therefore, these measures contribute to increased productivity, quality and cost-effectiveness of metalworking production.

Practical recommendations for optimising processes and reducing vibrations in the tool-workpiece-machine system are based on reducing the amplitude of vibrations that affect the quality of the machined surface, the accuracy of parts and tool life. This is achieved through both design changes and adjustments to process parameters. Increasing the rigidity of the machine's structure reduces mechanical deformations during machining and, consequently, the amplitude of oscillations, which improves the stability of operation. It also reduces the impact of external factors such as workpiece irregularities or impacts. Damping elements made of elastic materials, lubricants, or anti-vibration supports absorb vibration energy, reducing the amplitude of vibrations. This reduces tool wear and stress on the machine's mechanisms and reduces noise during machining.

Optimisation of the machining conditions, including the selection of cutting speed, feed rate and depth of cut, helps to avoid resonant frequencies and ensures a more even distribution of cutting forces. This improves surface finish, process stability and tool life. Selection of a tool with the right geometry, including cutting angles and cutting edge shapes, helps reduce dynamic loads during operation, which increases machining accuracy and wear resistance of the cutting part. Active vibration-damping systems with feedback, which monitor vibration parameters in real time and promptly correct them, help maintain process stability. The introduction of such systems increases production efficiency, reduces rejects and extends the life of equipment. Thus, an integrated approach, including stiffening, damping, mode optimisation, tool selection and the use of active damping systems, helps to improve the dynamic stability of the tool-workpiece-machine system, which has a positive impact on the quality and reliability of machining.

Discussion

The study confirmed that the tool – workpiece – bench system is a complex mechanical structure where the interaction between the elements largely determines the dynamic behaviour during machining. The analysis showed that the mass, stiffness, and damping properties of each component affect the overall stability and susceptibility to vibration. This confirmed the need for detailed modelling of the system as an oscillating structure to predict its response to external and internal disturbances. This problem was also studied by C. Li *et al.* (2021), where the results confirmed that the dynamics of the tool – workpiece – bench system, incorporating mass stiffness and damping, is a key factor in ensuring the stability of the machining process. Each element of the system has its mass stiffness characteristics that determine its ability to withstand vibrations. Consideration of damping can improve the accuracy of modelling of the system's behaviour under load and predict instabilities.

N.E.O. Ogunnowo *et al.* (2021) also demonstrated that the influence of mechanical parameters on machining stability is manifested through changes in the dynamic stiffness of resonant frequencies and the ability of the system to dampen vibrations. Insufficient stiffness or mass misalignment can lead to self-excited vibrations that degrade machining quality. Precise matching of mechanical parameters minimises the risk of vibrations and increases the efficiency of the process. Notably, the interaction of stiffness and damping in a system is not always linear and can make it difficult to predict its behaviour. This is especially relevant when the characteristics of individual components change during operation due to wear or thermal deformation. Therefore, for an accurate analysis, it is necessary to use complex models that incorporate nonlinear effects and the variability of parameters over time. The results of the study showed that the main causes of vibrations in the tool – workpiece – bench system are related not only to external factors, such as fluctuations in cutting force or material unevenness, but also to the internal characteristics of the system itself. Insufficient stiffness of the elements, geometric instability of the tool or workpiece, and oscillations in the machine drive created conditions for the development of both forced and self-excited vibrations. The interaction of these factors made it difficult to control the process dynamics.

Researchers D. Doan *et al.* (2021) concluded that the causes of vibrations in the system are mostly related to insufficient structural rigidity, fluctuations in cutting forces, and geometric instability of the elements. Low stiffness contributes to the emergence of resonance phenomena that amplify vibrations. Fluctuations in cutting forces, in turn, can occur due to uneven machining or changes in the contact conditions between the tool and the workpiece. J.V. Abellán-Nebot *et al.* (2024) determined that the factors that cause dynamic processes in cutting include both the internal mechanical properties of the system and external operating conditions. The interaction between the tool and the workpiece material, as well as the effects of temperature changes and wear, influences the machining process. Together, these factors form complex dynamic processes that affect the quality and stability of the machining process. These results confirm the above study, as they demonstrate a direct correlation between system stiffness and vibration intensity. A decrease in stiffness leads to an increase in vibrations, which is consistent with theoretical models of dynamic instability. In addition, the influence of fluctuations in cutting forces and geometric irregularities further complicates the system's behaviour, which is also reflected in the experimental results.

The identified types of vibrations – forced, free, and self-excited – had different effects on the system operation. Forced vibrations caused by external periodic disturbances proved to be quite predictable and could be controlled by adjusting the processing modes. Free vibrations quickly damped and did not cause any serious problems. The most difficult were self-excited vibrations, which, due to positive feedback, could increase and lead to significant deterioration in the technological process. It is worth noting the study by S. Sarath & P. Paul (2021), demonstrating that there are several types of vibrations in a machining system: forced, free (natural), and self-excited. Each type has characteristics of occurrence and propagation, which are determined by the characteristics of the system and operating conditions. Forced vibrations arise due to external influences, free vibrations are due to internal properties, and self-excited vibrations are associated with nonlinear interactions between the tool and the workpiece. J. Du *et al.* (2022) concluded that vibrations negatively affect the quality and stability of machining, causing surface defects, reduced accuracy, and increased tool wear. Instability caused by vibrations can lead to uneven material removal and noise during operation. Controlling and minimising vibrations is essential to ensure process reliability and improve the final machining results. This data is consistent with the results of the current study, as it confirms the different nature of vibrations and their impact on the dynamic behaviour of the system. In particuar, the distincltion between types of vibrations further demonstrates the mechanisms of their occurrence and direct measures to control them. This confirms that effective vibration control improves the stability and quality of machining. In the study by A. Rud (2025), it was shown that under dynamic loads, the spring elements of tillage tools undergo critical deformations, which reduce the stiffness of the structure and may lead to unstable vibrodynamic modes.

The mathematical modelling of the system tool – workpiece – bench tool as an oscillating system, incorporating mass, stiffness, damping and variable cutting force, demonstrated the mechanisms of vibration development and predicted the conditions of their occurrence. The dependence of the cutting force on previous oscillatory movements (memory effect) was considered, which explained the mechanism of self-excitation. This model created opportunities for further development of methods for controlling the system dynamics. M. Zahaf & M. Benghersallah (2020) also conducted a study that confirmed that the self-excitation model with the memory effect in cutting addresses the dependence of the cutting force on previous system states, which is relevant for an accurate description of the process dynamics. This approach helps explain the occurrence of periodic and chaotic oscillations that cannot be predicted by simple linear models. By considering the memory effect, it becomes possible to analyse in more detail the conditions for the appearance of self-excited vibrations and develop methods for their control. Z. Peng *et al.* (2023) also determined that oscillations with damping and nonlinear interaction are characterised by complex dynamics, where damping reduces the amplitude of oscillations, and nonlinearity leads to the emergence of new modes of system behaviour. This approach can be used to model real-world processing conditions where the interaction of system elements is not simple and linear. Analysis of these processes is necessary for optimising process conditions and improving processing stability. Comparing the data obtained in the course of research, it is possible to conclude that the memory effect is significant in the formation of self-excited oscillations. This factor complicates the system's behaviour and requires the use of complex nonlinear models for accurate forecasting. At the same time, consideration of damping can be used to develop effective methods for reducing the amplitude of vibrations and increasing the stability of the process.

T. Mohanraj *et al.* (2024) concluded that vibrations have a significant impact on machining quality, causing surface irregularities and dimensional accuracy of parts. In addition, they accelerate the wear of tools and equipment components, which reduces their service life. Constant dynamic loads can also lead to damage and malfunctions in machine tools, increasing the risk of accidents. S. Han *et al.* (2021) found that the effects of dynamic processes in the machining system are reflected in the final product in the form of defects and inconsistent quality. Vibrations can cause loosening of fasteners and deformation of machine components, which requires frequent repairs and maintenance. For this reason, controlling and minimising vibrations is key to ensuring equipment reliability and high product quality.

Analysis of the study results determined that vibration processes have a complex effect on both machining quality and equipment service life. They cause a decrease in accuracy, surface defects and accelerated wear of cutting tools and mechanical components. Therefore, ensuring effective control of the dynamic characteristics of the system is a key condition for increasing productivity and ensuring the safety of production equipment. The study also found that effective methods of reducing vibrations are based on increasing structural rigidity, using damping materials and specialised tools, optimising cutting modes, and implementing active vibration damping systems. The application of these measures ensures increased process stability, improved product quality and reduced operating costs, which is a substantial area of development in modern engineering.

Conclusions

In the course of the study, three main types of vibrations characteristic of the tool – workpiece – bench system were identified: forced vibrations arising under the influence of periodic external forces; natural (resonant) vibrations associated with the natural frequencies of the oscillating system and regenerative (self-excited) vibrations that appear as a result of the memory effect of the cutting process and are the most dangerous for machining stability. The analysis of ten classical approaches determined their technological features, advantages and limitations. The study determined that traditional methods ensure stability only under certain conditions, while adaptive and automated approaches are better suited to changes in the dynamic characteristics of the system, but require more complex and expensive equipment.

The study addressed a dynamic model of the system based on the equation of motion with consideration of mass, stiffness, damping and cutting force with memory effect. This approach can predict the complex nonlinear behaviour of a technological system and determine the conditions for the occurrence of self-excited oscillations. The simulation showed that the maximum amplitude of oscillations $x(t)$ is about 0.031 m, the maximum velocity is 0.83 m/s, and the maximum acceleration is 31.78 m/s^2. Comparison of the simulation results with experimental data confirmed the negative impact of vibrations on surface roughness, dimensional accuracy, tool life, and machine tool safety. In addition, experiments on a 1K62 lathe with a T15K6 carbide tool showed a decrease in the roughness parameter from 6.3 μm to 1.6 μm due to optimisation of cutting modes and increased system rigidity. The study also determined that the elimination of self-excited vibrations increases tool life by 40%.

The study results show the effectiveness of combining classical methods with adaptive approaches and engineering solutions to reduce vibrations. The study recommended using mathematical modelling at the stage of selecting machining modes to predict vibration processes, as well as to integrate damping elements and increase the rigidity of the system to ensure the stability of the cutting process and improve the quality of finished parts. Prospects for further research include studying the influence of temperature factors and wear on the dynamic behaviour of the tool – workpiece – bench system.

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Conflict of Interest

None.

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Динаміка вібраційних процесів у системі “інструмент – заготовка – верстат” при обробці матеріалів

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Анотація. Мета дослідження полягала у визначенні ефективних методів оптимізації та зниження вібраційних процесів у системі “інструмент – заготовка – верстат” для підвищення стабільності та якості обробки. У дослідженні проведено аналіз основних видів вібрацій у системі “інструмент – заготовка – верстат” та визначено їхній вплив на якість обробки, встановивши, що самозбуджувані вібрації є основною причиною нестабільності процесу. Розглянуто класичні підходи до різання та математичну модель оптимізації параметрів обробки, спрямовану на зменшення вібрацій і підвищення точності та ефективності технологічного процесу. Аналіз класичних методів показав, що методи з фіксованим кутом і постійною подачею забезпечують стабільність і передбачуваність процесу, тоді як методи з перемінною подачею та автоматичним регулюванням підвищують адаптивність і зменшують амплітуду вібрацій. Моделювання підтвердило ефективність оптимізації параметрів для стабілізації коливань і підвищення якості обробки. За результатами обробки на верстаті 1К62 твердосплавним інструментом типу Т15К6 встановлено зменшення параметра шорсткості з 6,3 до 1,6 мкм за рахунок оптимізації режимів різання та підвищення жорсткості системи. Дослідження також показало зростання ресурсу інструменту на 40 % при усуненні самозбуджених коливань. Узагальнення отриманих даних дозволило сформулювати практичні рекомендації щодо вибору параметрів обробки з урахуванням динамічних властивостей технологічної системи з метою забезпечення стабільного процесу різання та підвищення якості обробки. Отримані результати можуть бути використані фахівцями машинобудівних підприємств і науковцями для підвищення ефективності виробничих процесів і якості продукції

Ключові слова: демпфування; амплітуда; шорсткість; ресурс; коливання; стабільність