Sound & Vibration 2026, 60(3), 4079.
doi: https://doi.org/10.59400/sv4079

Article

Synthesis of ultrasonic frequency generator in automatic control system of vibration cutting process

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CITATION

Yolchuyev I, Karimli T, Mammadov A. Synthesis of ultrasonic frequency generator in automatic control system of vibration cutting process. Sound & Vibration. 2026; 60(3): 4079. https://doi.org/10.59400/sv4079

ARTICLE INFO

Received: 25 February 2026
Revised: 5 April 2026
Accepted: 9 April 2026
Available online: 17 June 2026

Abstract: The article analyzes the characteristic features of the vibration cutting process with ultrasonic frequency (UF), which is one of the most effective methods that reduces labor costs and improves their quality and reliability during the mechanical processing of particularly hard and brittle materials. To stabilize the amplitude and frequency, changing as a result of changing the resonant frequency of the vibrator-concentrator-part (VCP) oscillatory system during processing, linear and relay-type generators are proposed that operate on the basis of excitation of the natural frequency of the mechanical vibration system VCP, and these generators are modeled and synthesized using MATLAB/Simulink. With the development of modern machinery and technology, new materials with improved mechanical properties are created, on the basis of which critical parts are manufactured, where high accuracy, quality, and reliability indicators are required. In the machining process, to stabilize the amplitude and frequency, which change as a result of the change in the resonant frequency of the vibrator-concentrator-part (VCP) oscillatory system, generators of the linear and relay type are proposed, which work on the basis of the excitation of the own frequency of the mechanical vibration system of the VCP. These generators are modeled and synthesized in MATLAB/Simulink. The obtained mathematical models and curves of the transition process show that, despite the change in the disturbing factor when the coefficient of friction is changed, conservatism is ensured, as a result of which there is an opportunity to improve the quality of surfaces machining of parts.

Keywords: vibration cutting process; ultrasonic frequency generator; oscillatory system; natural frequency; simulation

1. Introduction

Today, great strides have been made in the technology of mechanical processing of structural materials, and industrially produced metalworking machines have been significantly improved and have the necessary productivity. Modern technology for the mechanical processing of structural materials has achieved great success, and industrially produced metalworking machines have reached a high level and productivity, which allows them to successfully solve various problems posed by the rapid process of technological development.

Advances in technology have led to the emergence of new materials whose machining by traditional methods is difficult. These include, first and foremost, high-hardness materials such as tungsten-containing and titanium carbide alloys, diamond, ruby, hardened steels, magnetic alloys made from rare earth elements, thermal corundum, and others. Grinding is the only traditional method used to process these materials.

In conventional cutting, it is generally accepted that virtually all vibrational phenomena are undesirable. In this case, cutting conditions are selected that prevent vibrations from occurring.

During traditional mechanical processing and polishing with a grinding machine, using special abrasive wheels, the grain size of which varies depending on the surface of the part being processed and the specifics of the work.

To do this, the surface of the workpiece and the polishing wheels are wetted with water. The wheels rotate at approximately 1,400 rpm. Friction causes the water to evaporate due to the significant heating of the workpiece. The surface of the workpiece is smoothed, eliminating any unevenness or roughness. At certain intervals, the machine must be stopped and the surface of the part must be washed. If the surface of a part needs to be processed to a mirror shine and the processing process needs to be completed effectively, the grinding wheel with a felt attachment and the surface of the part are wetted with water, after which finishing processing is performed. If the workpiece is made of stone or metal, diamond paste applied to a special cloth can be used for a very fine polish. The cloth is then carefully rubbed onto the surface of the workpiece.

However, the development of technology and engineering has led to the creation of new materials, the mechanical processing of which by traditional methods is difficult. Since the reaction forces arising during traditional mechanical processing of these materials are relatively large, losses in drives increase and the efficiency of the engine decreases.

In many cases, materials that cannot be processed by these traditional methods determine the development of technology, and for this reason, the efficient processing of these parts is a very important and pressing issue.

Problems of processing brittle and particularly hard materials were solved theoretically and practically using special processing methods.

Among them are additive manufacturing, electrical discharge, electron beam, ultrasonic, etc. [1–5].

1.1. Additive manufacturing

In 1980, the first component was manufactured using Additive Manufacturing (AM) by depositing material. The deposition was computer-controlled. Additive manufacturing (AM) is used to create a variety of complex geometric shapes and lightweight structures with minimal material loss. The application range of AM is vast, from household and sustainable products to automotive and aerospace components. Recently, AM of metals has been developing in manufacturing, requiring in-depth study of raw material preparation methods, application areas, operating conditions, required manufacturing precision, and permissible mechanical stress [6,7].

When using AM extrusion, parts are manufactured by controlling the melting and extrusion of thermoplastic filament. Parts may contain void-like defects in certain locations. These defects negatively impact the structural quality and mechanical properties of the manufactured parts. Under these conditions, the development of a defect detection system with acceptable accuracy is required. There's a system for inspecting the structural quality of AM parts using an optical camera. This system has been tested on a 3D printer. Defect information is generated layer-by-layer based on the trained convolutional neural network. This verification system links the obtained information on structural defects with a decision boundary, which was developed based on the accumulation threshold and decision-making approach. The location and size of defects are linked by layer [8].

1.2. Electrochemical polishing

Optimization of the surface quality of AM-based parts is necessary in those industries that require high manufacturing precision. The geometry of parts that are insensitive to liquids is well suited for chemical and electrochemical polishing. For parts with a roughness of approximately 10 μm or greater, these methods have limited effectiveness. For polishing parts such as AM pipelines, where chemical and electrochemical polishing are ineffective, electrochemical-mechanical composite polishing is used. The advantage of this method over traditional electrochemical polishing is that it does not require anode hydrolysis, which occurs under the influence of high overvoltage. There is also a method for quantitatively controlling the rate of roughness removal from a material during electrochemical polishing using a solid dielectric, where the impedance of the solid dielectric changes with the change in roughness, which allows for dynamic control of the roughness removal from the workpiece [9].

1.3. Electrical discharge machining

In high-tech mechanical engineering and precision manufacturing, non-traditional machining methods, such as electrical discharge machining (EDM), are widely used. This non-contact machining method is effective for machining nickel and titanium alloys used in the automotive, oil and gas, and aerospace industries. The effectiveness of these processes is assessed by factors such as the rate of roughness and unevenness removal from the workpiece, machining time, dimensional accuracy, electrode wear, surface quality, and much more [10].

To improve the acceptability of external and internal surfaces of additively manufactured parts and individual components in industry, post-processing using chemical reagents, lasers, and wire-based electrical discharge polishing (WEDP) facilitates effective roughness removal. However, this can significantly deviate the shape and tolerances of the processed part from the required values.

Research is conducted to evaluate the microstructure, residual stress behavior in workpieces, and shape accuracy changes based on laser powder bed sintering (LPBF) methods before and after wire electrical discharge machining (WEDM) [11].

1.4. Electron beam melting (EBM)

Electron beam melting (EBM) is driving advances in additive manufacturing. This is facilitated by the use of a vacuum chamber, as it increases the density of the manufactured part. However, the surface roughness of the part is inferior to that achieved with other powder sintering technologies. The Italian Aerospace Research Center (CIRA) used EBM to produce a dense part with a uniform microstructure using standard Ti6Al4V melting conditions in a vacuum chamber at 10^{-4} mbar. The Ti6Al4V powder particle size ranged from 45 to 106 μm. The manufacturing process involved elevated temperatures to ensure the correct microstructure and eliminate residual stress in the components. Due to this factor, no heat treatment was performed after manufacturing. To improve the surface quality of the manufactured part from Ti6Al4V alloy, additional chemical treatment was carried out [12].

1.5. Laser machining

Compared with other methods of processing parts, laser polishing is superior because the laser source indicators are more accurate, and the polishing process parameters, such as scanning speed, laser power, track overlap, etc., are easily adjusted. These properties are essential for polishing surfaces of parts with random textures after AM. However, when processing internal surfaces and other hard-to-reach areas of parts, the inaccessibility of the laser beam limits the widespread use of this method [12].

They are characterized by energy-intensive processes and high environmental hazards.

To address the problem of machining super hard and brittle materials, specialized machining methods have been developed and implemented: diamond-based rotating tools, electrochemical machining, electrical discharge machining, electron beam machining, and ultrasonic machining.

The advantages of ultrasonic machining over other methods include the ability to machine non-conductive and opaque materials, as well as the absence of residual stress after machining, which, when used with other methods, leads to cracks on the machined surface.

Ultrasonics effectively processes fragile materials such as agate, alabaster, diamond, gypsum, germanium, granite, graphite, boron carbide, quartz, marble, jade, ruby, sapphire, glass, porcelain, earthenware, crystal, jasper, and others.

A significant factor in increasing the efficiency of industrial production is the introduction and improvement of advanced technologies, ensuring their technically and economically feasible automation.

One such technological process in mechanical engineering that reduces the labor intensity of manufacturing parts and improves their quality and reliability is so-called ultrasonic intensification, i.e., processes carried out using mechanical vibrations at ultrasonic frequencies for technological purposes. The successful and widespread implementation of various vibration metal cutting processes in industry depends significantly on the development of appropriate automated control systems for the primary and secondary movements of cutting tools and workpieces to ensure optimal values for the required process parameters characterizing the aforementioned processes, as well as the final product.

Developing effective control algorithms for such processes primarily requires in-depth study and research of the complex physical and mechanical phenomena occurring during their implementation—i.e., kinematics, dynamics, plastic and elastic deformations, friction, thermal processes, and other factors—followed by their adequate mathematical description as control objects.

At the same time, an important condition for the technical support of the proposed control algorithms is the creation of means for obtaining and converting primary information about the process, as well as the corresponding force control action on it. Studying the static and dynamic characteristics of vibration cutting under various operating conditions, identifying the degree of internal interconnectivity between control and disturbance channels, and determining energy and process constraints will enable the required identification of appropriate mathematical models for vibration cutting processes, as well as the adequate formulation and solution of problems related to automated optimization of productivity, product quality accuracy, and the reliability of equipment and tools.

Analysis of the current state of ultrasonic technology, the current level of electronics development, and the development of new materials for ultrasonic emitters suggests that promising development directions must be pursued to overcome the shortcomings of previously developed machines and proven machining methods.

High-intensity ultrasonic vibrations are currently used to weld thermoplastic polymer materials, as well as very thin foil and wire to metal parts. Since ultrasonic welding is a cold weld, the seam is formed at a temperature below the melting point. Ultrasonic welding can be used to join materials such as aluminum, zirconium, tantalum, niobium, molybdenum, and others. Ultrasonic welding is effectively used in high-speed packaging processes and the production of polymer packaging materials [13–17].

The physical phenomena occurring in the vibration cutting process are very different in quality from the physical phenomena in the conventional cutting process. The ultrasonic waves used (more than 20 kHz) create a pulsed cutting force and a pulsed cutting process. Here, the chip formation process occurs only over an equal period in a certain part of the period of the ultrasonic frequency wave. It should be noted that it is theoretically possible to direct ultrasonic waves in all three directions of the cutting force.

The research results showed that the ratio of cutting speed to critical speed should be the main control parameter for vibration cutting. To achieve maximum efficiency in vibration cutting, it is necessary to ensure the condition: $V/V_c = 1/3 = const$ [6]. When changing the cutting speed, in order to maintain a stable value of V/V_c, it is necessary to change the frequency or amplitude of the generator [18–21].

In vibration cutting with ultrasonic vibration in the cutting depth direction, it is possible to effectively suppress the serrated chips and form smooth and continuous chips, but in cutting in the cutting speed direction, there is an opposite effect [22].

Due to the periodic vibration applied to the machining path, the surface texture created by ultrasonic vibration milling (UVM) has unique characteristics [23,24].

Improving the plastic machining quality during ultrasonic milling depends on friction, axial vibration speed or frequency, deformation rate, and material removal mechanism. Experimental and theoretical results have opened up new possibilities for ultrasonic vibration machining of composites [25,26].

Precision machining of intricately shaped micro texture surfaces with wavelengths of more than tens of micrometers is achieved by ultrasonic cutting using elliptical vibration [27,28].

Ultrasonic assisted machining is commonly used for high-precision machining of difficult-to-machine materials [29].

Ultrasonic vibration cutting (UVC) minimizes residual stress after machining, reduces the likelihood of cracks forming in the machining plane. These properties are essential in the production of parts and assemblies in the aerospace industry [5,30].

2. Materials and methods

2.1. Extracting features

Based on the theoretical model, the four key parameters are nominal cutting speed, vibration frequency and amplitude, and rotation angle. Experimental results showed that ultrasonic cutting offers clear technical advantages in reducing cutting force, improving surface quality, suppressing burrs, and optimizing chip formation [31].

Changing the frequency causes a change in the chip formation time during vibration cutting. In this sense, it is considered more appropriate to use the amplitude control channel to maintain a constant relative speed [32,33].

The following parameters were taken as output indicators of the cutting process:

1. Amplitude of oscillations of the cutting tool: A, μm.
   This indicator is considered constant for each specific part: $A = g_a = const$.
2. Oscillation frequency of the cutting tool: f, kHz.
   In order not to awaken the dynamics of the auxiliary elements of the mechanical vibration system and for lower energy consumption, the frequency f_g of the generator should be adjusted to the resonant frequency f_R of the mechanical part, i.e., the condition $f_g \approx f_R$ should be met under the existing disturbances.
3. During vibrating cutting, the optimal cutting speed should be $V \approx V_c/3$.

2.2. Database

This indicator is achieved by changing n the number of revolutions of the machine drive.

Vibratory cutting uses a generator that generates ultrasonic harmonic oscillations in the frequency range of $f = 20 \div 30$ kHz. The vibratory concentrator operates at a frequency of $f = 22$ kHz. The maximum oscillation amplitude with a value of $a = 12$ μm is achieved at the end of the concentrator at this frequency. The generator is tuned to the resonant frequency for the cutting blade of the cutter in operating mode.

In the VCP oscillatory system, changing the parameters m, c, and k shifts the concentrator's resonant frequency ($f = 22$ kHz).

This leads to a decrease in the amplitude of oscillations. Disturbing excitations that change the parameters of the oscillatory system are the mechanical properties of the perpendicular component of the speed of cutting (V_g), depth of cut (t_c), feed (S) and also the machined surface.

Typically, the vibrator is designed according to the nominal amplitude A and frequency f, which are the main parameters of the vibration cutting process.

One of the practical methods to control the generator's frequency is to excite a mechanical oscillation system (with amplitude feedback) using its natural frequency [6,33].

3. Results and discussion

3.1. Formation of the VCP oscillatory system model

The main objective of the research is to change the resonant frequency of the oscillation system VCP, which affects the quality indicators of the machined surfaces of parts made from various materials.

A change in the resonant frequency can be due to several reasons: firstly, the use of a vibrator designed for a certain resonant frequency when processing various parts; secondly, changes in cutting parameters, temperature, etc. When processing the same parts, in addition, when the pulse radial force P_y changes, the concentrators resonant frequency also changes.

Theoretical and practical studies have shown that the VCP oscillation system is adequately described by a second-order linear differential equation [33]:

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = F(t)). \quad (1)$$

Where, m is the mass of the oscillation system; x is the linear displacement of the center of mass relative to the equilibrium position; c is the coefficient of friction; k is the coefficient of elasticity; $F(t)$ is the force of control used to maintain oscillations in the resonant mode.

The mechanical model of the VCP oscillatory system is shown in **Figure 1**.

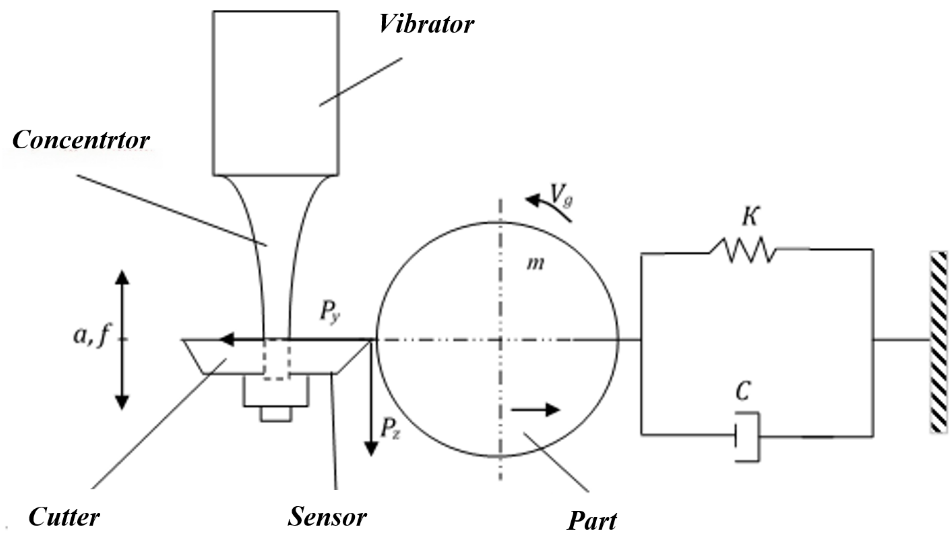


Figure 1. Model of the VCP oscillatory system.

To achieve a forced frequency close to the system's resonant frequency and an amplitude equal to the reference value, it is necessary to select an external force *F(t)*.

To obtain Equation (2), we need to divide the right and left sides of Equation (1) by the reduced mass *m*:

$$\frac{d^2x}{dt^2} + B\frac{dx}{dt} + A_0X = DF(t). \tag{2}$$

Where the corresponding canonical form is given by:

$$\frac{d^2x}{dt^2} + 2\xi\omega_0\frac{dx}{dt} + \omega_0^2x = DF(t). \tag{3}$$

Here, ξ is the coefficient of damping, given the value of this coefficient as $0 < \xi < 1$. Equation (3) describes the oscillation system, ω_0 is the resonant frequency of the oscillation system. This frequency depends on the system's internal characteristics and is independent of the external disturbance $F(t)$, as well as the initial conditions $x(0) = x_0, x^{'}(0) = x^{'}_0$.

When a step action is applied to the input signal of the system, the natural frequency of the oscillatory system differs from the resonant frequency and is determined as follows:

$$\omega = \omega_0\sqrt{1-\xi^2}, \text{ or } \omega = \sqrt{A_0 - \left(\frac{B}{2}\right)^2} = \sqrt{\frac{k}{\mathrm{m}} - \frac{\mathrm{c}^2}{4\mathrm{m}^2}}.$$

If the choice of *F(t)* allows $B \approx 0$, then the oscillatory system approaches a conservative system ($\xi = 0$), and in calculations we can use the expression $\omega = \omega_0 = \sqrt{k/m}$. To achieve this goal, we create an external force in the feedback form from the derivative:

$$F(t) = K_sK_eK \cdot \frac{dx(t)}{dt}. \tag{4}$$

Here, K_s, K_e, K, are the gains of the sensor, exciter, and coupling device.

The sensor output of the system generates a signal proportional to the oscillations of *x(t)*. To generate feedback regarding the derivative, the *x(t)* signal must pass through a differentiating link.

Taking into account Equation (4) in Equation (2), we obtain the formula:

$$\frac{d^2x}{dt^2} + (B - DK_sKK_e)\frac{dx}{dt} + Ax = 0. \tag{5}$$

The system described by Equation (5) is a homogeneous system with free oscillations.

For a system to be conservative, that is, for it to exhibit undamped oscillations, the following condition must be met:

$$\delta = (B - DK_sKK_e) = 0. \tag{6}$$

Given that the gains K_s and K_e are predetermined, this equality holds when choosing the coefficient K_c.

As can be seen, if the condition of Equation (6) is satisfied, the generator equation takes the form:

$$\frac{d^2x}{dt^2} + A_0x = 0. \tag{7}$$

Equation (7) represents a conservative system, i.e., an ideal oscillatory system without damping, where the oscillation amplitude depends on the initial conditions as $x(0) = x_0,\ x^{'}(0) = x^{'}_0$.

However, it should be noted that in practice, a free oscillatory system becomes unstable and can turn into an unstable oscillatory system when exposed to small external forces.

In general, such a system has the following modes:

1. $\delta = 0$—conservative;
2. $\delta < 0$—unstable oscillatory process;
3. $\delta > 0$—stable oscillatory process.

As can be seen, systems with small parameters δ are insensitive to small changes in external disturbances.

To apply this method in a real system, it is necessary to obtain the required amplitude of oscillations g and ensure the stability of self-oscillations [33].

For this purpose, a conservative system can be controlled by the regulation law P:

$$u = k_p\varepsilon(t). \tag{8}$$

Here, $\varepsilon(t) = g_a - x(t)$ is the amplitude control error; k_p—regulator gain; g_a—task; $x(t)$—amplitude value measured by the piezoelectric element.

Equation of the control system at the value $\delta = 0$ with P-regulation:

$$x^{''} + A_0x = k_p\varepsilon(t)$$

As can be seen above, a variable force has emerged on the right-hand side of the equation for the conservative system.

When a conservative system enters a stable mode, the coefficient A decreases, ε > 0. However, in an unstable mode, the coefficient A increases, ε < 0.

In this case, the system, without shutting down, constantly alternates between non-zero equilibrium points "+" and "–" and oscillates with a given amplitude g_a at the resonant frequency.

Moreover, when the problem statement changes, the resonant frequency ω_0 does not change. This is the most important case, that is, the ACS setting signal should not change the characteristics of the system.

So, since the natural frequency is $\omega = \sqrt{A_0 - (\frac{\delta}{2})^2}$ and in the system, along with providing amplitude $A = g_a$, $\delta \approx \pm 0$ is provided, thus ensuring the resonant frequency $\omega = \sqrt{A_0}$.

Figure 2 shows the block diagram of the proposed vibration cutting control system [33].

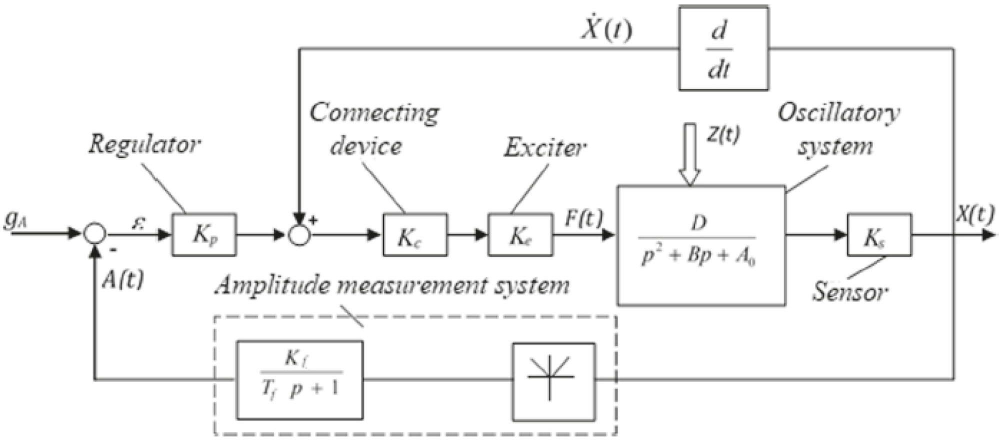


Figure 2. Amplitude control circuit.

The proposed stabilization method is more accurate and theoretically justified than the method based on a zero-phase difference between the current and voltage passing through the piezoelectric element.

Based on the following mathematical model of the VCP mechanical oscillatory system, computer modeling of this system, designed for a frequency of $\omega = 22$ kHz, was performed:

$$W(p) = \frac{0.2}{0.00204p^2 + 0.0181p + 1} \tag{9}$$

Figure 3 shows the transient response of the mechanical system.

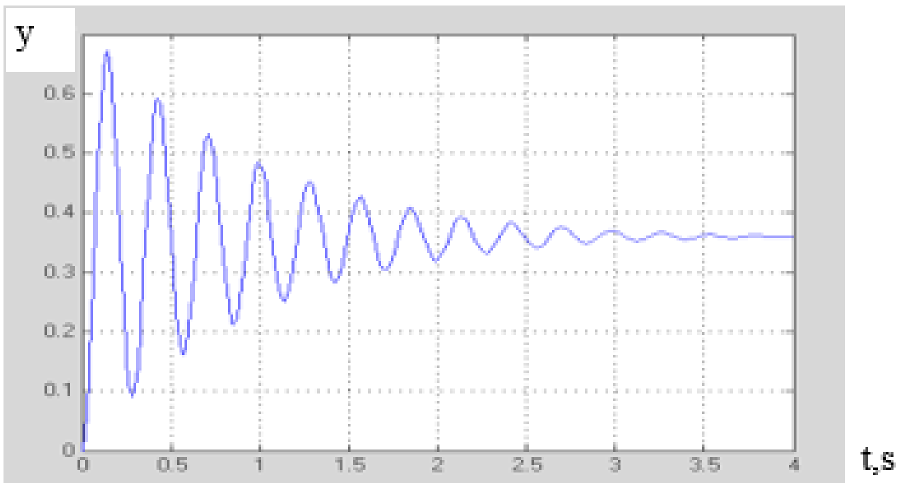


Figure 3. Transient characteristics of mechanical oscillatory system.

Transfer function (9) is reduced to normal form in the MATLAB system simulation, written in state coordinates:

$$\dot{x}_1 = x_2,$$

$$\dot{x}_2 = -487.8x_1 - 8.8195x_2 + 97.56F(t),$$

$$x_1 = y.$$

The corresponding modeling scheme is shown in **Figure 4**.

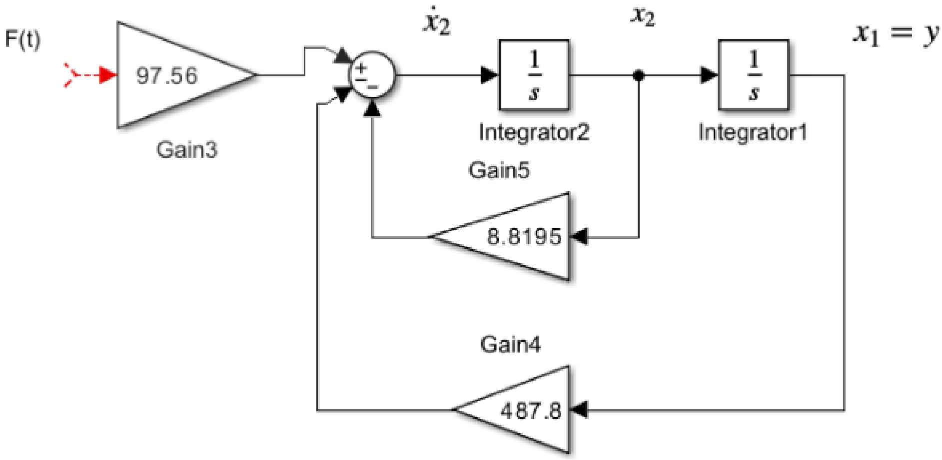


Figure 4. Scheme for modeling an oscillatory system.

The linear generator simulation diagram in MATLAB/Simulink is shown in **Figure 5**. The parameters in the diagram are: $K_s = 1.5; K_e = 1; K = 0.0603; K_p = 50.1; T_f = K_f = 1$.

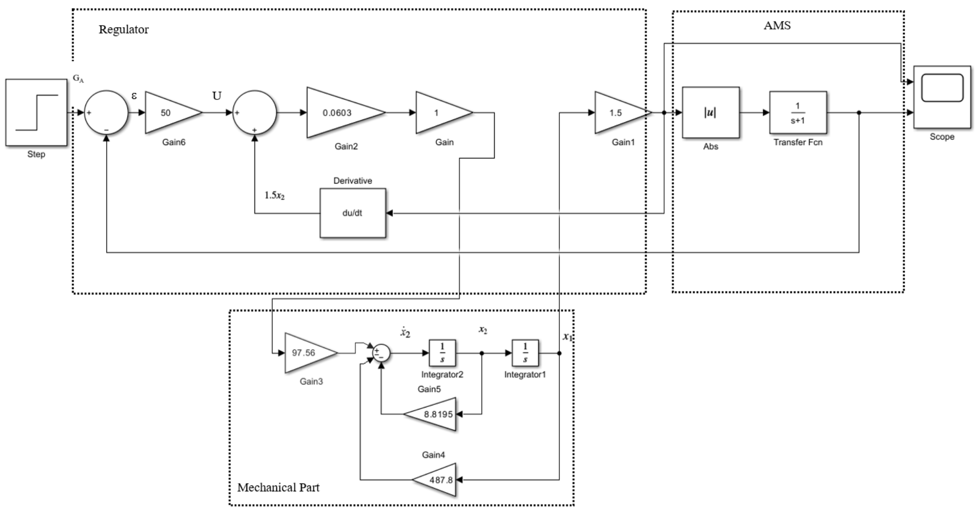


Figure 5. Simulation scheme of a linear generator in MATLAB.

Figures 6 and **7** show the system characteristics, respectively.

The first case corresponds to the task value $g_A = 6.2$ µm. In this case, the resonant frequency $\omega_0 = f_0 \approx 22.5$ kHz. Real amplitude $A(\infty) = 6.35$ µm [33].

In the second case, the task was increased and $g_A = 12$ µm was taken. At the same time, the resonant frequency did not change and amounted to approximately $\omega_0 = 22.7$ kHz. The set value of the real amplitude was $A(\infty) = 11.8$ µm. As can be seen, the main result here is that the resonant frequency does not depend on the value of the problem g_A.

Let us assume that the elasticity coefficient k has changed as a result of some exciting disturbance. In the model for this case, $\widetilde{k} = 487.8$ was changed to $\widetilde{k} = 400.0$ (i.e., 30%). The corresponding transient process is shown in **Figure 8** for the value $g_A = 10$ µm. As you can see, the real amplitude $A(\infty) \approx 9.8$ µm is close to the specified one, and the frequency has decreased and become equal to the resonant frequency $f_0 = 20$ kHz.

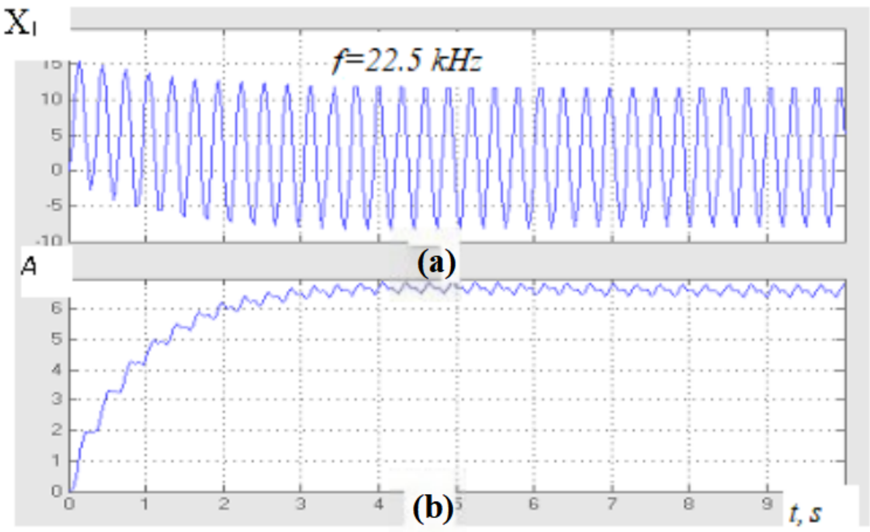


Figure 6. Dynamic characteristics of the system at the target value $A_0 = 6.2$ µm: **(a)** Vibration of the cutting tool; **(b)** Amplitude of the cutting edge.

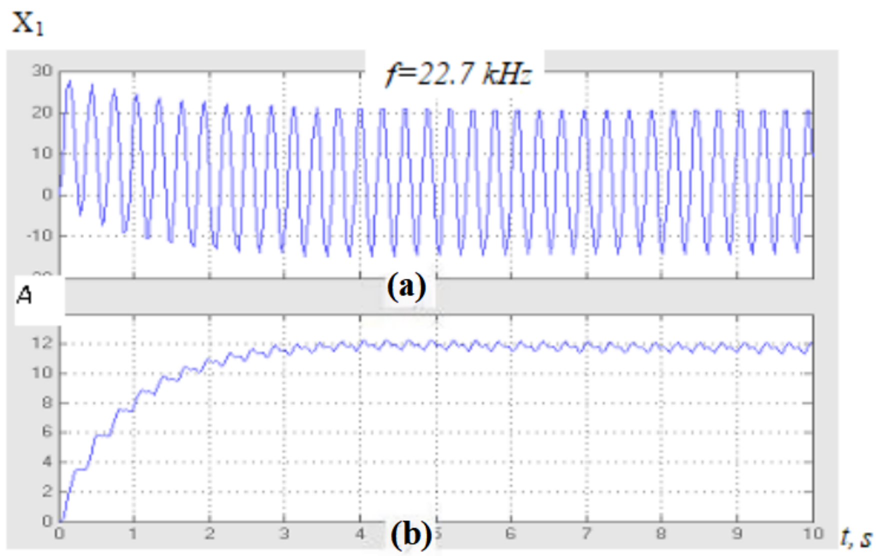


Figure 7. Dynamic characteristics of the system at the target value $A_0 = 12$ µm: **(a)** Vibration of the cutting tool; **(b)** Amplitude of the cutting edge.

A drawback of the previously proposed linear generator is the violation of the conservatism condition of Equation (6) when the coefficient of friction changes as a result of any excitation disturbance. In this case, a static error occurs when tuning the amplitude.

To eliminate this drawback, a relay-type control system is proposed. In this case, there is no need to make object Equation (7) conservative. The final conservative, i.e., movement along a closed trajectory (ellipse), consists of parts of two trajectories of stable forced movement (stable oscillator) [33].

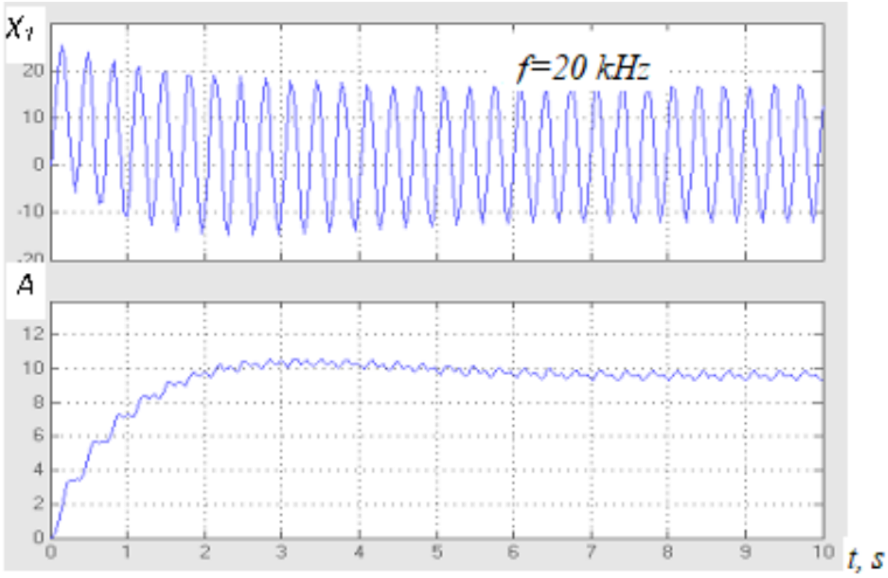


Figure 8. Transient processes under exciting disturbance.

3.2. Formation of the VCP control algorithm

The control algorithm is presented in the following form [33]:

$$F(t) = \begin{cases} -G_A, & if \quad dx/dt < 0 \\ +G_A, & if \quad dx/dt > 0 \end{cases}$$

The block diagram of the system is presented in **Figure 9**.

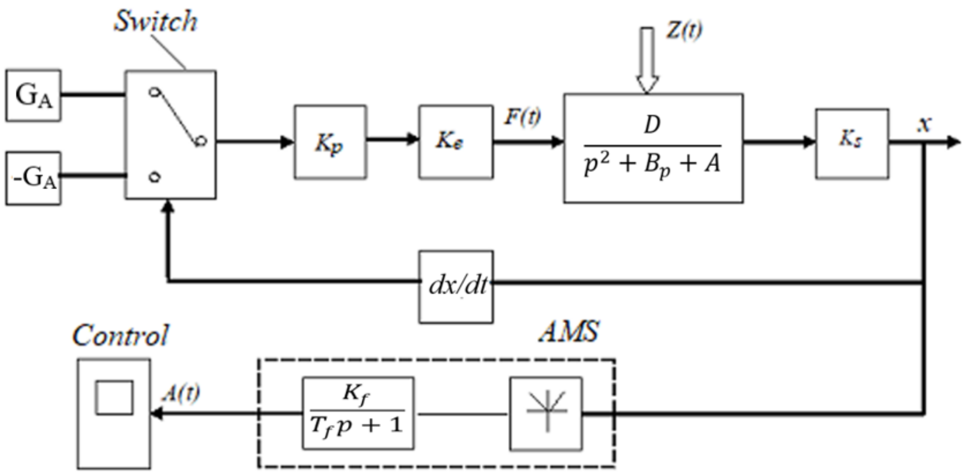
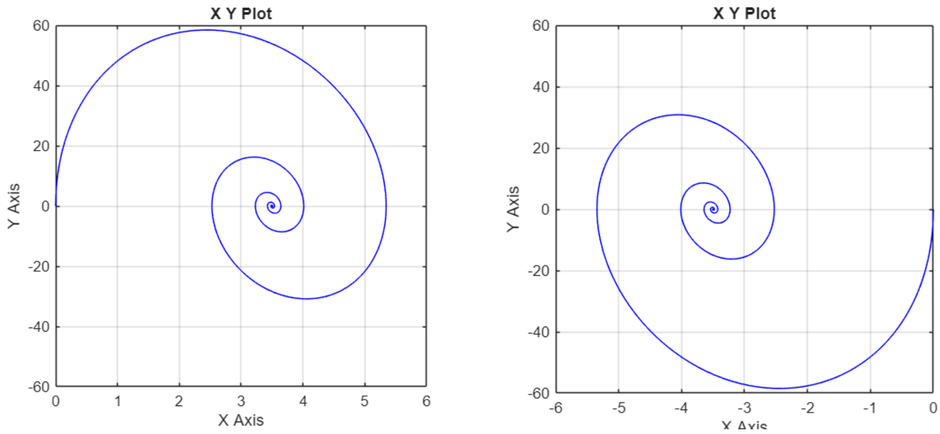


Figure 9. Relay generator control system.

The correspondence of the g_A reference to the real A is performed by selecting the gain coefficient K_p of the controller.

System equation for values $F(t) = \pm g_A$ is $0.00204\ddot{x}(t) + 0.0181\dot{x}(t) + x(t) = \pm 0,9g_A$.

The corresponding phase portraits are shown in **Figure 10**.



(a) **(b)**

Figure 10. Phase portraits of a self-oscillating system operating in the forced oscillation mode: **(a)** With a value of $g_A = -10$; **(b)** With the value $g_A = +10$.

Figure 11 shows the simulation diagram of the proposed relay-type control system in MATLAB. The final phase portrait of the system is shown in **Figure 12**.

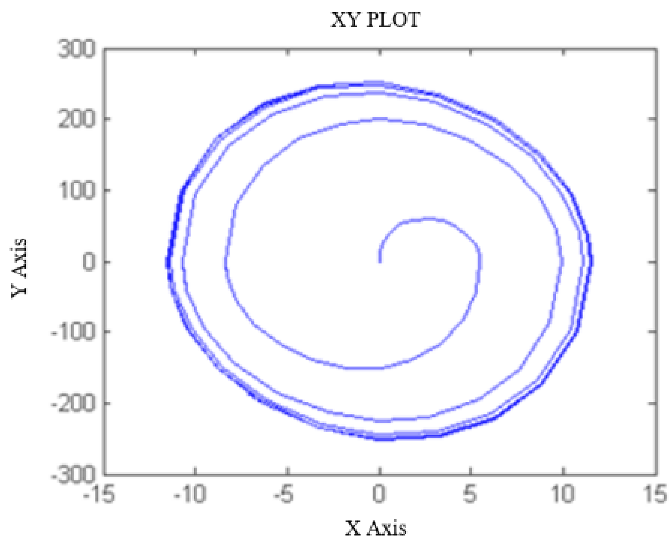


Figure 11. Final phase portrait of a self-oscillating system operating in forced oscillation mode.

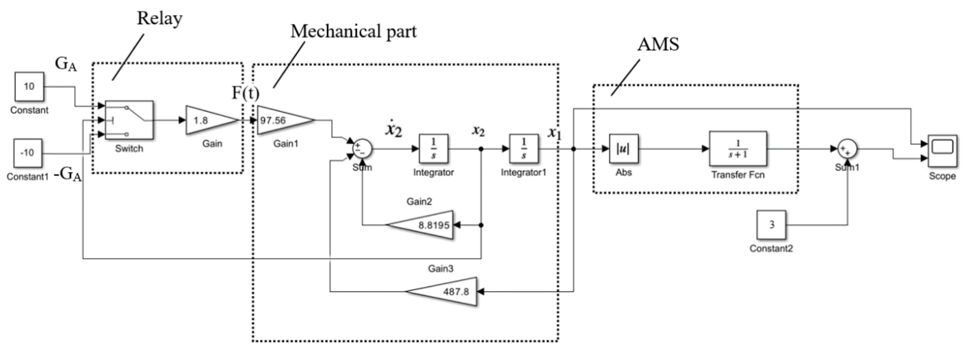


Figure 12. The modeling scheme of the proposed vibration cutting control system in MATLAB of a self-oscillating system operating in the forced oscillation mode.

As you can see, the resulting motion is conservative and occurs along a closed trajectory (ellipse).

Figure 13 shows the frequency and amplitude transients characteristics of the control system. As you can see, for $g_A = 10$ µm, setting $k_p = 1.8$, the real amplitude was $A = 10.2$ µm, and the frequency value $f = 22.5$ kHz.

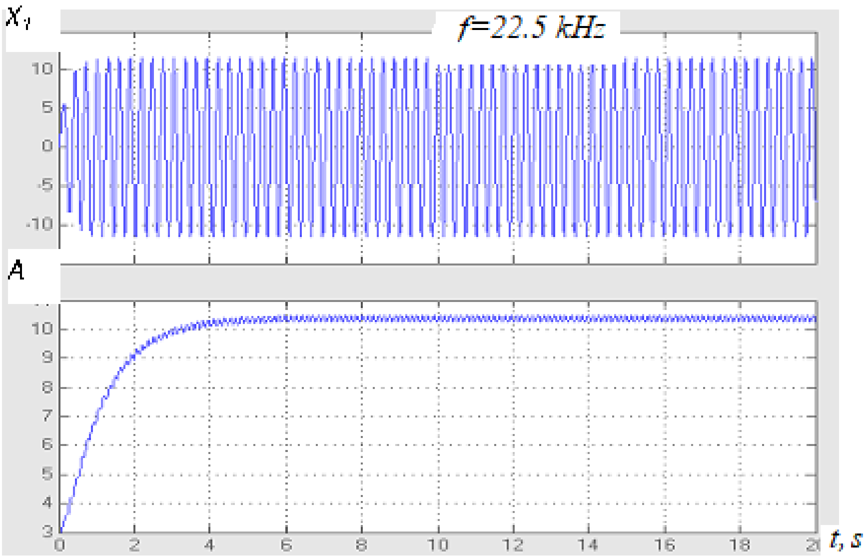


Figure 13. The frequency and amplitude transients characteristics of the control system.

4. Conclusion

As can be seen from the computer simulation, curves of dynamic characteristics, transition process, frequency and amplitude characteristics, conservatism is ensured when the coefficient of friction is changed as a result of any exciting disturbance. Due to this, generators of linear and relay type, working on the basis of the excitation of the own frequency of the mechanical vibration system of the VCP, have an actual and practical importance, as there is an opportunity to improve the quality of machining surfaces of various materials.

Author contributions: Conceptualization and supervision, IY and TK; software and resources, AM; validation, IY, TK and AM; formal analysis and editing, AM; investigation and data curation, IY and TK; writing original draft preparation, IY; visualization, AM. All authors have read and agreed to the published version of the manuscript.

Funding: This work received no external funding.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Data availability statement: All data that support the findings of this study are included within the article.

Conflict of interest: The authors declare no conflict of interest.

AI use statement: The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

1. Abramov OV, Khorbenko IG, Shvegla S. Ultrasonic Processing of Materials. Mechanical Engineering; 1984. (in Russian)
2. Golyamina IP. Ultrasound: A Little Encyclopedia. Soviet Encyclopedia; 1979. (in Russian)
3. Agranata BA, Ultrasound Technology. Mechanical Engineering; 1974. (in Russian)
4. Korytin A, Petrov N, Radimov S, et al. Automation of Standard Technological Processes and Installations. Energoatomizdat; 1988. (in Russian)
5. Peng Z, Han A, Wang C, et al. Ultrasonic vibration cutting of advanced aerospace materials: A critical review of in-service functional performance. Journal of Intelligent Manufacturing and Special Equipment. 2024; 5(1): 137–169. doi: 10.1108/JIMSE-12-2023-0016
6. Kumabe D. Vibration Cutting. Mechanical Engineering; 1985. (in Russian)
7. Patel S, Liu Y, Siddique Z, et al. Metal additive manufacturing: Principles and applications. Journal of Manufacturing Processes. 2024; 131: 1179–1201. doi: 10.1016/j.jmapro.2024.09.101
8. Fu Y, Downey ARJ, Yuan L, et al. Real-time structural validation for material extrusion additive manufacturing. Additive Manufacturing. 2023; 65: 103409. doi: 10.1016/j.addma.2023.103409
9. Liu S, Li C, Jin X, et al. Quantitative-regulated material removal rate in solid dielectric electrochemical polishing (QRR-SDEP) for smoothing high roughness surface of additively manufactured 316L stainless steel components. Additive Manufacturing. 2023; 73: 103689. doi: 10.1016/j.addma.2023.103689
10. Rahman MA, Ahmed A, Mia M. Trends in electrical discharge machining of Ti- and Ni-based superalloys: Macro-micro-compound arc/spark/melt process. In: Micro Electro-Fabrication. Elsevier; 2021. pp. 63–87. doi: 10.1016/B978-0-12-820049-0.00006-2
11. Boban J, Ahmed A. Electric discharge aided surface post-treatment of laser powder bed fused non-planar metallic components for enhanced form accuracy. Journal of Manufacturing Processes. 2024; 109: 564–582. doi: 10.1016/j.jmapro.2023.12.028
12. Manco E, Scherillo F, Franchitti S, et al. Improving Surface Quality and Fatigue Life of Electron Beam Melted Ti6Al4V by Chemical Machining. Journal of Materials Engineering and Performance. 2024; 33(5): 2552–2561. doi: 10.1007/s11665-023-08865-7
13. Yuan J, Xiao H, Wang Y, et al. Ultrasonic welding process and strategies for performance regulation of Fiber reinforced thermoplastic composites: A review. Journal of Manufacturing Processes. 2026; 157: 531–553. doi: 10.1016/j.jmapro.2025.11.084
14. Liu J, Quan D, Scarselli G, et al. Developments and future prospects of welding technology for carbon fiber thermoplastic composites. Composites Part B: Engineering. 2025; 297: 112314. doi: 10.1016/j.compositesb.2025.112314
15. Al Mahmoud Z, Asmael M, Ahmad R, et al. Recent developments in ultrasonic welding of similar and dissimilar joints of carbon fiber reinforcement thermoplastics with and without interlayer: A state-of-the-art review. Reviews on Advanced Materials Science. 2025; 64(1): 20240077. doi: 10.1515/rams-2024-0077
16. Ni Z, Han B, Nazarov AA, et al. Enhanced formation quality and mechanical properties of ultrasonic spot welding of TA2 Ti sheets by pure Al coating. Journal of Manufacturing Processes. 2025; 156: 1–16. doi: 10.1016/j.jmapro.2025.10.084
17. Bautin V, Bulanova S, Enik T, et al. Ultrasonic welding technology for future Straw Trackers and performance studies with small-size tracker prototypes. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2026; 1081: 170767. doi: 10.1016/j.nima.2025.170767
18. Markov AI. Ultrasonic Cutting of Difficult-To-Cut Materials. Mechanical Engineering; 1968. (in Russian)
19. Mal'tsev AA, Maslennikov RO, Khoryaev AV, et al. Adaptive active noise and vibration control systems. Acoustical Physics. 2005; 51(2): 195–208. doi: 10.1134/1.1884495
20. Khorbenko I. Ultrasound in Mechanical Engineering. Mechanical Engineering; 1974. (in Russian)
21. Khmelev VN, Barsukov RV, Barsukov V, et al. System of phase-locked-loop frequency control of ultrasonic generators. In: Proceedings of the 2nd Siberian Russian Workshops EDM2001; 3–4 July 2001; Erlagol, Russia. pp. 56–57. doi: 10.1109/SREDM.2001.939147
22. Zhao Q, Guo X, Wang H, et al. Effects of ultrasonic vibration cutting trajectories on chip formation of tungsten alloys. Journal of Manufacturing Processes. 2023; 92: 147–156. doi: 10.1016/j.jmapro.2023.02.053

23. Lu H, Zhu L, Yang Z, et al. Research on the generation mechanism and interference of surface texture in ultrasonic vibration assisted milling. International Journal of Mechanical Sciences. 2021; 208: 106681. doi: 10.1016/j.ijmecsci.2021.106681
24. Fang B, Yuan Z, Li D, et al. Effect of ultrasonic vibration on finished quality in ultrasonic vibration assisted micromilling of Inconel718. Chinese Journal of Aeronautics. 2021; 34(6): 209–219. doi: 10.1016/j.cja.2020.09.021
25. Xu J, Feng P, Feng F, et al. Subsurface damage and burr improvements of aramid fiber reinforced plastics by using longitudinal–torsional ultrasonic vibration milling. Journal of Materials Processing Technology. 2021; 297: 117265. doi: 10.1016/j.jmatprotec.2021.117265
26. Zhang B, Wang F, Fan J, et al. Simulation and experimental analysis on influences of axial cutting-induced vibration on edge trimming quality of Carbon Fiber Reinforced Plastics. Journal of Manufacturing Processes. 2021; 68: 632–645. doi: 10.1016/j.jmapro.2021.05.067
27. Zhang C, Shi G, Ehmann KF. Investigation of hybrid micro-texture fabrication in elliptical vibration-assisted cutting. International Journal of Machine Tools and Manufacture. 2017; 120: 72–84. doi: 10.1016/j.ijmachtools.2017.04.009
28. Sajjady SA, Nouri Hossein Abadi H, Amini S, et al. Analytical and experimental study of topography of surface texture in ultrasonic vibration assisted turning. Materials & Design. 2016; 93: 311–323. doi: 10.1016/j.matdes.2015.12.119
29. Yip WS, To S, Sun Z. Hybrid ultrasonic vibration and magnetic field assisted diamond cutting of titanium alloys. Journal of Manufacturing Processes. 2021; 62: 743–752. doi: 10.1016/j.jmapro.2020.12.037
30. Soni R, Verma R, Kumar Garg R, et al. A critical review of recent advances in the aerospace materials. Materials Today: Proceedings. 2024; 113: 180–184. doi: 10.1016/j.matpr.2023.08.108
31. Lei X, Wang R, Ding W, et al. Ultrasonic cutting of aerospace difficult-to-cut alloys: Current status and prospects. Journal of Manufacturing Processes. 2025; 142: 191–221. doi: 10.1016/j.jmapro.2025.03.103
32. Ni C, Zhu L, Liu C, et al. Analytical modeling of tool-workpiece contact rate and experimental study in ultrasonic vibration-assisted milling of Ti–6Al–4V. International Journal of Mechanical Sciences. 2018; 142–143: 97–111. doi: 10.1016/j.ijmecsci.2018.04.037
33. Yolchuyev I, Karimli T, Aliyev S. Simulation of an Ultrasonic Generator with Excitation of the Natural Frequency of a Mechanical Vibration System During the Vibration Cutting Process. In: Research and Updates on the Use of Artificial Intelligence in Drone Technology, Sustainable Aviation. Springer Nature; 2026. pp. 161–165. doi: 10.1007/978-3-032-07678-6_29