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RESEARCH OF NATURAL FREQUENCIES OF THE CUTTER-OSCILLATOR DURING TURNING

Purpose. *To investigate the main methods for determining the natural frequency of the cutter-oscillator X and to analyze the influence of its geometric and inertial parameters on the dynamic characteristics during the study of the physical foundations of cutting process dynamics in turning conditions.*

Research methods. *The experimental study was carried out using the impact hammer test, in which the additional mass and the tool overhang were varied. During each test, oscillation oscillograms were recorded, allowing for the determination of the corresponding natural frequencies. The analytical approach involved deriving formulas for estimating the natural frequency based on the geometric and mass-inertial characteristics of the structure. The SolidWorks software system with the Simulation module was used for the numerical simulation of the spatial oscillations of the cutter-oscillator X, which provides frequency analysis and model creation considering real geometric parameters.*

Results. *Comparison of the analytical, experimental, and numerical methods for determining the natural frequency of the cutter-oscillator X showed high consistency of the results, confirming their reliability and practical applicability. The influence of geometric and inertial parameters on the dynamic characteristics of the cutter-oscillator X was determined. In particular, when increasing the overhang from 60 mm to 140 mm, the natural frequency decreased by 3.6…4.1 times, and when increasing the mass of the concentrated load from 0.2 kg to 0.52 kg – by 1.4...1.6 times. Frequency analysis in SolidWorks Simulation demonstrated sufficient accuracy (error of 2…3%), high efficiency, and cost-effectiveness, especially when designing complex structures. Numerical simulation proved to be a convenient tool for optimizing structures and reducing costs at the development stage.*

Scientific novelty. *For the first time, a comprehensive comparison of analytical, experimental, and numerical methods for determining the natural frequency of the cutter-oscillator X was carried out. The influence of geometric and inertial parameters on its dynamic characteristics was analyzed. The effectiveness of using frequency analysis in CAD systems for studying the dynamics of the turning process was demonstrated, which is relevant for optimizing complex structures.*

Practical value. *The computer simulation method demonstrated high accuracy and repeatability of results in determining the natural frequency of the cutter-oscillator X, confirming its suitability for vibration analysis of lathe cutting tools. Using frequency analysis in SolidWorks Simulation simplifies design, reduces costs, and is especially effective for complex structures.*

Key words: *regenerative self-oscillations, cutter-oscillator, oscillogram, natural frequency, overhang, concentrated mass.*

Introduction

The cutting process is the main operational process that exerts a force influence on the technological system "machine-device-tool-workpiece" [1]. In studies of cutting dynamics, the machine and devices are considered absolutely rigid, and the influence of other processes is disregarded. To simplify the research, the workpiece must be rigid, and the lathe cutting tool serves as an oscillator. The oscillations of the cutting edge of the lathe cutting tool within the cutting allowance volume are considered as the result of elastic displacements of the oscillator under the action of all types of forces arising during the cutting process.

During turning, the lathe cutting tool has a decisive influence on the efficiency of the process, which largely depends on its static and dynamic characteristics [2]. Under unfavorable machining parameters, vibrations may occur, which deteriorate the accuracy, worsen the machining quality and reduce the wear resistance of the tool [3, 4]. The most undesirable vibrations are regenerative self-oscillations, which are self-excited and arise due to variations in the thickness of the cut allowance, caused by waves on the cutting surface [5].

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Understanding the physical causes of regenerative self-oscillations allows reducing its intensity. The most effective way to study such oscillations is to use a cutter-oscillator with a single degree of freedom [6, 7], the direction of oscillation of which coincides with the direction of cutting thickness variation (along the X-axis) – i.e., the cutter-oscillator X.

Since regenerative self-oscillations occur in resonance mode, when the natural frequency (NF) of the cutter-oscillator X coincides with the self-oscillation frequency, it is important to be able to accurately determine and predict changes in the NF depending on the geometric and inertial parameters of the cutter-oscillator X.

Analysis of Research and Publications

Three main methods are used to study the dynamic characteristics of oscillators: analytical [8], simulation [9], and experimental [10]. For the analytical calculation of the NF of oscillators, approximate methods are applied, such as the Rayleigh-Ritz method, Grammel's method, Dunkerley's formula, the method of successive approximations, and others.

The dynamic models of cutter-oscillators are usually studied using Euler-Bernoulli beam theory [4] and verified through finite element modeling (FEM). The frequency response functions (FRF), obtained through the impact hammer tests, are used to evaluate the modal parameters of cutter-oscillators. These modal parameters are then used to construct semi-analytical stability lobe diagrams (SLD), which are employed to assess machining stability (absence of vibrations) during turning. Additionally, the oscillations of the cutter-oscillator can be simulated as a mass-spring-damper system [11].

Computer simulation is the most efficient method for evaluating the dynamic characteristics of oscillators [12]. For example, in study [9], a 3D model of a cutter-oscillator with three degrees of freedom is used to simulate the turning process under both stable conditions and the presence of vibrations. In work [13], a combination of FEM and experimental verification is used to analyze the machining mechanisms of a copper workpiece, with a detailed study of the vibrating tool behavior. Compared to experimental results, computer simulation allows for more accurate estimation of modal parameters and better prediction of vibrations.

For experimental investigation of the NF of cutter-oscillator, the impact hammer method is often used, involving a special hammer equipped with a piezoelectric force transducer [14, 15]. The resulting vibrations are then measured using displacement sensors [16, 5] or accelerometers [17, 18, 19].

Each of the above-mentioned methods for studying the NF of cutter-oscillators has its own advantages and limitations, which justifies the combined use of these methods to obtain the most reliable results.

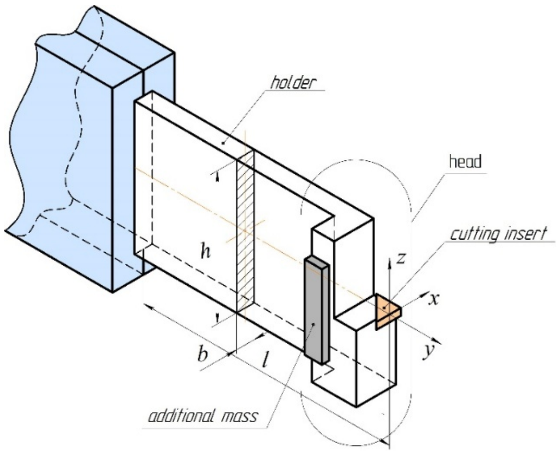
Purpose of the Work

The purpose of the work is to investigate the main methods for determining the NF of the cutter-oscillator X and to analyze the influence of its geometric and inertial parameters on the dynamic characteristics during the study of the physical foundations of cutting process dynamics in turning conditions.

Research Material and Methodology

The research methodology includes both analytical, numerical simulation, and experimental investigation.

The cutter-oscillator X (Fig. 1) consists of a rectangular cross-section holder and a head on which a cutting insert is mounted, with the possibility of attaching additional masses. The cutter-oscillator X has one degree of freedom in the direction of cutting thickness variation [7]. To ensure this, the holder was structurally designed to provide maximum stiffness relative to the *z* and *y* axes and minimum stiffness relative to the *x* axis [6]. To eliminate torsional vibrations, the cutting edge had a principal approach angle of 90° and was positioned along the *y*-axis – the symmetry axis of the holder.



a

b

Figure 1. Design of the cutter-oscillator X (a) and photo of the cutter-oscillator X mounted in a device for installation on a lathe (b)

For the experimental studies, the cutter-oscillator X was manufactured from steel 65G (steel 66Mn4) (ρ = 7850 kg/m³), with holder dimensions of $b \times h$ = 0.008 m × 0.06 m

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and the possibility to vary the overhang l during clamping from 0.08 m to 0.14 m. To determine the mass of the head (concentrated mass) of the cutter-oscillator X, the mass of the holder was subtracted from the total weight. The holder mass was calculated based on its geometric dimensions and material density. The resulting head mass was m_{s1} = 0.2 kg. During the study, the mass of the head was varied from 0.2 kg to 0.52 kg by attaching additional weights of 0.1 kg and 0.32 kg. These parameters were used for the analytical determination of the NF and for computer simulation.

The analytical method for determining the NF of the cutter-oscillator X, which is a cantilever beam with a concentrated mass at its free end, is based on the derivation of calculation formulas.

For 3D computer simulation of the cutter-oscillator X, the SolidWorks software with the Simulation module was used.

Analytical Method for Determining the NF of Cutter-Oscillator X

The following assumptions were made for the analytical calculation of the NF of the cutter-oscillator X:

1. The bending deformations of the holder during oscillations are small compared to its thickness, and elastic deformations obey Hooke's law.
2. The cutter-oscillator X has a constant cross-section of the holder.
3. The material of the cutter-oscillator X is homogeneous and isotropic.

To simplify the analytical calculation of the NF, the cutter-oscillator X is replaced by an equivalent model of a cantilever beam. In this model, the rectangular cross-section holder of the cutter-oscillator X is considered as a beam with uniformly distributed load of linear mass density m_0, with one end rigidly fixed and the other end free. The head of the cutter-oscillator X is modeled as a concentrated mass m_s (see Fig. 2).

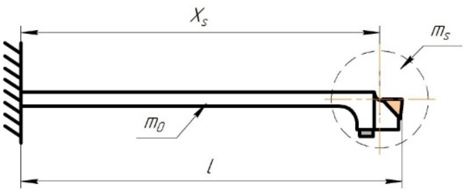


Figure 2. Diagram for determining the NF of the cutter-oscillator X

The NF of the equivalent model of the cutter-oscillator X (Fig. 2) can be determined using the well-known formula [20]:

$$f_n = \frac{\varphi}{l^2}\sqrt{\frac{EJ}{m}}, Hz, \tag{1}$$

where φ is the dimensionless frequency coefficient (Fig. 3a);
m is the equivalent linear mass density, which accounts for both the distributed and concentrated masses and is determined by the formula [20]:

$$m = m_0 + \frac{1}{l}\sum_{S=1}^{S_0} k_S m_S, \frac{kg}{m}, \tag{2}$$

where m_S is the concentrated mass, kg;
s is the index of the mass;
s_0 is the total number of concentrated masses;
k_s is the coefficient for converting the concentrated mass to an equivalent uniformly distributed mass;
m_0 is the uniformly distributed linear mass density, calculated by the formula:

$$m_0 = \rho \cdot b \cdot h, \frac{kg}{m}, \tag{3}$$

where ρ is the density of the cutter-oscillator X holder material, kg/m³;
b is the width of the cutter-oscillator X holder, m;
h is the height of the cutter-oscillator X holder, m.

To determine the frequency coefficient φ, according to the graph in Fig. 3a, the mass ratio for each overhang value of the cutter-oscillator X was calculated using the formula:

$$n = \frac{m_s}{m \cdot l}. \tag{4}$$

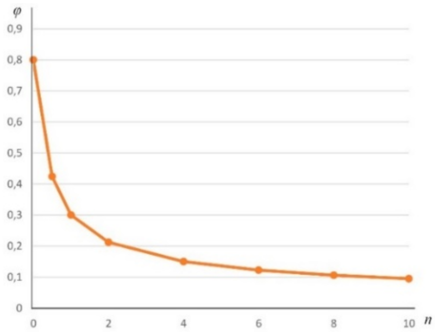
For the manufactured cutter-oscillator X, the uniformly distributed linear mass density was:

$$m_0 = 7850 \cdot 0{,}06 \cdot 0{,}008 = 3{,}768\ \frac{kg}{m}.$$

The values of the coefficient k_s were determined from the graph in Fig. 3b. The relative abscissa of the concentrated mass is defined by the formula [20]:

$$\alpha_s = \frac{x_s}{l}, \tag{5}$$

where x_s is the distance from the clamping point to the center of mass of the concentrated mass, m;
l is the overhang of the cutter-oscillator X, m.



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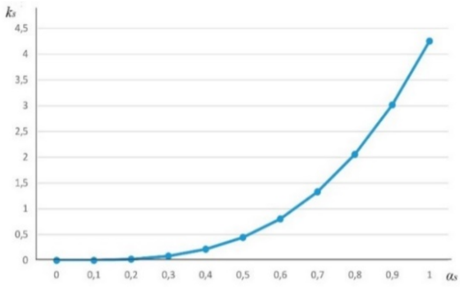

b

Figure 3. Graphs for determining the coefficients φ (a) and k_s (b) [20]

The results of the analytical calculation of the coefficients k_s, n, φ, and the equivalent distributed linear mass density m are presented in Table 1.

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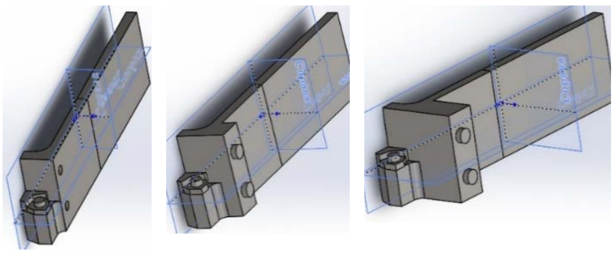
Table 1 – Results of the calculation of coefficients k_s, n, φ, and the equivalent distributed linear mass density m

l, m	m_{s1}=0,2 kg				m_{s2}=0,3 kg				m_{s3}=0,52 kg			
	m, kg/m	n	φ	k_s	m, kg/m	n	φ	k_s	m, kg/m	n	φ	k_s
0,06	7,546	0,442	0,471	1,13	9,434	0,530	0,430	1,13	13,590	0,638	0,392	1,13
0,07	7,823	0,365	0,518	1,42	9,850	0,435	0,475	1,42	14,310	0,519	0,434	1,42
0,08	7,927	0,315	0,557	1,66	10,007	0,375	0,511	1,66	14,582	0,446	0,469	1,66
0,09	7,931	0,280	0,591	1,87	10,012	0,333	0,542	1,87	14,591	0,396	0,497	1,87
0,1	7,875	0,254	0,621	2,05	9,928	0,302	0,569	2,05	14,445	0,360	0,522	2,05
0,11	7,785	0,234	0,648	2,21	9,794	0,278	0,593	2,21	14,213	0,333	0,543	2,21
0,12	7,677	0,217	0,672	2,35	9,632	0,260	0,614	2,35	13,932	0,311	0,561	2,35
0,13	7,561	0,203	0,694	2,47	9,457	0,244	0,634	2,47	13,629	0,293	0,578	2,47
0,14	7,441	0,192	0,714	2,57	9,278	0,231	0,651	2,57	13,318	0,279	0,593	2,57

Determination of the NF of the Cutter-Oscillator X by Simulation

During the simulation in SolidWorks, solid models of the cutter-oscillator X (Fig. 4) were created with parameters corresponding to the real physical object. The materials, boundary conditions (rigid fixation), depending on the overhang length l of the cutter-oscillator X, and the load in the form of a concentrated mass m_s at the free end were specified.

A frequency analysis was performed using the Simulation module in SolidWorks, which allows visualization of NF and obtaining potential resonance modes.



a b c

Figure 4. 3D models of the cutter-oscillators X: a – without additional mass (m_{s1}= 0.2 kg); b – with additional mass 0.1 kg (m_{s2}= 0.3 kg); c – with additional mass 0.32 kg (m_{s3}= 0.52 kg)

Experimental Method for Determining the NF of the Cutter-Oscillator X

The experimental investigation of the NF of the cutter-oscillator X was carried out using the impact hammer test [21], with variation of the additional mass and the overhang length. The cutter-oscillator X 2 was installed in the tool holder of the CNC lathe Zenitech WL 320 (Fig. 5). A non-contact displacement sensor 4 of model Schneider Electric XS4P12AB110 was connected via an analog-to-digital converter 5 of model L-Card E14-140-M to a personal computer 6. A steel ball 1 suspended on a thin thread 3 was used to strike the tip of the cutter-oscillator X 2. The vibration displacement of the lathe cutting tool was detected by the sensor 4 and recorded on the personal computer 6 as oscillograms using the LGraph2 software.

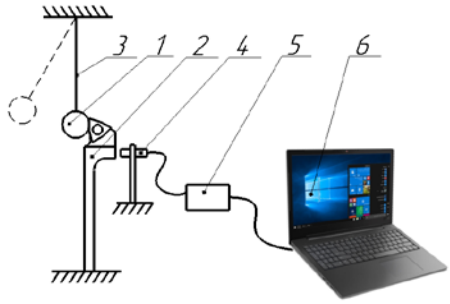


Figure 5. Experimental setup for investigating the NF of the cutter-oscillator X

The obtained oscillograms (Fig. 6) were analyzed using the PowerGraph Demo software. The Fast Fourier Transform (FFT) function was used to convert the data from the time domain to the frequency domain. As a result of the transformation, an amplitude spectrum graph was generated: the X-axis represented frequency, and the Y-axis represented amplitude. The peak of the spectrum corresponded to the dominant oscillation frequency.

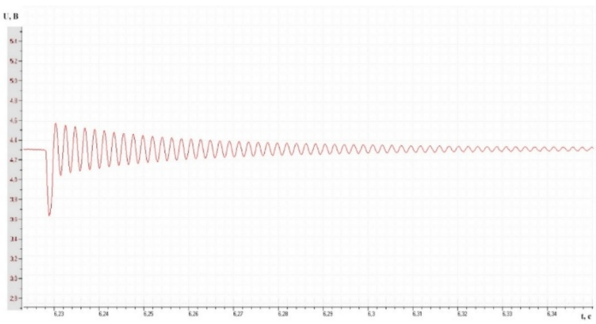


Figure 6. Fragment of the oscillation oscillogram of the cutter-oscillator X (overhang l = 100 mm, without additional mass)

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Research Results and Discussion

Table 2 presents the results of the analytical calculations and experimental measurements of the NF of the cutter-oscillator X, as well as the simulation results obtained using SolidWorks software.

During the simulation in SolidWorks, for each value of the overhang of the cutter-oscillator X and different additional masses, the visualization of the natural frequencies was obtained (Fig. 7).

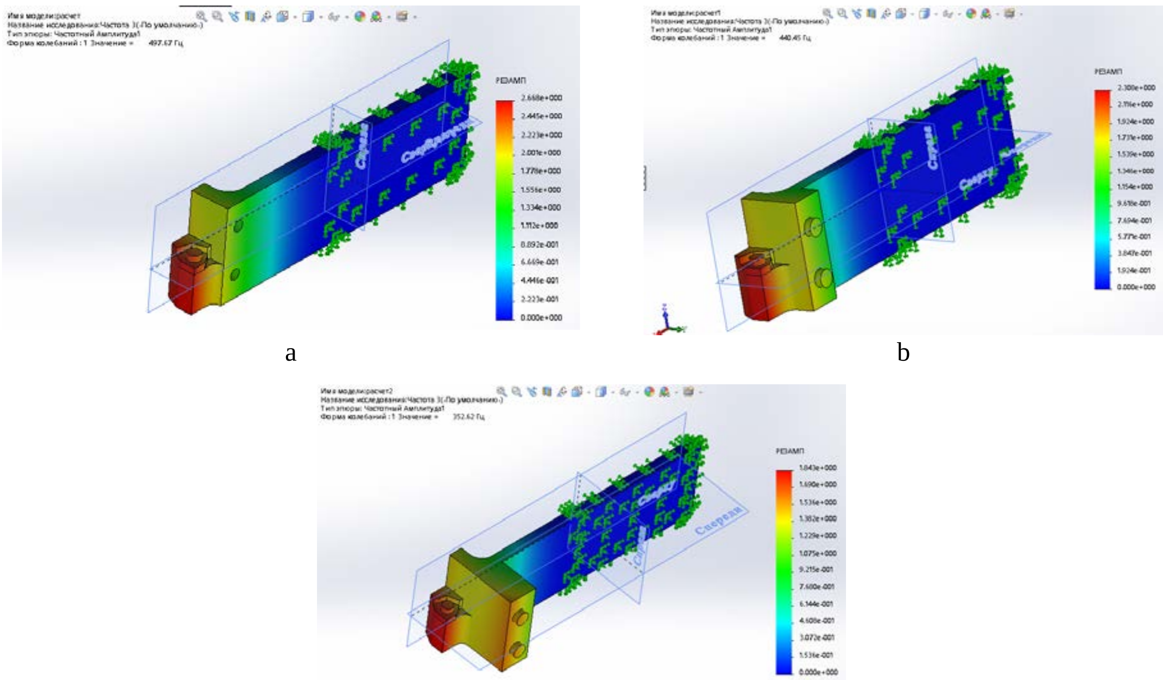
The results of the study showed that increasing the overhang of the cutter-oscillator X from 60 mm to 140 mm led to a decrease in the NF by 3.6...4.1 times. Increasing the concentrated mass from 0.2 kg to 0.52 kg reduced the NF by 1.4...1.6 times.

Based on the obtained results (Table 2), graphs were constructed showing the dependence of the NF on the overhang length l of the cutter-oscillator X and the concentrated mass m_s (Fig. 8).

Table 2 shows that the results of analytical calculations of the NF of the cutter-oscillators X deviate from the experimental data and the SolidWorks Simulation results by no more than 2…3 %. This confirms the high accuracy of frequency analysis in engineering CAD systems and demonstrates their advantages over manual calculations and experimental methods, which require expensive equipment and prototype manufacturing. This is especially relevant when analyzing complex structures. Using numerical simulation at the design stage of new or during the optimization of existing oscillators allows for a significant reduction in development time and cost.

Table 2 – Results of the NF study

l, m	$f_{n\ calc}$, Hz			$f_{n\ exp}$, Hz			$f_{n\ sim}$, Hz		
	m_{s1}	m_{s2}	m_{s3}	m_{s1}	m_{s2}	m_{s3}	m_{s1}	m_{s2}	m_{s3}
0,06	1117,2	912,2	692,9	1093,7	1003,7	789,1	1150,716	966,932	762,19
0,07	871	705	532	859,4	781,2	664	897,13	747,3	585,2
0,08	714	605	436	674,7	586,4	478,5	735,42	641,3	479,6
0,09	598	484	365	605,4	546,8	449,2	615,94	513,04	401,5
0,1	492	413	312	468,7	419,9	341,8	497,67	440,45	352,62
0,11	443	358	270	410,1	366,2	302,7	456,29	379,48	297
0,12	388	314	237	361,3	317,4	263,7	399,64	332,84	260,7
0,13	345	279	210	312,5	273,4	224,6	355,35	295,74	231
0,14	308	249	188	283,4	244,1	200,2	317,24	263,94	206,8



a b c

Figure 7. Calculation of the NF of cutter-oscillator X in SolidWorks:
a – without additional mass (m_{s1}= 0.2 kg); b – with additional mass 0.1 kg (m_{s2}= 0.3 kg);
c – with additional mass 0.32 kg (m_{s3}= 0.52 kg)

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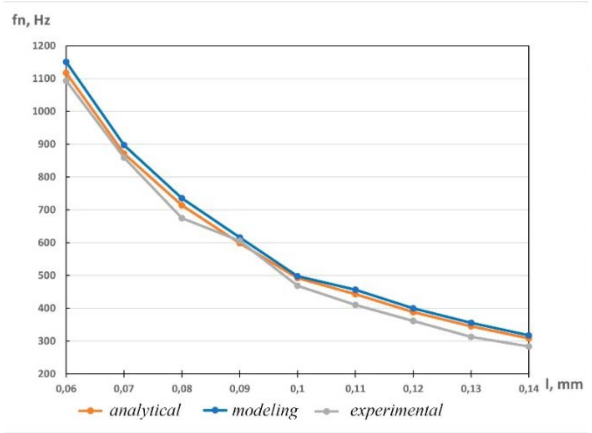

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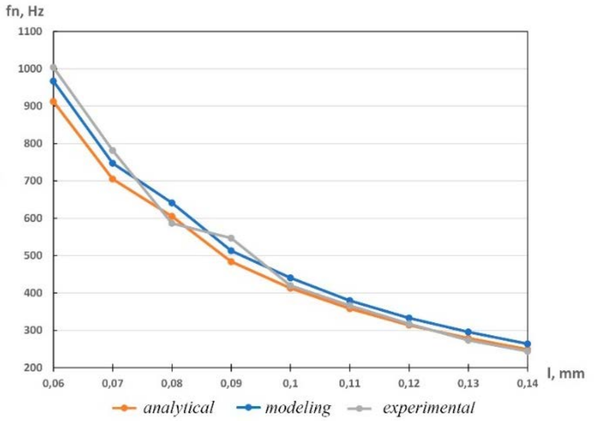

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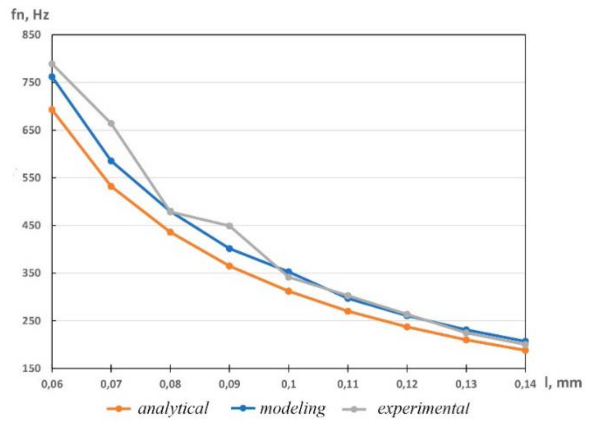

c

Figure 8. Dependence of the NF f_n on the overhang l of the lathe cutting tool for concentrated masses: m_{s1} = 0.2 kg (a), m_{s2} = 0.3 kg (b), and m_{s3} = 0.52 kg (c)

Conclusions

The determination of the NF of cutter-oscillators serves as a foundation for further calculations aimed at studying the dynamic characteristics of the turning process.

The comparison of three approaches – analytical, experimental and numerical simulation – showed a high level of consistency of the results. This confirms the reliability of each method and their applicability in engineering analysis practice.

The study examined the influence of geometric and inertial parameters of oscillators on their dynamic behavior, which is crucial for understanding the physical foundations of the cutting process dynamics. The choice of a particular method may depend on the ease of its implementation and the availability of the necessary equipment.

The research results confirmed the effectiveness and accuracy of the computer simulation method in determining the NF of cutter-oscillator X. The analysis of the obtained data showed good repeatability of the results, making this approach promising for practical applications in vibration analysis of lathe cutting tools.

The use of frequency analysis within engineering CAD systems such as SolidWorks Simulation significantly simplifies and accelerates the design process while reducing costs compared to experimental methods and manual calculations. This is especially important when dealing with complex structures, where numerical simulation becomes an indispensable tool for optimization.

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ДОСЛІДЖЕННЯ ВЛАСНИХ КОЛИВАНЬ РІЗЦЯ-ОСЦИЛЛЯТОРА ПРИ ТОЧІННІ

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Мета роботи. *Дослідити основні методи визначення частоти власних коливань різця-осцилятора X та проаналізувати вплив його геометричних і інерційних параметрів на динамічні характеристики під час вивчення фізичних основ динаміки процесу різання в умовах точіння.*

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Методи дослідження. *Експериментальне дослідження здійснювалося методом ударного збудження, при якому змінювали додаткову масу та виліт різця. Під час кожного випробування фіксувалися осцилограми коливань, що дозволяло визначити відповідні частоти власних коливань. Аналітичний підхід передбачав виведення розрахункових формул для оцінки частоти власних коливань на основі геометричних і масо-інерційних характеристик конструкції. Для чисельного моделювання просторових коливань різця-осцилятора Х використовувалась програмна система SolidWorks з модулем Simulation, що забезпечує проведення частотного аналізу та побудову моделей з урахуванням реальних геометричних параметрів.*

Отримані результати. *Порівняння аналітичного, експериментального та чисельного методів визначення частоти власних коливань різця-осцилятора Х показало високу узгодженість результатів, що підтверджує їхню надійність і практичну застосовність. Встановлено вплив геометричних та інерційних параметрів на динамічні характеристики різця-осцилятора Х. Зокрема, при збільшенні вильоту з 60 мм до 140 мм частота власних коливань зменшилась у 3,6…4,1 рази, а при збільшенні маси зосередженого вантажу з 0,2 кг до 0,52 кг — у 1,4…1,6 рази. Частотний аналіз у середовищі SolidWorks Simulation продемонстрував достатню точність (похибка 2…3%), високу ефективність та економічну доцільність, особливо при проєктуванні складних конструкцій. Чисельне моделювання виявилося зручним інструментом для оптимізації конструкцій та скорочення витрат на етапі розробки.*

Наукова новизна. *Вперше проведено комплексне порівняння аналітичного, експериментального та чисельного методів визначення частоти власних коливань різця-осцилятора Х. Проаналізовано вплив геометричних та інерційних параметрів на його динамічні характеристики. Показано ефективність використання частотного аналізу в САПР-системах для дослідження динаміки процесу точіння, що є актуальним для оптимізації складних конструкцій.*

Практична цінність. *Метод комп'ютерного моделювання продемонстрував високу точність і повторюваність результатів при визначенні частоти власних коливань різця-осцилятора Х, що підтверджує його придатність для вібраційного аналізу ріжучих інструментів. Застосування частотного аналізу в SolidWorks Simulation спрощує проєктування, скорочує витрати та є особливо ефективним для складних конструкцій.*

Ключові слова: *регенеративні автоколивання, різець-осцилятор, осцилограма, частота власних коливань, виліт, зосереджена маса.*

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