МОДЕЛЮВАННЯ ПРОЦЕСІВ В МЕТАЛУРГІЇ ТА МАШИНОБУДУВАННІ

MODELING OF PROCESSES IN METALLURGY AND MECHANICAL ENGINEERING

UDC 621.941.08

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CALCULATION OF PARAMETERS OF A CUTTER-OSCILLATOR WITH TWO DEGREES OF FREEDOM

Purpose. *The main purpose of the work is to conduct a comprehensive assessment of the parameters of a cutter-oscillator with two degrees of freedom using three methods: analytical, computer, and experimental.*

Research methods. *The analytical approach included determining the natural frequency of oscillations and the angle of the resulting displacement of the cutter-oscillator with two degrees of freedom. For numerical modeling of the cutter-oscillator, the SolidWorks and NX software packages were used. The research was also conducted by an experimental method, within which the oscillograms of the oscillations of the cutting edge were recorded. On their basis, the static deflection of the cutter-oscillator and the frequency of its free oscillations were determined.*

Results. *As a result of the study, it was found that the use of an cutter-oscillator is effective for determining the dynamic characteristics of the turning process. The analytical method made it possible to obtain preliminary estimates of the frequencies of natural oscillations and the direction of the resulting displacement. Computer modeling in SolidWorks and NX provided increased accuracy of calculations and allowed varying the system parameters without additional experiments. Experimental measurements based on the analysis of the oscillograms of the cutting edge oscillations confirmed the consistency of the theoretical and model data. The obtained results prove the reliability of the adopted models and the feasibility of using computer modeling for further improvement of the dynamic analysis of the turning process.*

Scientific novelty. *The scientific novelty of the work lies in the integrated approach to the study of the dynamic characteristics of a cutter-oscillator with two degrees of freedom, which combines analytical, numerical and experimental methods of evaluation.*

Practical value. *The practical value of the work lies in the development and justification of a methodology for evaluating the dynamic parameters of a two degree of freedom cutter-oscillator, which can be used during the design and adjustment of tool systems in the turning process. The use of computer modeling allows you to change quickly the design parameters of the tool without conducting a significant number of experiments, reducing the cost of time and resources. The obtained results can be implemented in production practice and used to improve dynamic control systems in metalworking.*

Key words: *oscillogram, self-oscillations, angle of the resulting displacement, regenerative self-oscillations, the natural frequency of oscillations.*

Introduction

Vibrations during turning largely determine the quality of processing, dimensional accuracy and tool durability. One of the effective tools for studying vibrations is the cutter-oscillator. Such tools make it possible to assess the influence of the design parameters of the tool, the material being processed and the cutting modes on the dynamics of

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the cutting process. Accurate determination of the parameters of the cutter-oscillator is necessary for a qualitative study of the parameters of vibrations during turning.

Modern research methods include analytical calculations, computer modeling and experimental measurements. Each of these approaches has its advantages: analytical methods allow for a quick assessment of system parameters, computer modeling allows for the consideration of complex design and physical factors, and experimental studies ensure the verification of models in real conditions.

Analysis of research and publications

The most undesirable and difficult to eliminate vibrations during cutting are self-oscillations – self-sustaining vibrations that arise due to the internal feedback between the cutting process and the vibrations of the tool. Today, a number of reasons for the excitation of self-oscillations during turning are distinguished: the regenerative effect (regenerative self-oscillations) [1, 2], the coordinate coupling (mode coupling) [3, 4], the decreasing characteristic of the cutting force from the processing speed (tangential self-oscillations) [5]. At the same time, it is important to note that in real conditions of cutting, oscillations are always coupled and consist of different types of oscillation, including self-oscillation, of different directions of action, depending on the direction of the degree of freedom of the tool.

To study self-oscillation, various methods and means of measurement: acoustic emission [6, 11, 12], dynamometers [10, 14], variation of the torque of the electric motor of the machine tool [7, 8, 9], etc. are used. However, the most methodically correct study of self-oscillation is with cutters-oscillators, the oscillatory movement of the cutting edge of which corresponds to the law of oscillatory motion of the self-oscillating system. Works [14, 16] present the design of an oscillator cutter with two degrees of freedom in the direction of changing the thickness of the cut and the cutting speed. Accelerometers are used as sensors. The use of accelerometers does not allow to estimate the direction of the resulting movement of the cutting edge. Works [13, 15] present the design of the cutter-oscillator with one degree of freedom in the direction of change in the thickness of the cut. As a means of measuring the oscillating cutting edges, the moved sensors are used. The impact method [17], which requires the production of full-scale samples, is mainly used to study the natural frequencies of oscillating cutters-oscillators. Most of the investigated authors do not pay due attention to the calculation of the direction of the resulting movement of the cutting edge of the cutter-oscillator. That leads to failure to take into account all causes of self-oscillatory excitation in models of oscillatory motion.

The work [5] proposed the design of a cutter-oscillator with two degrees of freedom along the X and Z axes, with the same stiffness in any direction in the XOZ plane. The cutting edge is located on the axis of the holder, which excludes torsional vibrations. However, only analytical formulas for calculating the displacement of the cutting edge are given to calculate the parameters of the cutter-oscillator. Currently, the use of 3D modeling allows you to automate these calculations.

In the works of the authors [18, 19], the results of calculations of the main dynamic characteristics of cutter-oscillators with one degree of freedom are presented by the modeling method, using modern computer programs. This method showed a number of advantages compared to analytical and experimental methods.

Analysis of the dynamic characteristics of the cutter-oscillator with two degrees of freedom allows you to qualitatively assess the dynamic picture of the turning process, predict the behavior of the system under the influence of vibrations, and develop measures to prevent them.

Purpose of work

The purpose of this work is a comprehensive study of the parameters of a cutter-oscillator with two degrees of freedom using three evaluation methods - analytical, computer and experimental.

Research material and methodology

Method for determining the frequency of natural oscillations of the cutter-oscillator and determining the angle of direction of the resulting movement of the cutting edge.

Analytical method

The approximate value of the natural oscillation frequency (NOF) of the first mode of the cutter-oscillator can be found using the formula from the classical Euler–Bernoulla model using the empirical approximation $0\leq \mu \lesssim 10$:

$$f \approx \frac{1}{2\pi}\cdot\frac{1{,}875^2}{L^2}\cdot\sqrt{\frac{EI}{\rho A}}\cdot\frac{1}{\sqrt{1+0{,}236\mu+0{,}024\mu^2}}, \text{Hz}, \quad (1)$$

where L – the length of the cutter-oscillator overhang, m;

E – Young's modulus of the material of the cutter-oscillator holder, Pa;

I – moment of inertia of the cutter-oscillator cross-section, m⁴;

$$I = I_x = I_z = \frac{\pi d^4}{64}, \quad (2)$$

A – cross-sectional area of the cutter-oscillator holder, m²;

$$A = \frac{\pi d^2}{4}. \quad (3)$$

ρ – material density of the holder of the cutter-oscillator, kg/m³;

m – mass of the cutter-oscillator head, kg;

μ – the dimensionless ratio of the mass of the head to the mass of the cutter-oscillator holder;

$$\mu = \frac{m}{\rho A L} \quad (4)$$

d – cross-sectional diameter of the cutter-oscillator holder, m;

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Based on the data: $L = 0.08, 0.1, 0.12$ m, $E = 2{\cdot}10^{11}$Pa, $\rho = 7850$ kg/m³, $m = 0.46$ kg, $d = 0.025$ m, were fined:

$$A = \frac{3{,}14 \cdot 0{,}025^2}{4} = 4{,}9 \cdot 10^{-4}\text{m}^2.$$

$$I = I_x = I_z = \frac{3{,}14 \cdot 0{,}025^4}{64} = 1{,}9 \cdot 10^{-8}\text{m}^4.$$

$$\mu_{0,08} = \frac{0{,}46}{7850 \cdot 4{,}9 \cdot 10^{-4} \cdot 0{,}08} = 1{,}49.$$

$$\mu_{0,1} = \frac{0{,}46}{7850 \cdot 4{,}9 \cdot 10^{-4} \cdot 0{,}1} = 1{,}19.$$

$$\mu_{0,12} = \frac{0{,}46}{7850 \cdot 4{,}9 \cdot 10^{-4} \cdot 0{,}12} = 0{,}99.$$

$$f_{0,08} \approx \frac{1}{2 \cdot 3{,}14} \cdot \frac{1{,}875^2}{0{,}08^2} \times \sqrt{\frac{2 \cdot 10^{11} \cdot 1{,}9 \cdot 10^{-8}}{7850 \cdot 4{,}9 \cdot 10^{-4}}} \times$$

$$\times \frac{1}{\sqrt{1 + 0{,}236 \cdot 1{,}49 + 0{,}024 \cdot 1{,}49^2}} = 2327 \text{ Hz}.$$

$$f_{0,1} \approx \frac{1}{2 \cdot 3{,}14} \times \frac{1{,}875^2}{0{,}1^2} \times \sqrt{\frac{2 \cdot 10^{11} \cdot 1{,}9 \cdot 10^{-8}}{7850 \cdot 4{,}9 \cdot 10^{-4}}} \times$$

$$\times \frac{1}{\sqrt{1 + 0{,}236 \cdot 1{,}19 + 0{,}024 \cdot 1{,}19^2}} = 1535 \text{ Hz}.$$

$$f_{0,12} \approx \frac{1}{2 \cdot 3{,}14} \times \frac{1{,}875^2}{0{,}12^2} \times \sqrt{\frac{2 \cdot 10^{11} \cdot 1{,}9 \cdot 10^{-8}}{7850 \cdot 4{,}9 \cdot 10^{-4}}} \times$$

$$\times \frac{1}{\sqrt{1 + 0{,}236 \cdot 0{,}99 + 0{,}024 \cdot 0{,}99^2}} = 1090 \text{ Hz}.$$

For a cutter-oscillator with two degrees of freedom, the bending occurs in two main mutually perpendicular planes of inertia and can be represented as the joint action of two axial bendings f_x and f_z. The magnitude of the total bending of the cutter-oscillator is calculated by the formula [5]:

$$f = \sqrt{f_x^2 + f_z^2} \qquad (5)$$

The plane in which the bending of the cutter-oscillator occurs is inclined at an angle γ to the Z axis, the value of which can be found by equation [6]:

$$\gamma = arctg\left(\frac{f_x}{f_z}\right) = arctg\left[\text{tg}(\alpha) \cdot \frac{I_x}{I_z}\right] = \alpha, \qquad (6)$$

where α – the angle of action of the cutting force.

The direction of the resulting displacement (DRD) of the cutting edge of the cutter-oscillator coincides with the direction of action of the cutting force (DAF) $\gamma = \alpha$, since the holder has a circular cross-section, the stiffness K and the moments of inertia I along the X and Z axes are the same (Fig. 1)

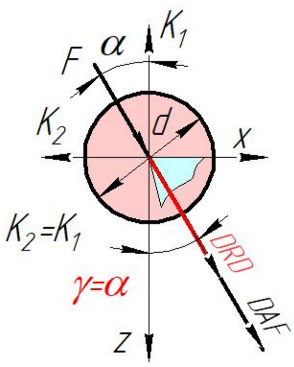

Figure 1. Scheme for calculating the angle of the DRD

The angle of action of the cutting force is found by the ratio of the components of the cutting force:

$$\alpha = F_x/F_z. \qquad (7)$$

The components of the cutting force were calculated using the formula [19]:

$$F_{z,x} = 10C_p t^x S^y v^n K_p\ , \qquad (8)$$

where Cp – a constant that takes into account the processing conditions;

x, y, n – exponents;

t – the cutting depth, mm;

S – the feed, mm/rev;

v – the cutting speed, m/min;

K_p – the generalized correction factor that takes into account changes in processing conditions relative to the tabular values.

The following cutting modes were adopted for calculating the force: $t = 1$ mm, $S = 0.2$ mm/rev, $v = 150$ m/min, the workpiece material is Steel 45 ($\sigma = 600$ MPa), without a cooling medium. Cutting insert parameters: material - T15K6, $\gamma = 0°$, $\alpha = 10°$, $\varphi = 90°$, $\lambda = 0°$, r = 0.5 mm.

According to equations (7), (8), the values of the components of the cutting forces and the angle of inclination of the cutting force were determined: $F_x = 279.9$ N, $F_z = 304.6$ N, $\alpha = 46.2°$.

Modeling method

Using a 3D model of the cutter-oscillating created in *Unigraphics*, a frequency analysis was performed in the *SolidWorks Simulation* module, resulting in the calculated NOF as a function of the cutter's oscillating projection (L), with deformation visualization. The initial data for the calculations were the model material (65G steel) and constraints (cantilever clamping). The 3D model of the oscillating cutter is shown in (Fig. 2).

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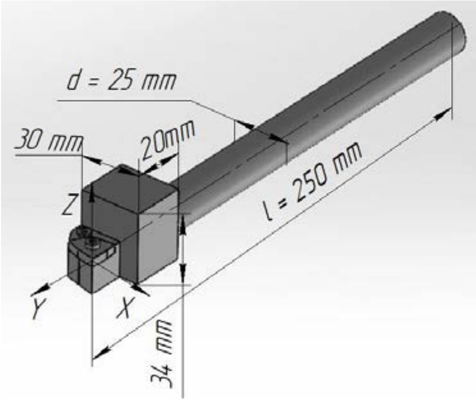


Figure 2. 3D model of a cutter-oscillator with two degrees of freedom

The angle of the cutting edge of the cutter-oscillator was determined by calculating the axial displacements from the action of the cutting force components using the SolidWorks Simulation software module. Further, according to formula (6), the angle of the cutting edge of the cutter-oscillator was determined using the formula for the cutting edge of the cutter-oscillator.

Experimental method

The experimental technique for determining the NOF, described in the authors' work [5]. The cutter-oscillator was fixed in a special device installed in the tool holder of a Zenitech WL 320 CNC lathe (Fig. 3). Two contactless displacement sensors mod. Schneider Electric XS4P12AB110 were installed in the housing of the special device along the X and Z axes. The sensors measured the axial deflections of the cutter-oscillator and were connected via an L-Card E14-140-M ADC to a personal computer. The cutter-oscillator was calibrated using a dynamometer and a dial indicator.

Figure 3. Image of devices for conducting experiments

During the experiments, the cutter-oscillator overhang length, *L*, was varied. The NOF was measured using the impact hammer test. The vibration displacement of the cutter-oscillator after the impact was recorded and stored as oscillograms. The NOF was measured using the oscillograms obtained and processed in *PowerGraph*. To experimentally investigate the direction of the resulting displacement of the cutter-oscillator under the action of turning, longitudinal turning of a rigid part was performed. Cutting edge movements during turning were recorded as oscillograms (Fig. 4), from which static deflections along the X and Z axes were measured.

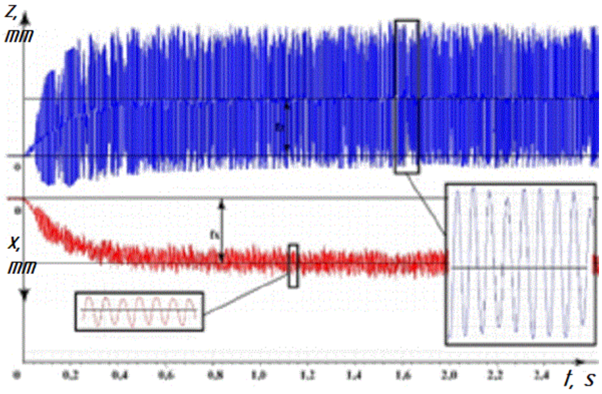
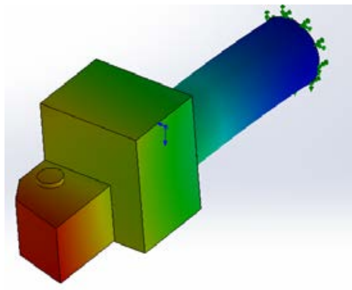


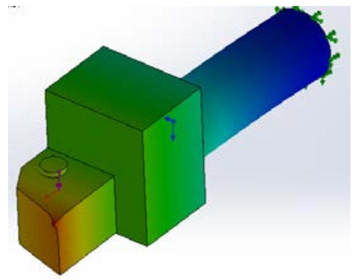
Figure 4. Oscillogram of the cutter-oscillator oscillation during turning

Research results and discussion

Fig. 5 shows a visualization of the calculation of the NOF (a) and static analysis (b) of the cutter-oscillator in the *SolidWorks Simulation* module.



a



b

Figure 5. Visualization of the calculation of the NOF (*a*) and the angle - γ of the DRD (*b*) of the cutter-oscillator (*L*=120 mm)

Table 1 and Fig. 6 present the results of calculations of the NOF of the cutter-oscillator depending on the over-

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hang *L* using analytical, experimental and modeling methods.

Table 1 – Results of the calculation of the NOF

L, mm	f_{an}, Hz	f_{exp}, Hz	f_{mod}, Hz
80	2327	1400…1430	1441
100	1535	1111…1250	1094
120	1090	714…769	725

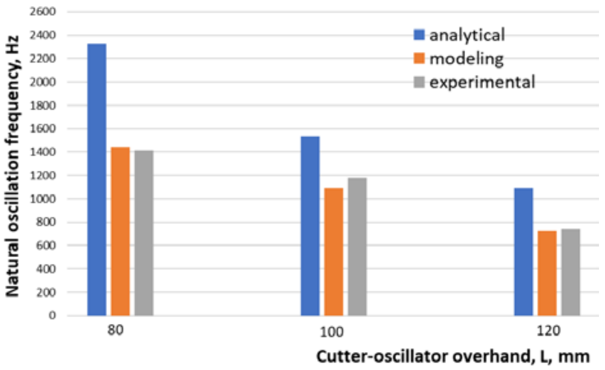

Figure 6. Results of calculating the NOF using different methods

The results demonstrate consistency between the experimental and modeling data. As the cutter-oscillator overhang increased from L = 80 mm to L = 120 mm, the oscillation frequency decreased by more than 2 times. The calculated values exceed the experimental values because the simplified oscillation frequency calculation used, based on the classical Euler-Bernoulli model, is well suited for thin, long bars. For bars with a short length relative to their diameter ($L/d \lesssim 10$), the effects of shear deformation and rotational inertia of the sections have a greater impact on the oscillation frequency, leading to a reduction (Timoshenko theory). The actual geometry of the cutter-oscillator and the rigidity of the actual mounting also influence the experimental values, which can often also reduce the frequency.

Table 2 and Fig. 7 show the results of calculating the angle of the DRD γ depending on the overhang of the cutter-oscillator, obtained by analytical method, experimentally and using computer modeling.

Table 2 – Results of calculating the angle of the NRP

Parameter	**Cutter-oscillator overhang**		
L, mm	80	100	120
	Analytical method		
γ,°	46,2	46,2	46,2
	Computer modeling method		
f_x, mm	0,01411	0,03135	0,05108
f_z, mm	0,01525	0,03395	0,05495
γ,°	42,8	42,7	42,9
	Experimental method		
f_x, mm	0,02…0,023	0,06…0,073	0,103…0,093
f_z, mm	0,026…0,033	0,06…0,08	0,1…0,096
γ,°	46,9	45,6	45,0

The obtained results demonstrated good consistency between the various calculation methods. As the tool overhang increases from L = 80 mm to L = 120 mm, the DRD angle remains virtually unchanged.

The computer simulation results are in good agreement with the experimental results, compared to the analytical method, indicating the potential for this calculation method to be effectively used to predict the parameters of cutter-oscillating of any design.

Conclusions

The dynamic characteristics of the turning process should be investigated using cutter-oscillators, which provide the ability to measure accurately both static and dynamic components of cutting forces. The work evaluated the parameters of the cutter-oscillator with two degrees of freedom using three methods – analytical, computer simulation, and experimental. The obtained results showed consistency between theoretical calculations and experimental data, which confirmed the correctness of the adopted models and assumptions.

A comparison of different approaches demonstrated that the choice of a specific method may depend on the available equipment, the required accuracy, and the ease of implementation in the conditions of a specific experiment. The analytical method provides a quick preliminary assessment, the experiment most fully takes into account real cutting conditions, and the computer simulation method combines high accuracy with the ability to vary system parameters without conducting a large number of physical tests.

The results of the study confirmed the effectiveness and feasibility of using the computer modeling method to determine the angle of the resulting cutting edge movement and the natural frequency of oscillations of the cutter-oscillator, which makes it a promising tool for further improving dynamic analysis systems for the turning process.

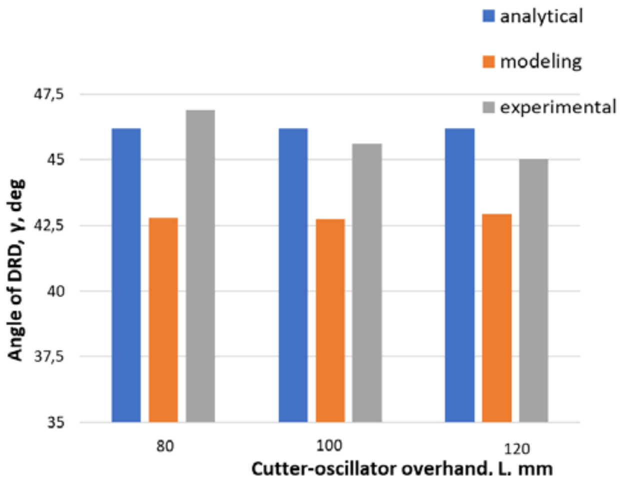

Figure 7. Results of calculating the angle - γ of DRD at L = 80, 100, 120 mm

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РОЗРАХУНОК ПАРАМЕТРІВ РІЗЦЯ-ОСЦИЛЯТОРА З ДВОМА СТУПЕНЯМИ СВОБОДИ

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Мета. *Основною метою роботи є проведення комплексної оцінки параметрів різця-осциляторного з двома ступенями свободи за допомогою трьох методів: аналітичного, комп'ютерного та експериментального.*

Методи дослідження. *Аналітичний підхід включав визначення власної частоти коливань та кута результуючого переміщення різця-осцилятора з двома ступенями свободи. Для числового моделювання різця-осцилятора використовувалися програмні пакети SolidWorks та NX. Дослідження також проводилося експериментальним методом, в рамках якого реєструвалися осцилограми коливань різальної кромки. На їх основі визначався статичний вигин різця-осцилятора та частота його вільних коливань.*

Результати. *В результаті дослідження було встановлено, що використання різця-осцилятора є ефективним для визначення динамічних характеристик процесу точіння. Аналітичний метод дозволив отримати попередні оцінки частот власних коливань та кута напрямку результуючого переміщення. Комп'ютерне моделювання в SolidWorks та NX забезпечило підвищення точності розрахунків та дозволило варіювати параметри системи без додаткових експериментів. Експериментальні вимірювання, засновані на аналізі осцилограм коливань різальної кромки, підтвердили узгодженість теоретичних та модельних даних. Отримані результати доводять надійність прийнятих моделей та доцільність використання комп'ютерного моделювання для подальшого вдосконалення динамічного аналізу процесу точіння.*

Наукова новизна. *Наукова новизна роботи полягає в комплексному підході до дослідження динамічних характеристик різця-осцилятора з двома ступенями свободи, який поєднує аналітичні, числові та експериментальні методи оцінки.*

Практична цінність. *Практична цінність роботи полягає в розробці та обґрунтуванні методології оцінки динамічних параметрів різця-осцилятора з двома ступенями свободи, яка може бути використана під час проектування та налаштування інструментальних систем у процесі точіння. Використання комп'ютерного моделювання дозволяє швидко змінювати конструктивні параметри інструменту без проведення значної кількості експериментів, зменшуючи витрати часу та ресурсів. Отримані результати можуть бути впроваджені у виробничу практику та використані для вдосконалення систем динамічного керування в металообробці.*

Ключові слова: *осцилограма, автоколивання, кут результуючого переміщення, регенеративні автоколивання, власна частота коливань.*

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