МОДЕЛЮВАННЯ ПРОЦЕСІВ В МЕТАЛУРГІЇ ТА МАШИНОБУДУВАННІ

MODELING OF PROCESSES IN METALLURGY AND MECHANICAL ENGINEERING

UDC 621.941.08

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MODELING THE ANGLE OF THE DIRECTION OF THE RESULTING DISPLACEMENT OF THE CUTTING EDGE OF THE CUTTER-OSCILLATOR

Purpose*. Establishing the dependence of the angle of the direction of the resulting displacement of the cutting edge of the cutter-oscillator on the geometric parameters of the holder using various methods and substantiating the feasibility of using cutter-oscillators with single degree of freedom for targeted modeling of the influence of individual factors, such as the regenerative effect or a change in the instantaneous cutting speed.*

Research methods*. The analytical method involved obtaining calculation formulas for determining the angle of the direction of the resulting displacement of the cutter-oscillator. For numerical modeling of the bending of the cutter-oscillator during turning, the SolidWorks and Unigraphics NX programs were used. The research was also conducted by an experimental method, in which oscillograms of the oscillations of the cutting edge were recorded, from which the static bending of the cutter-oscillator was determined.*

Results*. Methods for determining the direction of the resulting displacement of the cutting edge of the cutter-oscillator have been developed based on analytical calculation, computer modeling, and experimental methods. Computer modeling of the bends of the cutters-oscillator has been carried out in the SolidWorks program, which made it possible to determine with high accuracy the angle of the direction of the resulting displacement of the cutting edge at different ratios of the cutter- oscillator holder dimensions. It has been shown that the optimal ratio of the height to the width of the holder (h/b > 3.3 for the oscillator X; h/b < 0.3 for the oscillator Z) provides the direction of movement with a deviation of no more than 5° from the X and Z axes, respectively. The accuracy of the computer modeling method has been experimentally confirmed, which allows it to be used for designing cutters-oscillators with specified dynamic properties.*

Scientific novelty*. The optimal dependence of the angle of the direction of displacement of the cutting edge of the cutter-oscillator on the geometric parameters of the holder has been established, which allows controlling the orientation of oscillations during cutting.*

Practical value*. The results of the work can be used in the design of cutters-oscillators to study the dynamics of the turning process. The developed methodology allows reducing the costs of manufacturing prototypes of cutters-oscillators due to preliminary modeling of their characteristics in the CAD/CAM environment.*

Key words*: oscillogram, self-oscillations, degree of freedom, regenerative self-oscillations, cutting speed.*

Introduction

Turning is one of the key metalworking methods, widely used for the manufacture of parts of varying complexity. However, this process is often accompanied by self-oscillation, known as chatter [1], the nature of which has not yet been fully elucidated due to its multifactorial nature and complexity. Chatter negatively affects the stability of the cutting process, worsens the quality of the machined surface, reduces dimensional accuracy, accelerates tool wear and can lead to equipment damage [2].

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Despite a significant amount of scientific research in this area, there is still no single theory that would fully explain the physical mechanism of self-oscillations during turning. The main sources of vibration are considered to be the regenerative effect [3] and coordinate (modal) coupling [4, 5].

For a deeper understanding of the mechanism of self-oscillations and the development of effective methods for their suppression, specialized experimental approaches are necessary. One of such approaches is the use of cutters-oscillators with single degree of freedom along the X or Z axis [6, 7]. This allows us to exclude the influence of the coordinate connection and separately investigate the influence of the regenerative effect (with oscillations along the axis of change of the cut thickness - the X axis) or the influence of instantaneous changes in the cutting speed (with oscillations along the Z axis). This is the basis for building a reliable experimental base and testing analytical models of the dynamics of the turning process.

Analysis of research and publications

In the field of vibration research, which occurs during turning, a large number of scientific works have been carried out, the main attention of which is paid to the prediction and prevention of self-oscillations [8, 9]. In order to detect and analyze vibration processes, various experimental and analytical methods are used.

One of the widely used approaches is the analysis of acoustic emission signals [10, 11]. However, the reliability of such studies significantly depends on a number of factors, including the accuracy of the sensor location and the level of external noise, which can distort the results. A more reliable alternative is the use of dynamometers [12], since cutting forces are more sensitive to vibrations compared to acoustic signals. At the same time, due to the inertial properties and design limitations of the dynamometers themselves, distortion of the measured values is possible.

Experimental studies of vibration during turning are often carried out using oscillators [7, 12], which allow recording the movement of the cutting edge during machining. Of particular note is the use of cutters-oscillators [13, 14] with single or two degrees of freedom, which, due to their low rigidity, are able to perform oscillatory movements under the action of cutting forces, which are recorded using displacement sensors [13] and accelerometers [15]. However, despite the prevalence of such devices, in most studies insufficient attention is paid to the coordination of the direction of oscillations of the oscillator with the direction of the sources of the acting vibration disturbances, which is critically important for the correct analysis of the dynamics of the cutting process. In this regard, there is a need to develop a method for calculating the direction of the resulting movement of the cutting edge of the cutter-oscillator. This technique allows to ensure coordinated oscillation along a given axis, which, in turn, increases the accuracy and reliability of measurements. The use of modern 3D modeling tools in CAD/CAM environments for designing cutters-oscillators and comparing the results of numerical modeling with experimental data opens up new opportunities for analyzing vibration processes and improving the design of experimental devices.

Purpose of work

The aim of the work was to compare different methods for determining the direction of movement of the cutting edge of a cutter-oscillator during oscillations and to determine the conditions that allow for the constructive implementation of oscillations along a certain axis.

Research material and methodology

Analytical method for determining the angle of direction of the resulting cutting edge movement

The simplest design of a cutter-oscillator is a cantilevered rectangular rod of length l with a cross-section $h \times b$ (Fig. 1*a*). When placing the cutting edge on the central axis of rigidity of the cutter-oscillator holder, it is easy to provide two degrees of freedom, eliminating torsional vibrations. The cutting force F is applied at point O on the free end of the cutter-oscillator. The direction of action of the cutting force (DAF) is located at an angle α to the Z axis. The direction of the resulting displacement (DRD) of the cutting edge does not coincide with any of the main axes of inertia of the state. The deformation of the cutter-oscillator that occurs in this case is known as “oblique” bending.

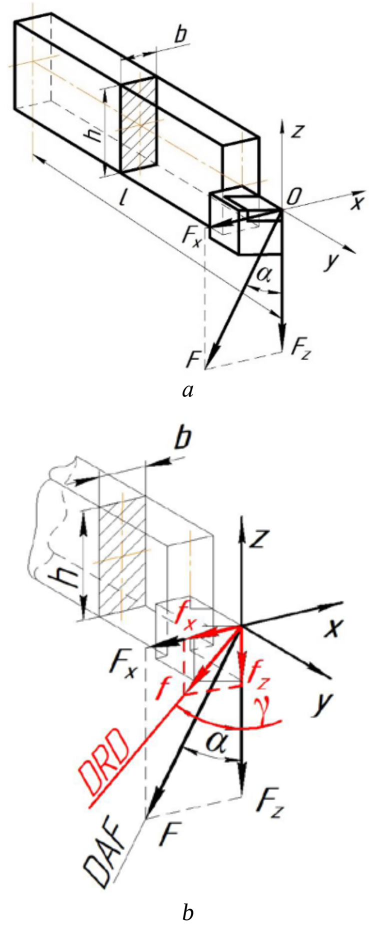

Figure 1. Design of a cutter-oscillator with two degrees of freedom (*a*) and a scheme for determining the DRD of the cutting edge of a cutter-oscillator (*b*)

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For cutters-oscillators with two degrees of freedom, the "oblique" bend can be represented as the joint action of two axial bends f_x and f_z in two main mutually perpendicular planes of inertia (Fig. 1*b*). The magnitude of the "oblique" bend of the cutter-oscillator is calculated by the formula [13]:

$$f = \sqrt{f_x^2 + f_z^2}. \qquad (1)$$

The plane in which the "oblique" 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 [13]:

$$tg(\gamma) = \frac{f_x}{f_z} = \frac{F_x}{F_z} \cdot \frac{I_x}{I_z} = tg(\alpha) \cdot \frac{I_x}{I_z} \qquad (2)$$

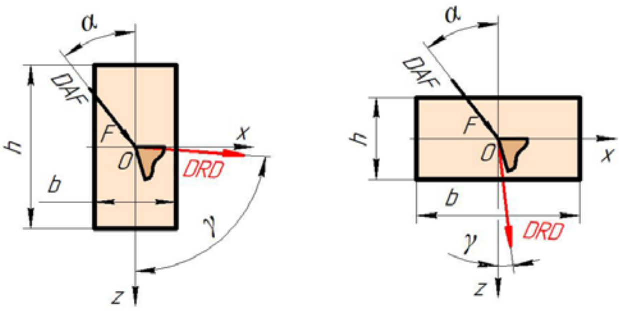
$$\gamma = arctg\left[tg(\alpha) \cdot \frac{I_x}{I_z}\right] = arctg\left[tg(\alpha) \cdot \left(\frac{h}{b}\right)^2\right]. \qquad (3)$$

To study vibration during turning, it is necessary to provide the possibility of oscillations of the cutter-oscillator in a certain direction, which may coincide:

1) With the direction of change in the thickness of the layer being cut (X axis).

2) With the direction of cutting speed (Z axis).

In the case of a cutter-oscillator with a rectangular cross-section of the holder, it is possible to artificially limit the bending only along one axis (X or Z), thereby realizing single degree of freedom. This is achieved by selecting the dimensions of the cross-section of the holder according to equation (3) in such a way that the angle of the DRD γ coincides with the X or Z axis. The cross-section diagrams of the cutter-oscillator holder for these cases are presented in Fig. 2.



a *b*

Figure 2. DRD for a cutter-oscillator with single degree of freedom along the X axis (*a*) and along the Z axis (*b*)

Modeling the angle of direction of the resulting cutting edge displacement

To model the DRD of the cutting edge due to the action of the cutting force components, the Unigraphics NX and SolidWorks programs were used. In the Unigraphics NX program, six solid-state models of cutters-oscillators with different ratios of the holder cross-section *h*×*b* were constructed (Fig. 3):

- for the cutter-oscillator with oscillations along the X axis (cutter-oscillator X): 60 mm × 8 mm, 60 mm × 15 mm, 60 mm × 30 mm;

- for the cutter-oscillator with oscillations along the Z axis (cutter-oscillator Z): 8 mm × 60 mm, 10 mm × 60 mm, 15 mm × 60 mm.

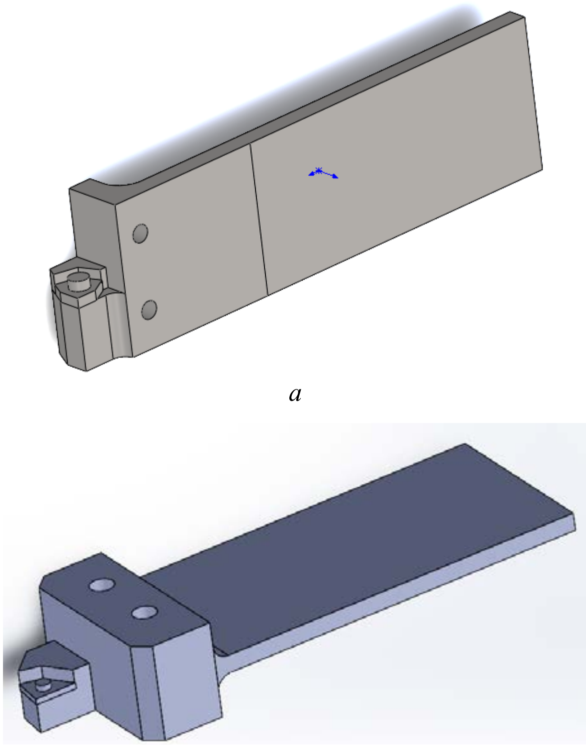
Next, the models were exported to the SolidWorks program for further calculations. The stages of the DRD modeling were the determination of:

- material parameters of the cutter-oscillator (steel 65G);

- fixation surfaces, depending on the toolholder overhang;

- components of the cutting forces acting on the cutting edge of the cutter-oscillator.

Using the SolidWorks program, a static analysis was performed, which allowed obtaining the axial deflections f_x and f_z of cutters-oscillators of all types under the action of the components of the cutting forces. Next, the DRD angle of the cutting edge γ was determined by formula (2).



a

b

Figure 3. Models of cutters-oscillators:
a – cutter-oscillator X, 60 mm × 8 mm;
b – cutter-oscillator Z, 8 mm × 60 mm

Components of the cutting force were calculated by the formula [16]:

$$F_{z,x} = 10 C_p t^x S^y v^n K_p, \qquad (4)$$

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

x, *y*, *n* – power indices;

t – cutting depth, mm;

S – feed, mm/rev;

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v – cutting speed, m/min;

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

$$K_p = K_{Mp} K_{\varphi p} K_{\gamma p} K_{\lambda p} K_{rp}, \quad (5)$$

where K_{Mp} – correction factor that takes into account the properties of the material being processed

$K_{\varphi p}$, $K_{\gamma p}$, $K_{\lambda p}$, K_{rp} – coefficients that take into account the geometric parameters of the cutting insert.

Since the cutting insert had principal approach angle φ = 90°, the component of the cutting force along the X axis was absent.

The following cutting modes were adopted for the calculation: t = 1 mm, S = 0.2 mm/rev, v = 150 m/min, workpiece material – Steel 45 (σ_B = 600 MPa), without a cooling liquid.

Cutting insert parameters: material – hard alloy T15K6, γ = 0°, α = 10°, φ = 90°, λ = 0°, r = 0.5 mm. According to equations (4), (5), the values of the components of the cutting forces were determined: F_x = 279.9 N F_z = 304.6 N. The angle of inclination of the cutting force was – $\alpha = F_x/F_z = 279.9/304.6 = 46.2°$.

Experimental method for determining the angle of the resultant displacement direction

For the experimental study, a cutter-oscillator X was manufactured with the dimensions of the cross-sectional holder $h \times b$ = 60 mm × 8 mm and a cutter-oscillator Z with the dimensions of the cross-sectional holder $h \times b$ = 8 mm × × 60 mm. A special device was used to install the cutters-oscillators in the tool holder of the lathe [14]. The cutter-oscillator was placed inside the device housing between two guide inserts. To adjust the departure of the cutter-oscillator, the inserts could move along the Y axis until they were fixed. Two inductive displacement sensors (mod. Schneider Electric XS4-P12AB110) were installed on the housing, with the help of which the oscillations of the cutting edge of the cutter-oscillator along the X and Z axes were monitored during turning (Fig. 4).

Figure 4. Image of the experimental setup

The study used round-section workpieces that had sufficient rigidity, which allowed us to neglect their own vibrations during cutting.

When performing the experiments, the following cutting modes were used: t = 1 mm, S = 0.2 mm/rev, v = = 150 m/min, workpiece material – Steel 45, without cooling liquid. Cutting insert parameters – alloy T15K6, γ = 0°, α = 10°, φ = 90°, λ = 0°, r = 0.5 mm.

Signals from the displacement sensors were fed to a multi-channel analog-to-digital converter (mod. L-Card E140) and transmitted to a personal computer in the form of oscillograms. On the obtained oscillograms, the static deviation B_x, B_z of the cutting edge along the X and Z axes during turning was measured (Fig. 5). Before conducting the research, the cutters-oscillators were calibrated using a dynamometer DOSM-3-0.2 and a clock-type indicator ICH10B.

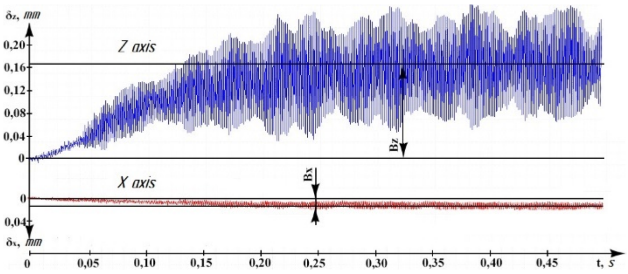

Figure 5. Example of an oscillogram for a cutter-oscillator Z

Research results and discussion

Fig. 6, 7 present the results of static analysis of cutter-oscillators in the SolidWorks environment. The toolholder overhang was l = 100 mm.

Table 1 shows the results of calculating the angle of the cutting edge DRD γ depending on the ratio of the cross-sectional dimensions of the cutter-oscillator holder, obtained by the analytical method, according to formula (3), and using computer modeling, formula (2).

The values of static deflections of the cutters-oscillators obtained from the oscillograms were:

1) for the cutter-oscillator X: $B_x = f_x$ = 0.175 mm; B_z = f_z = 0.011 mm;

2) for the cutter-oscillator Z: $B_x = f_x$ = 0.013 mm; B_z = f_z = 0.166 mm. Accordingly, according to formula (3), the experimentally obtained and calculated angle of the DRD for the cutter-oscillator X was γ = 86.4°, and for the cutter-oscillator Z – γ = 4.5°.

Based on the results of analytical calculations, computer modeling, and experiments, histograms were constructed (Fig. 8).

The obtained results showed that the analytical method of calculating the angle of the DRD does not take into account the geometric features of the real design of the cutter-oscillator. At the same time, the method of computer modeling using the SolidWorks analysis module allows you to obtain more accurate results, close to the characteristics of the actually manufactured cutter-oscillators. This emphasizes the advantage of static computer analysis in comparison with analytical and experimental methods, especially given the complexity of the design and the high cost of manufacturing cutters-oscillators.

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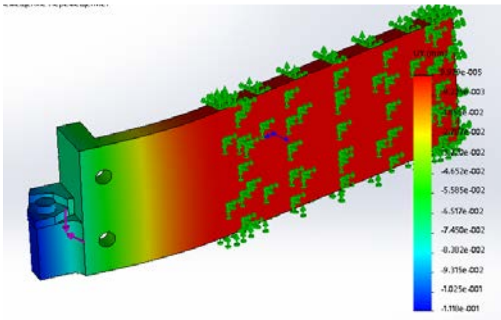
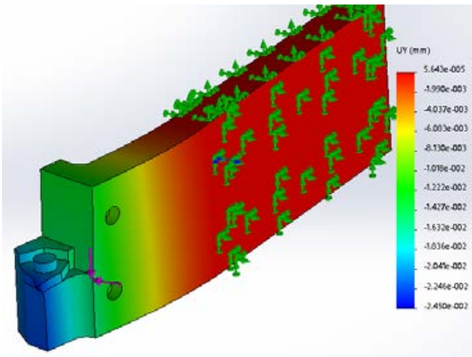
60 mm × 8 mm



60 mm × 15 mm



60 mm × 30 mm

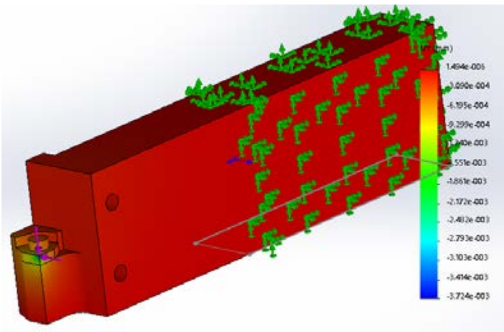
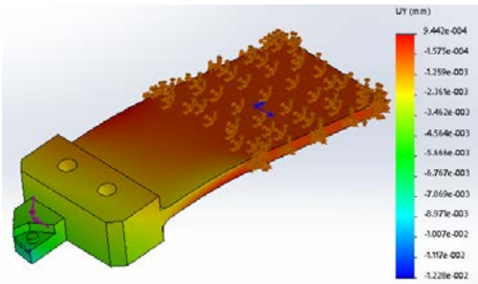
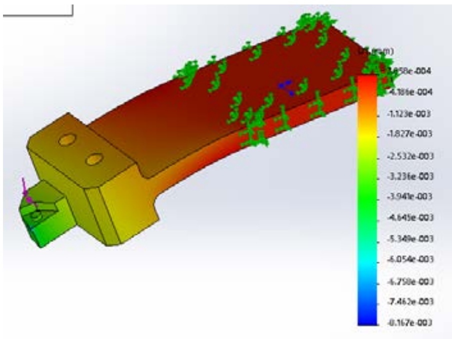


Figure 6. Results of static analysis in SolidWorks (cutter-oscillator X)

8 mm × 60 mm



10 mm × 60 mm



15 mm × 60 mm

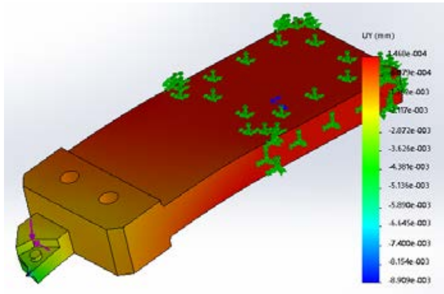


Figure 7. Results of static analysis in SolidWorks (cutter-oscillator Z)

Table 1 – Results of calculation of the cutting edge angle of the DRD γ, deg

Param-eters	**Analytical method**					
	Cutter-oscillator X			**Cutter-oscillator Z**		
h, mm	60	60	60	8	10	15
b, mm	8	15	30	60	60	60
h/b	7.5	4	2	0.13	0.16	0.25
γ, *deg*	89.0°	86.6°	76.5°	1.0°	1.6°	3.7°
Computer modeling method						
h, mm	60	60	60	8	10	15
b, mm	8	15	30	60	60	60
f_x, mm	0.108	0.033	0.009	0.013	0.008	0.008
f_z, mm	0.007	0.007	0.006	0.426	0.090	0.036
γ, *deg*	86.0°	78.0°	56.3°	1.7	5.2	12.6

The modeling results are in high agreement with experimental data, which confirms the feasibility of using computer modeling in the design of cutter- oscillators.

Additionally, calculations have shown that to ensure the optimal angle of deflection of the DRD γ (no more than 5° relative to the X or Z axis), it is necessary to adhere to the ratio of the dimensions of the holder cross section:

- for the cutter-oscillator X: *h/b* > 3.3;
- for the cutter -oscillator Z: *h/b* < 0.3.

Such a minimum deflection of the angle γ from the axis gives grounds to assert that the cutter-oscillator performs oscillatory movements mostly along one X or Z axis, i.e. has single degree of freedom. Thus, the results of the study confirm that the cutter-oscillator with oscillations along the X axis allows for an isolated study of the influence of the regenerative effect on the excitation of self-oscillations. In turn, the oscillations of the cutter-oscillator

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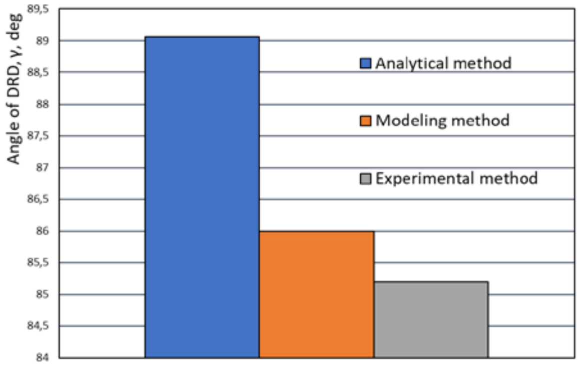
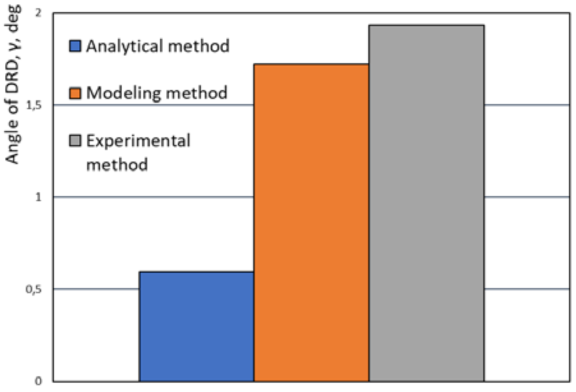
along the Z axis make it possible to analyze the occurrence of self-oscillations when the instantaneous cutting speed changes and in the absence of a regenerative effect.



a



b

Figure 8. Results of the calculation of the DRD:
a - cutter-oscillator X, $h \times b$ = 60 mm × 8 mm,
b - cutter-oscillator Z, $h \times b$ = 8 mm × 60 mm

Conclusions

The dynamic characteristics of the turning process should be investigated using cutters-oscillators with single degree of freedom, which provide the possibility of accurate measurement of both static and dynamic components of cutting forces. This approach allows to eliminate the coordinate coupling and to study individual mechanisms of self-oscillations.

The proposed methods for determining the direction of the resulting movement of the cutting edge of the cutter-oscillators demonstrate similar results, which indicates their consistency and practical applicability. The results of the study confirmed the possibility of effective use of the computer modeling method. The choice of a specific method may depend on the available equipment and the convenience of its implementation in the conditions of a specific experiment.

The optimal ratios of the dimensions of the holder section were obtained: for the cutter-oscillator X: $h/b > 3.3$; for the cutter-oscillator Z: $h/b < 0.3$, which provide the minimum values of the direction angle of the resulting movement - γ (no more than 5°), i.e. single degree of freedom.

Analysis of the obtained data showed sufficient accuracy of calculations and reproducibility of results, which allows us to recommend this approach for the development and optimization of the design of cutters-oscillators with one-dimensional oscillations.

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МОДЕЛЮВАННЯ КУТА НАПРЯМКУ РЕЗУЛЬТУЮЧОГО ПЕРЕМІЩЕННЯ РІЗАЛЬНОЇ КРОМКИ РІЗЦЯ-ОСЦИЛЯТОРА

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Мета роботи. *Встановлення залежності кута напрямку результуючого переміщення різальної кромки різця-осцилятора від геометричних параметрів державки різними методами та обґрунтування доцільності використання різців з одним ступенем свободи для цілеспрямованого моделювання впливу окремих факторів, таких як регенеративний ефект або зміна миттєвої швидкості різання.*

Методи дослідження. *Аналітичний метод передбачав отримання розрахункових формул для визначення кута напрямку результуючого переміщення різця-осцилятора. Для чисельного моделювання вигинів різця-осцилятора при точінні використовувалися програми SolidWorks та Unigraphics NX. Дослідження також проводили експериментальним методом, при якому записували осцилограми коливань різальної кромки, по яких визначали статичні вигини різця-осцилятора.*

Отримані результати. *Розроблено методики визначення напрямку результуючого переміщення різальної кромки різця-осцилятора на основі аналітичного розрахунку, комп'ютерного моделювання та експериментального методу. Проведено комп'ютерне моделювання вигинів різців-осциляторів у програмі SolidWorks, що дозволило з високою точністю визначити кут напрямку результуючого переміщення різальної кромки при різних співвідношеннях розмірів державки різця. Показано, що оптимальне співвідношення висоти до ширини державки (h/b > 3,3 для осцилятора X; h/b < 0,3 для осцилятора Z) забезпечує напрямок переміщення з відхиленням не більше 5° від осі X та Z, відповідно. Експериментально підтверджено точність методу комп'ютерного моделювання, що дозволяє застосовувати його для проєктування різців-осциляторів із заданими динамічними властивостями.*

Наукова новизна. *Встановлено оптимальну залежність кута напрямку переміщення різальної кромки різця-осцилятора від геометричних параметрів державки, що дозволяє керувати орієнтацією коливань під час різання.*

Практична цінність. *Результати роботи можуть бути використані при проєктуванні різців-осциляторів для дослідження динаміки процесу точіння. Розроблена методика дозволяє знизити витрати на виготовлення дослідних зразків різців-осциляторів за рахунок попереднього моделювання їх характеристик у CAD/CAM середовищі.*

Ключові слова: *осцилограма, автоколивання, ступінь свободи, регенеративні автоколивання, швидкість різання.*

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