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CUTTER-OSCILLATOR WITH SINGLE-DEGREE-OF-FREEDOM FOR THE STUDY OF CUTTING VIBRATIONS

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Abstract: The work includes theoretical analysis of the design of a single-degree-of-freedom cutter-oscillator. An improved design, allowing for the adjustment of mass and overhang length, is proposed. An experimental stand for recording oscillograms of cutting-edge motion is developed. The proposed approach allows the cutter-oscillator operation to be effectively tuned depending on the cutting conditions. The results provide a flexible system for parameter estimation under different cutting conditions.

KEYWORDS: turning; cutter-oscillator; single-degree-of-freedom; regenerative chatter

1 Introduction

For many years, vibrations during machining have remained a pressing issue in industrial production for two reasons.

Firstly, it is a non-trivial and difficult phenomenon to study, since it involves many factors related to the variety of cutting conditions, as well as significant differences in the dynamic properties of the elastic systems of MFTW (machine tool, fixture, tool and workpiece).

Secondly, the excitation of vibrations during cutting significantly deteriorates the accuracy and quality of machining, reduces the service life of the machine and tool, creates uncomfortable conditions (noise) for the operator, and, in general, leads to an increase in financial costs in the manufacture of the part.

Currently, the main efforts to eliminate the conditions leading to the excitation of oscillations during cutting are aimed at:

a) creation of mathematical models of stable cutting that allow predicting or correcting machining modes [1];

b) development of technological methods of active and passive damping of vibrations directly in the process of machining of specific parts [2].

Successful development of these approaches requires further deepening of knowledge about dynamic processes accompanying cutting conditions and clarification of some provisions adopted more than 50 years ago.

2 Literature review

The first devices for experimental study of vibrations in machining appeared in the early 20th century. They were systems consisting of elastic elements with finite deformations that responded to external or internal forces. Today, advancements in science and technology,

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particularly in sensors and signal processing techniques, have significantly contributed to the development of online vibration measurement devices [3, 4]. As input signals, these devices can use components of cutting force [5, 6], acceleration signals [7, 8], motor current [9], acoustic emission signals [10, 11], torque signal [12, 13], displacement signal [14]. In modern machine tools, vibration monitoring sensors are integrated into the control elements [15]. Also, miniature sensors can be installed in cutting tools [16]. The vibration signal from different sensors is widely used to monitor machining conditions, but they are poorly filtered, which affects the accuracy of the measured signals. The application of artificial intelligence in vibration research can expedite signal analysis, filter out defective signals, and reduce the risk of analysis errors [17, 18]. Also, in vibration research, devices based on acoustic emission signal monitoring are widely used [19, 20]. However, the success of these sensors depends on many factors such as installation location, operating mode, etc. They are also sensitive to environmental noise, which undoubtedly complicates the extraction of useful signal [21]. Furthermore, dynamometers find extensive use in vibration studies [22, 23]. Cutting forces exhibit good sensitivity to vibration compared to acoustic emission and are a fundamental indicator of the cutting process state in various machining types. However, force sensors are usually bulky and expensive, and their measurement range has limitations. Dynamometers operate on the principles of static equilibrium between the cutting force and the elastic force of the device itself. Thus, the forces of elasticity, friction and inertia will reflect the elastic system of the dynamometer rather than the object of study. Analogous to the dynamometer can be various oscillators, which also allow measuring the static and dynamic (vibration) component of the cutting force.

Among all methods, it is necessary to emphasize the use of special devices designed to secure the object of study in a manner that allows for oscillatory movements. The advantage of these devices is their low stiffness, which allows the study of conditions related to the origin, development and degeneration of oscillations. The main part of the designs of special devices are oscillators with one [7, 24] or two-degree-of-freedom [25]. For example, in [26], a cutter-oscillator with a flexible holder in the X-axis direction was used to study the effect of changing the cutting speed on the suppression of regenerative chatter. In the study [15], the influence of the scheme of attaching dampers with tuned mass on the occurrence of vibrations in the process of turning a thin-walled cylinder, which in turn was an oscillator, was determined. In [27], a special design of an oscillator of low stiffness along the X-axis was used to study vibration in the turning process. The author [28] presented an experimental setup for investigating the stability of turning processes, where a circular workpiece was used as an oscillator, which received external vibration from actuators that, in turn, simulated the contact force characteristics, including the effect of surface regeneration between the cutting tool and the workpiece. However, in the mentioned papers, the oscillator systems have more than single-degree-of-freedom. In vibration analysis, this requires the consideration of two factors: the regenerative effect and the coordinate coupling effect, which complicates the process of analysing the experimental results. Therefore, despite the fact that the turning process, in general, has six-degree-of-freedom (3 - the workpiece and 3 - the cutter), studies using oscillators with single-degree-of-freedom are the most informationally valuable because they allow us to study different types of vibrations, excluding the realization of the principle of coordinate coupling.

The authors of the article propose a design of a cutter-oscillator and an experimental stand, with the help of which it is possible to study any types of oscillations, including regenerative chatter excited during cutting, without significant influence on the results of studies of the principle of coordinate relations.

3 Determination of the shape and dimensions of the cutter-oscillator (holder) for the study of vibration during longitudinal turning

The most convenient scheme for investigating cutting vibrations is longitudinal turning under orthogonal cutting conditions (Fig. 1). The scheme of research in planning limits the possibility of increasing the cutting speed, and the scheme of research in cross turning leads to a decrease in both the cutting speed and the length of the cutting surface at each subsequent revolution. This is unacceptable, since the cutting speed - v unambiguously determines the wavelength on the cutting surface-λ.

$$\lambda = \frac{1000v}{60f}, \text{ [mm]}, \tag{1}$$

where v - cutting speed, [m/min];

f - natural frequency of cutter-oscillator elastic system (ES) oscillations, [Hz].

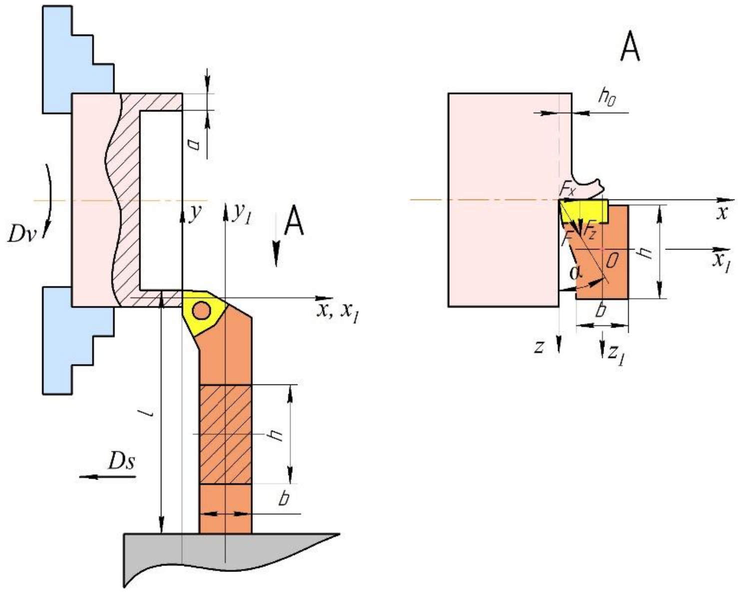


Fig. 1 Schematic of longitudinal turning under orthogonal cutting conditions (side cutting-edge angel φ = 90°, back rake angle λ = 0, side rake angle γ = 0).

And the length of the cutting surface, at each revolution, will determine the number of waves on it - N and their fractions.

$$N = \frac{\pi D}{\lambda}, \tag{2}$$

where D - diameter of the workpiece.

However, in the longitudinal turning with through cutters of conventional designs, a problem arises in the study of vibrations due to the simultaneous effect of two mechanisms on the excitation conditions of the most difficult to study self-oscillations (SO):

A. Cutting along the previous vibration trace on the cutting surface.

B. dPrinciple of coordinate coupling.

And if cutting "along the trace" (regenerative chatter) - always takes place for excitation of SO, the principle of coordinate coupling arises in conditions when the cutter ES has more than single-degree-of-freedom. Moreover, the principle of coordinate coupling can be realized even if the cutter-oscillator has only single-degree-of-freedom, but if the direction of the resultant displacement (DRD) of the cutting edge does not align with the direction of cut thickness change (DCTC) - h_0 (i.e., the X-axis).

In other words, if the principle of coordinate coupling is realized, the cutting-edge during vibrations describes a complex trajectory in space, similar to an ellipse. If the influence of the principle of coordinate coupling is eliminated, the cutting edge will vibrate only in DCTC. Such conditions allow us to experimentally study the phenomenon of SO excitation during cutting associated with the appearance of undulations on the cutting surface.

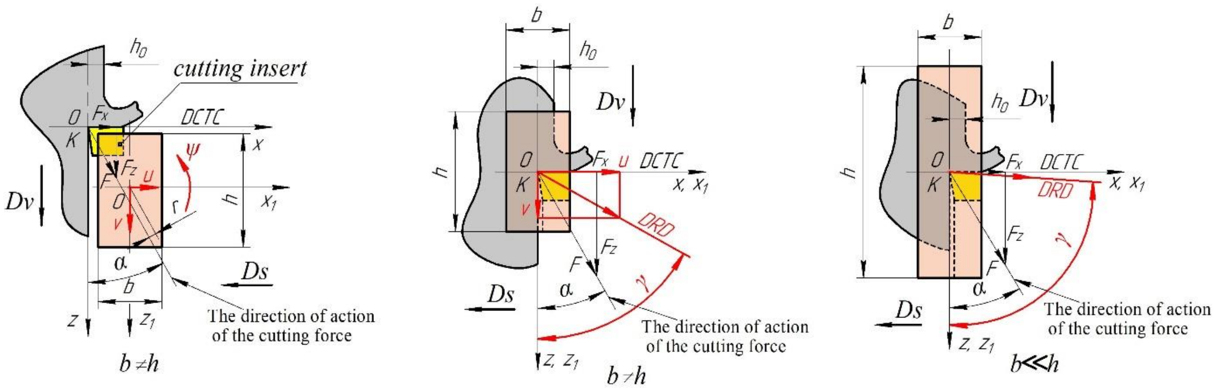
Thus, when developing a cutter-oscillator design, the goal was to create an oscillator with a single-degree-of-freedom, in which DRD of the cutting edge should align with DCTC (the *X*-axis).

4 Theoretical analyses of the possibility of obtaining a cutter-oscillator (with single-degree-of-freedom in which DRD aligns with DCTC

In the general case of longitudinal turning, a turning tool is a bar (holder) cantilevered in the toolholder with cross-sectional dimensions *b* x *h* and overhang length *l*. Fig. 1. A cutting insert is fixed on the free end of the bar, which is subjected to a force *F* at an angle α to the *Z*-axis under orthogonal cutting conditions.

Fig. 2 a shows the diagram of the action of forces at the free end of the cutter-oscillator. From the action of the torque $M = Fr$, the bar will rotate by the angle ψ, and from the action of the components of the cutting force F_z and F_x will be subject deflection v and u along the *Z* and *X*-axes. Thus, the cutting edge - *K*, rigidly connected with the bar, will have three-degree-of-freedom.

If the cutting edge - *K* is placed in the centre of symmetry of the bar, the direction of action of the cutting force - *F* will pass through the point *O* and the bar will not be subjected to torque *M*. Thus, it is easy to eliminate single-degree-of-freedom - rotation of the bar. Fig. 2, b shows a diagram of the action of the cutting force *F* and its components F_z and F_x when the cutting edge - *K* is located on the neutral axis of the bar - *Y* at the point *O*. In this case, the bar is subjected to sloping deflection and has two-degree-of-freedom. it is known that in sloping deflection of a bar of rectangular cross-section, DRD of the point *O* does not align with the direction of action of the cutting force - *F*.



a b c

Fig. 2 Schemes of cutter-oscillators: *a* - with three-degree-of-freedom, *b* - with two-degree-of-freedom, *c* - with single-degree-of-freedom (Fig. 4).

The deflections of the bar in sloping deflection in the direction of *X* and *Z*-axes will be respectively:

$$u = \frac{F_x l^3}{3EI_Z}, \text{ and } v = \frac{F_Z l^3}{3EI_x}. \quad (3)$$

where E - the modulus of elasticity of the bar (holder) material.
I_X and I_Z - the moments of inertia of the bar section along the X and Z-axes.

$$I_X = \frac{bh^3}{12}, \text{ and } I_Z = \frac{b^3 h}{12},. \tag{4}$$

where b - the thickness of the holder;

h - height of the holder.

Then the total deflection in sloping deflection will be: $f = \sqrt{u^2 + v^2}$ and DRD of the cross-section centre (point O), is determined by the value of the angle γ to the vertical Z-axis.

If $\quad tan\gamma = \frac{u}{v} = \frac{F_X I_X}{F_Z I_Z} = tan\alpha \frac{I_X}{I_Z} = tan\alpha \left(\frac{h}{b}\right)^2,$

then:

$$\gamma = tan^{-1}\left(tan\alpha\left(\frac{h}{b}\right)^2\right) \tag{5}$$

Using equation (5), let us determine how the side ratio of the rectangular cross-section of the holder - h/b - affects DRD of the centre of the section (point O) where the cutting edge is located.

Table 1 shows the results of calculations of the angle γ for four shapes of rectangular cross-section with side ratio: $\frac{h}{b} = 1$, $\frac{h}{b} = 2$, $\frac{h}{b} = 4$, $\frac{h}{b} = 8$, and Fig. 3 shows the graph of the dependence of DRD determined by the angle γ on the ratio of the holder side dimensions - h/b.

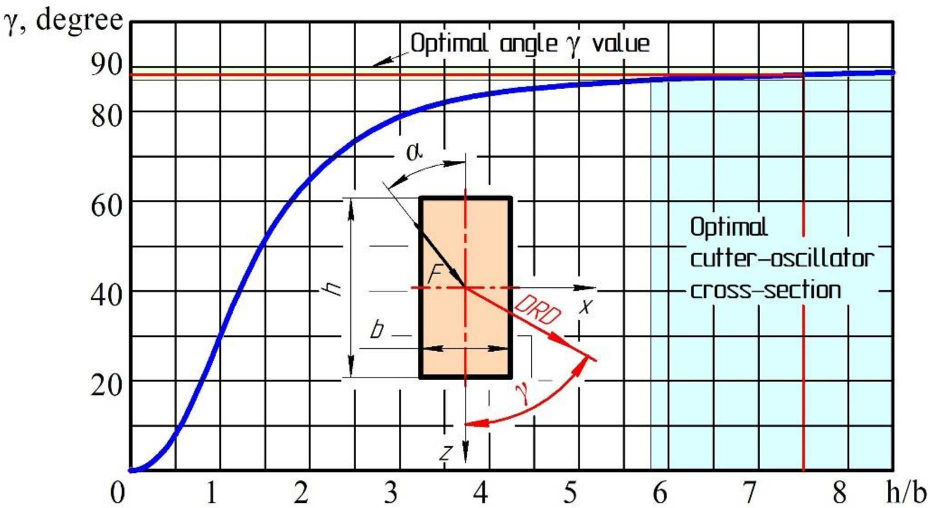
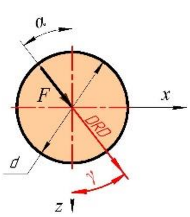
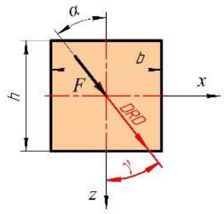
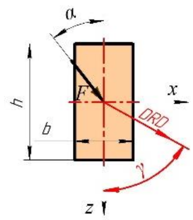
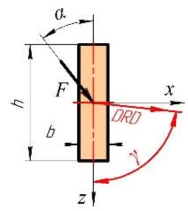
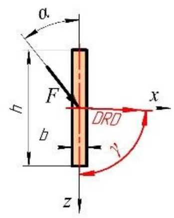


Fig. 3 Influence of cutter-oscillator cross-section dimensions on the angle γ

The graph is plotted at a constant direction of force determined by the angle α = 30°. At a ratio of $\frac{h}{b} = 1$ (the cross-section of the bar is a square or a circle) DRD aligns direction of action of the force, i.e. γ = α = 30°. In this case, the bar is not subject to sloping deflection. As the ratio increases $\frac{h}{b} > 1$ angle γ intensively increases and for the case of $\frac{h}{b} = 8$ angle γ = 88,4°, table 1. This means that if the holder has a size ratio of ($\frac{h}{b} = 8$), then when the force F is applied at an angle α = 30°, the cutting edge located at point O will move in DCTC layer (X-axis), deviating from it by only 1.6°.

Tab. 1 Results of calculations of the angle γ for four rectangular cross-section shapes

No.	$\boldsymbol{\frac{h}{b}}$	$\boldsymbol{\left(\frac{h}{b}\right)^2}$	**γ, degree**	**Shape of the cutter-oscillator holder**
1	1	1	γ = 30° γ = α	 
2	2	4	66,6°	
3	4	16	83,8°	
4	8	64	88,4°	

The cross-sectional dimensions of the actually designed holder are as follows 8 mm x 60 mm that is $\frac{h}{b} = \frac{60}{8} = 7{,}5$. Fig. 3 shows that for the ratio $\frac{h}{b} = 7{,}5$ angle γ = 88,2°. Thus, DRD of the cutting edge will deviate from DCTC by only 1.8°. This practically insignificant deflection allows us to consider that the cutter-oscillator carrying the cutting insert performs oscillatory motion in the direction of the *X*-axis and has only single-degree-of-freedom. Fig. 2 c.

5 Description of the design of the cutter-oscillator and the device for its mounting on the machine tool

5.1 Cutter-oscillator design

The design of the cutter-oscillator is shown in Fig. 4. It consists of a cutter head and a holder. A cutting insert is fixed on the head and there is a place for attaching an additional mass. The cutting insert is mounted so that its cutting edge lies on the longitudinal *Y*-axis passing through the centre of symmetry of the cross-section of the holder. This condition prevents the holder from rotating under the influence of force *F*. The holder is a bar of rectangular cross-section with dimensions (b x h = 8 mm x 60 mm). Thus, when a force F is applied at an angle α = 30°, the cutting edge will move in DRD, which almost aligns with DCTC (X-axis). Fig. 2, c.

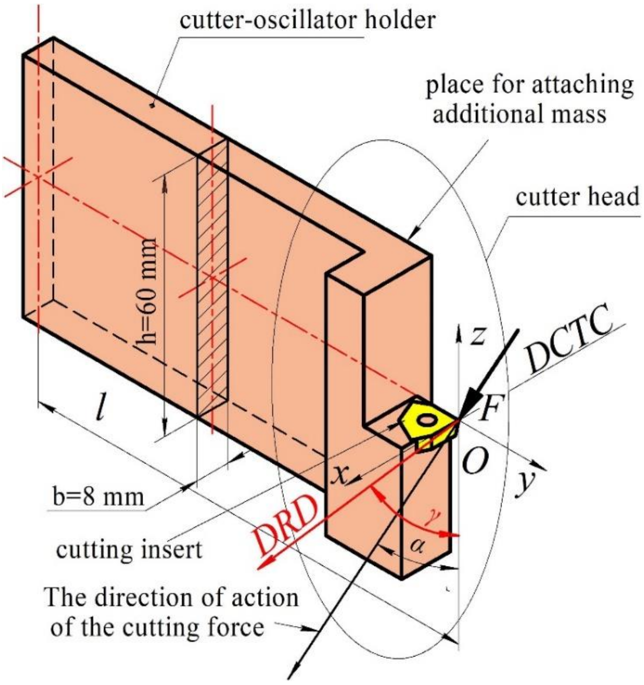
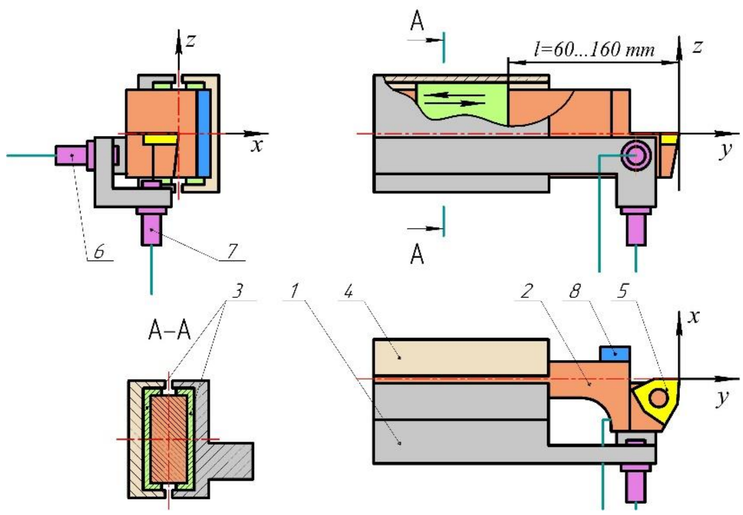


Fig. 4 Cutter-oscillator design with single-degree-of-freedom

5.2 Design of the cutter-oscillator clamping device in the machine tool

The device (Fig. 5) has a housing - 1, which is installed in the toolholder of a lathe. The cutter-oscillator - 2 is located between two rectangular guides - 3. The cover - 4 clamps the holder between the guides. In order to adjust the overhang length (stiffness) of the cutter-oscillator, the guides can be moved along the Y-axis before clamping. In this way the cutter-oscillator can become a cantilevered bar with a overhang length from l_{min} = 60 mm to l_{max} = 160 mm. Two eddy current displacement sensor 6 and 7 are installed on the body of the device, by means of which the horizontal (along the X-axis) and vertical (along the Z-axis) oscillations of the ES of the cutter-oscillator during the cutting process are determined.



1. Body, 2. Cutter-oscillator. 3. Rectangular guides - 2 pcs. 4. Cover. 5. Cutting insert. 6, 7 Eddy current displacement sensor. 8. Additional mass

Fig. 5 Device for setting the cutter-oscillator on the lathe

Changing the overhang length of the cutter-oscillator from 60 mm to 160 mm allows you to significantly change its stiffness in the direction of the *X*-axis from K_x = 5931 N/mm to K_x = 395 N/mm. Fig. 6.

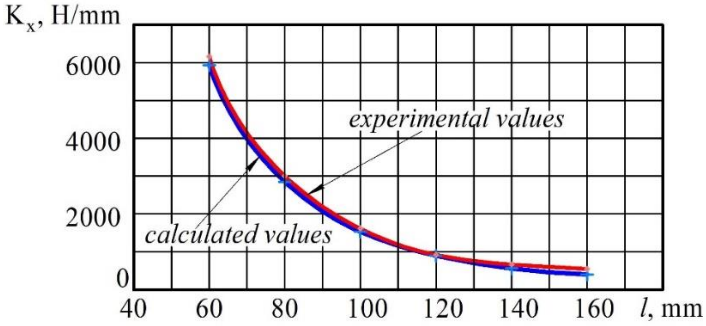


Fig. 6 Dependence of the cutter-oscillator stiffness K_x on the length of its overhang length - *l*

And the possibility of installing an additional mass to the head of the cutter, allows to obtain an cutter-oscillator with a large range of variation of the natural frequency (from 1278 Hz to 153 Hz). Fig. 7.

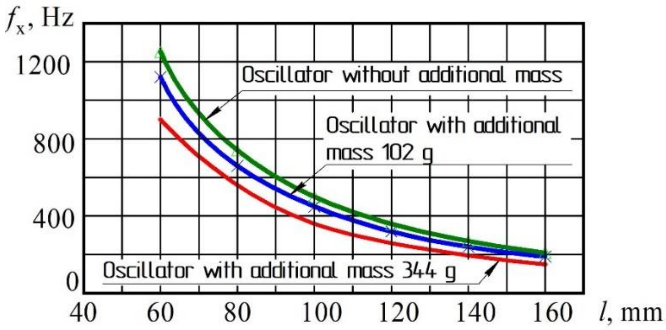


Fig. 7 Dependence of the natural frequency of the cutter-oscillator f_x on the length of its overhang length - *l* and additional mass m_1 = 102 g, m_2 = 344 g

6 Description of the experimental stand and cutting patterns for longitudinal turning for vibration studies

6.1 Description of the experimental and measuring stand

Fig. 8 shows a schematic diagram of the experimental and measuring stand for the study of vibrations during longitudinal turning. The device in which the cutter-oscillator is fixed is installed in the toolholder of the lathe. The workpiece to be machined is considered absolutely rigid in order not to consider its vibrations during the cutting process (length-to-diameter ratio $\frac{l}{D} = 1 - 1{,}5$).

To measure the oscillation of the cutter-oscillator during longitudinal turning, a digital data acquisition measurement system has been developed, which includes:

1. Eddy current displacement sensor (model Schneider Electric XS4-P12AB110) are attached to the device housing, registering real-time actual clearances -δ between the cutter-oscillator and the sensors along the *X* and *Z*-axes. The measurement of δ is performed at a data sampling frequency determined by the applied Analog-to-Digital Converter, which is set at 50 Hz per channel. Consequently, the data acquisition accuracy is 0.02 ms.
2. An analog encoder (model E6B2-CWZ6C1000P/R by Omron) converts the actual rotation frequency of the spindle with the workpiece - *n* into a sequence of square-wave pulses, where the period is proportional to the value of *n*. The installation of the encoder is necessary for

investigating the impact of cutting speed variation (modulation) on the conditions for suppressing SO.

3. A multi-channel Analog-to-Digital Converter (ADC) (model L CardE140) capable of converting analog signals from measurement sensors into digital form and storing them on a personal computer as a binary file.

4. A personal computer (PC) is required for storing and post-processing the recorded oscillograms.

5. LGraf v2.34 software is utilized for recording and saving digital data.

The post-processing of the obtained data is carried out using the MathLab Octave program.

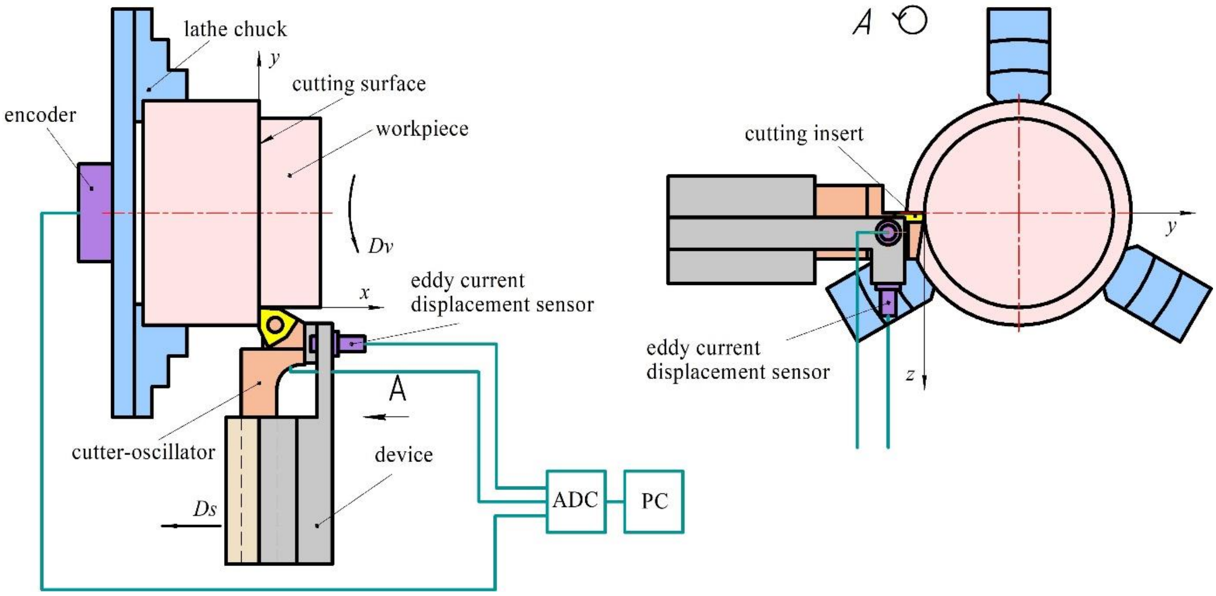


Fig. 8 Scheme of the experimental stand for vibration research during longitudinal turning

The experimental measurement setup allows for evaluating the influence of various conditions in longitudinal turning on the following characteristics of the cutter-oscillator's motion law:

1. Static deflection of the turning tool during cutting, B_x, represents the average deflection of the turning tool tip from the initial position of elastic equilibrium before the onset of the cutting process.

2. The amplitude of turning tool oscillation, A_x, is the deflection of the turning tool tip from the position of static deflection B_x.

On Fig. 9, an example of an oscillogram of the cutter-oscillator oscillation during continuous longitudinal turning is depicted. The magnitude of static deflection, B_x (along the X-axis), multiplied by the stiffness of the elastic element, K_x, along the X-axis in classical cutting theory, is considered as a component of the cutting force F along the X-axis, such as $F_x = B_x K_x$. Dynamic addition in the form of displacement amplitude - A_x is not taken into account in this case. All types of dynamometers for measuring static components of cutting forces are built on this principle. Thus, the proposed cutter-oscillator makes it possible to simultaneously measure both the static component of the ES deflection from the initial equilibrium position - B_x, and the dynamic correction in the form of the oscillation amplitude - A_x relative to the static deflection B_x during cutting.

The possibility to record and memorize the oscillations of the cutter-oscillator for a very short time with an accuracy of 0.02 ms allows measuring one more characteristic:

3. Frequency (period) of ES oscillations of the cutter-oscillator taking into account its damping characteristic. It should be noted here that the frequency and damping characteristic of the cutter-oscillator during cutting and idling (without cutting) will be different.

Experimental oscillograms of cutter-oscillator oscillations also allow us to measure:
- phase shift - ε waves on cutting surfaces at neighbouring workpiece revolutions;
- number of waves *N* on the cutting surface
- the length of waves *l* on the cutting surface.

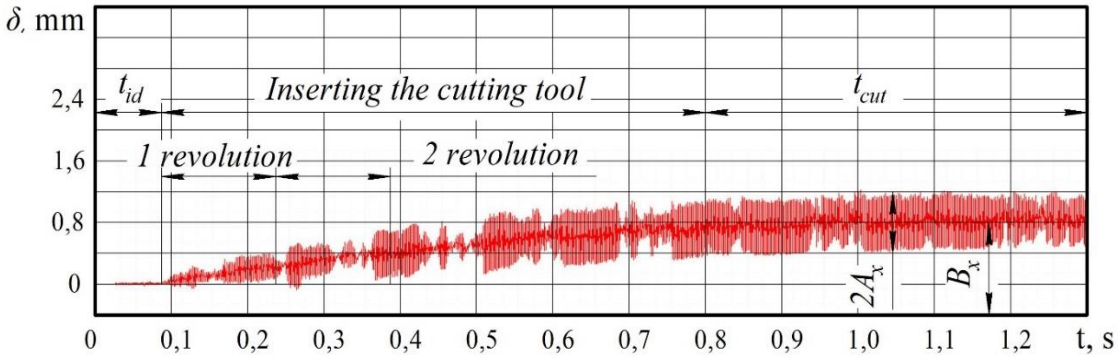


Fig. 9 Example oscillogram of cutter-oscillator oscillations during continuous longitudinal turning

CONCLUSION

In the course of this work, a theoretical analysis of the design of an cutter-oscillator with single-degree-of-freedom has been carried out, where DRD of the cutting edge - *K* aligns with DCTC, providing oscillatory motion in the direction of the *X*-axis.

On the basis of theoretical analysis, the design of the cutter-oscillator and the device for its mounting on the machine tool with the possibility of adding additional mass and changing the overhang length is proposed, which makes it possible to expand the range of regulation of the natural frequency and effectively adjust the cutter-oscillator operation depending on the required cutting conditions.

The design of an experimental and measuring stand is presented, which allows recording oscillograms of the oscillatory motion of the cutting edge - *K* cutter-oscillator, making it possible to evaluate the effect of different longitudinal turning conditions on the characteristics of the cutter-oscillator's law of motion, such as static deflection, oscillation amplitude, phase shift, number and length of waves on the cutting surface.

Overall, the developed designs provide a flexible system for controlling and evaluating various parameters, which may be useful in different cutting conditions and in machining different materials. Additional research and experiments can complement the current results and extend the application of this design.

Moreover, oscillograms of the oscillation of the cutter-oscillator allow the study of different types of oscillations (free, free accompanying, forced and self-oscillations) that are excited under changing cutting conditions, from continuous to discontinuous and unsteady.

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