Regularities of Oscillations During Turning and End Milling

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Abstract. The intensity of vibrations during machining negatively affects the quality of machined parts, tool life, and productivity. Research is being conducted to reduce it, and various measures are being implemented. They relate to the choice of cutting modes, machining strategy, tool geometry, application of damping media, and vibration control. But at the same time, it is essential to determine which types of oscillations need to be suppressed. Therefore, the work aimed to identify the pattern of oscillations during turning and final milling. The devices that allow you to adjust the tool's and parts' dynamic characteristics and record their oscillations during cutting were used for conducting experiments. During intermittent turning, the regularity of occurrence of oscillations in the following sequence was obtained. When the cutter cuts in, forced oscillations occur, which are superimposed on the accompanying free oscillations of the technological system "tool–part". After their damping, self-oscillations are superimposed on the forced oscillations. Each oscillation type has distinctive features and operates for a specific time. Unlike turning, the end milling process is short-term. Therefore, during cutting, only forced oscillations act, on which the accompanying free oscillations of the "tool–part". As the spindle speed increases, the cutting time decreases, and if it is shorter than the period of the accompanying free oscillations, only forced oscillations are effective. Determining the characteristic features of oscillations during cutting makes it possible to prescribe measures that suppress their intensity purposefully.

Keywords: Turning · End-Milling · Technological System · Forced Oscillations · Self-Oscillations · Accompanying Free Oscillations · Manufacturing Innovation

1 Introduction

The dynamic application of an external force to an elastic system brings it out of equilibrium and causes the appearance of vibrations. In blade processing, such a force is the cutting force. At the same time, the intensity of vibrations depends on such properties of the technological system "tool–part" (hereinafter TS), such as mass and rigidity. It is to reduce the intensity of vibrations or to control it that research and various proposed measures are aimed at. The main task of these works is to ensure surface quality during

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cutting [1] and processing productivity [2]. At the same time, the main attention is paid to studying the action of self-oscillations. But it is known that forced and free oscillations also occur during cutting. Therefore, the issue of determining which types of oscillations are prioritized for different processing methods is relevant.

The novelty of the work is the identification of patterns of oscillations during mechanical processing and the dependence of their action on the cutting time.

2 Literature Review

Regardless of the type of oscillations during cutting, the main focus is on limiting their intensity. To control them, vibration sensors are used, which are installed on the spindle [3], or they monitor the current of the spindle drive [4]. It allows monitoring of the level of oscillation. When choosing cutting modes for stable milling, frequency analysis of the tool [5] or part according to petal diagrams is used [6]. To predict the negative impact of vibrations in real conditions, with the help of a digital double, correlation interactions are built in machine structures during cutting [7], making choosing productive processing modes possible. The introduction into the production of milling cutters with a variable pitch of teeth [8], with a different angle of inclination of the helical cutting edges [9], with a comb [10] and toothed [11] cutting edges or variation in the cutting speed [12] allows to destroy the subsetting of regenerative self-oscillations to permanent [13]. A decrease in the intensity of oscillations is also achieved by increasing the tool's rigidity [14], using tool mandrels with damping properties [15]. But the latter is expensive, so the possibility of using the geometric dimensions of the tool following the modes of their oscillations and the mode of operation of the machine is being considered [8]. With the help of the RCSA matrix, it becomes possible to create and investigate different dynamic conditions when connecting the tool with the holder and the spindle [16] and implement those that ensure vibration resistance [17].

It should be noted that the research works consider either the general effect of vibrations on the cutting process without dividing it into types or the effect of self-oscillations.

In general, forced oscillations, free and self-oscillations, are known [13]. Each species has its characteristics that distinguish them from each other. Forced oscillations arise from the action of periodically changing external forces. Free oscillations of an elastic system occur under the action of internal forces. They are always damped due to the effect of friction. The amplitude of free oscillations depends on the initial conditions. Self-oscillations are constant, undamped oscillations that operate without a variable external force. The amplitude of self-oscillations does not depend on the initial conditions.

Because the main task in cutting is to ensure its constancy, and vibrations interfere with this, it is essential to know precisely which type of vibrations should be suppressed. Studying the regularity of their action will allow us to move away from uncertainty in the recommendations regarding the selection of anti-vibration measures.

3 Research Methodology

To determine the regularity of the action of oscillations during cutting, a study was performed during intermittent turning of a cylindrical workpiece with a longitudinal groove (Fig. 1). The turning operation was chosen because of the possibility of obtaining a long cutting time.

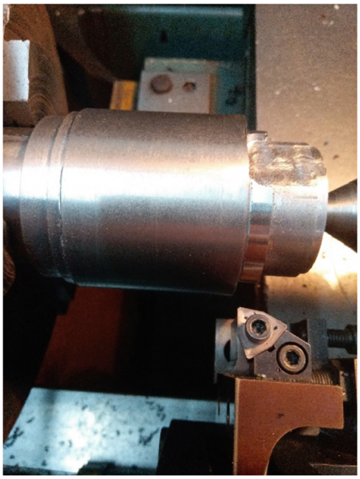


Fig. 1. A workpiece with a longitudinal groove for researching the regularity of the action of oscillations.

The design of the device used in this case allows you to adjust the dynamic characteristics of the cutter, record its oscillations during cutting, and determine the cutting time [19]. Table 1 shows the initial parameters for the research when turning a part made from steel 45 with a cutter with a VK8 carbide plate.

Table 1. Output parameters during turning.

Frequency of free oscillations, $f_{fo,}$ Hz	Spindle rotation frequency, n, rpm	Cutting depth, t, mm	Feed, S, mm/rev
463	1000	0.5	0.1

Studies of the patterns of the occurrence of oscillations during milling were performed on a special stand [20], which allows for simulating the processing of parts with different dynamic characteristics due to the ability to adjust the departure of the elastic element with the sample being processed. Table 2 shows the initial data for which the experiments were carried out when milling samples from St. 3, end-mill d = 16 mm.

The frequencies of oscillations that occur during cutting were determined in the MatLab program by fast Fourier digestion.

Table 2. Output parameters during milling.

Frequency of free oscillations, ffo, Hz	Mill rotation frequency, n, rpm	Radial depth, a_e, mm	Axial depth, a_p, mm	Feed per tooth, S_z, mm/rev
512	120 200 700	0.3	4	0.1

4 Results and Discussion

Figure 2 shows a fragment of the oscillogram of the longitudinal oscillations of the cutting tool when turning a cylindrical workpiece with a groove.

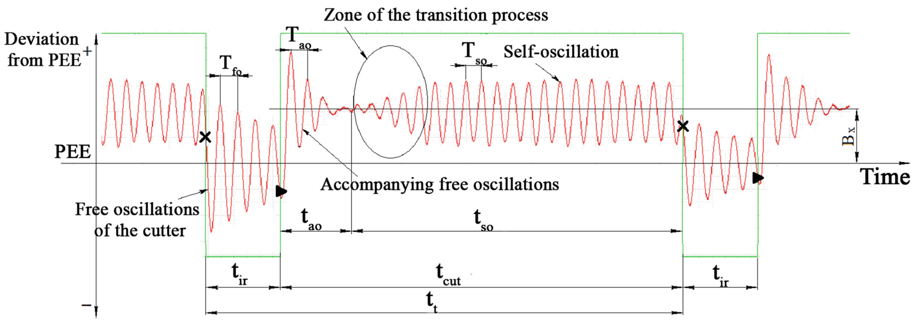


Fig. 2. A fragment of the oscillogram of cutter oscillations when turning a workpiece with a longitudinal groove: PEE - position of elastic equilibrium of the incisor; T_{fo} - the period of free oscillations of the incisor; T_{ao} - the period of accompanying free oscillations of the vehicle; T_{so} – self-oscillation period; t_{fo} – time of action of accompanying free oscillations; t_{so} – time of action of self-oscillations; t_{ir} – idling running time; tcut – cutting time; t_t – time of one turn of the workpiece; B_x - static deviation of the cutter from the PEE during turning; ► - the cutting point of the cutter in the workpiece; × - point of exit of the cutter from the workpiece

The presence of a groove on the surface of the workpiece leads to the cutting of the cutter with an impact at each turn in the time $t_t = 5.89 \cdot 10^{-2}$ s), which includes the cutting time $t_{cut} = 4.96 \cdot 10^{-2}$ s and the idle running time $t_{ir} = 0.93 \cdot 10^{-2}$ s.

Oscillations recorded when turning a workpiece with a groove have characteristic features of forced oscillations, free oscillations, and self-oscillations. Forced oscillations occur under the action of the cutting force, which presses the workpiece by the amount of B_x. On top of them are superimposed the damping accompanying free oscillations of the TS with a period of $T_{ao} = 2.05 \cdot 10^{-3}$ s ($f_{ao} = 488$ Hz) and undamped steady self-oscillations with a period of $T_{so} = 1.86 \cdot 10^{-3}$ s ($f_{so} = 537$ Hz) [19]. During the movement of the workpiece in the absence of cutting, there are damping-free oscillations of the cutter relative to the position of elastic equilibrium (PEE) with a period $T_{fo} = 2.16 \cdot 10^{-3}$ s ($f_{fo} = 463$ Hz). Based on the obtained result, it can be stated that the regularity of the action of oscillations during cutting has the following sequence: forced oscillations, which are superimposed on the accompanying free oscillations of the TS and self-oscillations, free oscillations of the cutter relative to the PEE after the end of the cutting. At the same time, each type of oscillation has its duration. Forced oscillations are active during the entire cutting time t_{cut} (in research $t_{cut} = 4.96 \cdot 10^{-2}$ s). Accompanying free oscillations of TS act during the time of t_{so} (in research $t_{so} = 1.1 \cdot 10^{-2}$ s). After their attenuation and until the end of the cutting, self-oscillations take place during the time t_{so} (in research $t_{so} = 3.86 \cdot 10^{-2}$ s). The time of free oscillations of the cutter is determined by the idle running time t_{ir} (in research $t_{ir} = 0.93 \cdot 10^{-2}$ s) from the end of cutting to the subsequent cutting of the tool.

The use of the term “accompanying free oscillations” of the TS superimposed on the forced oscillations was used by Ya.H. Panovko [18], which better reflects the physical process of oscillations during cutting than the term “free oscillations” of TS. It also separates them from the free oscillations of the cutter when idling.

Determining that when cutting, oscillations act in a certain sequence and for a certain time allows each type of blade processing to be considered considering their characteristics. At the same time, it should be noted that the accompanying free oscillations of the vehicle and self-oscillations occur under certain conditions, while forced oscillations always operate. Firstly, it is necessary to create initial conditions under which the amplitude of oscillations will arise. The others require a wavy mark on the cutting surface after the previous pass of the tool.

If there are reasons for self-oscillations in continuous turning, when the cutting time is extended, then intermittent cutting is short-lived in final milling. Therefore, the question regarding the current fluctuations is relevant.

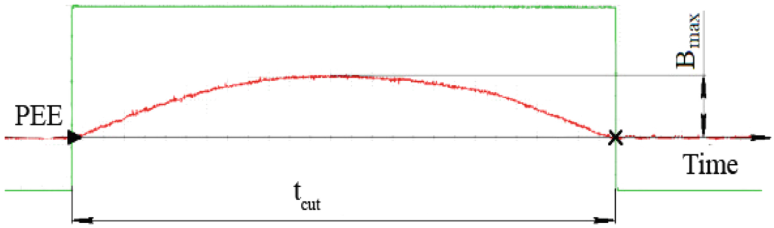
To answer it, research was carried out during the milling of samples from Steel 3 end-mill d = 16 mm with mechanical attachment of cutting plates. The stand on which the experiments were carried out allows you to adjust the protrusion of the elastic plate with the processed material [19]. Due to this, the necessary dynamic characteristics of it are established. When the plate flew out by h = 80 mm, the frequency of free oscillations was $f_{fo} = 512$ Hz ($T_{fo} = 1.95 \cdot 10^{-3}$ s). Counter and parallel milling occurred at an axial cutting depth of $a_p = 4$ mm, a radial depth of $a_e = 0.3$ mm, and feed per tooth of $S_z = 0.1$ mm, with spindle rotation frequencies of n = 120, 200, and 700 rpm.

Figure 3 shows a fragment of oscillograms of sample oscillations during up and down milling with a spindle rotation frequency of n = 120 rpm.

When milling with a spindle rotation frequency of n = 120 rpm, only forced oscillations are active during the cutting time $t_{cut} = 4.36 \cdot 10^{-2}$ s. Due to the peculiarities of the change in the thickness of the layer to be cut, during up-milling, the indentation of the sample B_{max} under the action of the cutting force is less than during down-milling.

Figure 4 shows fragments of oscillograms of sample oscillations during up- and down milling with a spindle rotation frequency of n = 200 rpm.

Increased spindle rotation frequency decreases the cutting time ($t_{cut} = 2.69 \cdot 10^{-2}$ s). During up-milling, oscillations occur, which are superimposed on the forced ones. These are the accompanying free oscillations of the TS with the T_{fo} period ($t_{fo} = 1.16 \cdot 10^{-3}$ s, $f_{fo} = 862$ Hz), the amplitude of which depends on the initial conditions, particularly the initial speed. They act during the t_{ao} time ($t_{ao} = 0.08 \cdot 10^{3}$ s) and decay. During the down final milling, the accompanying free oscillations of the TS when cutting with



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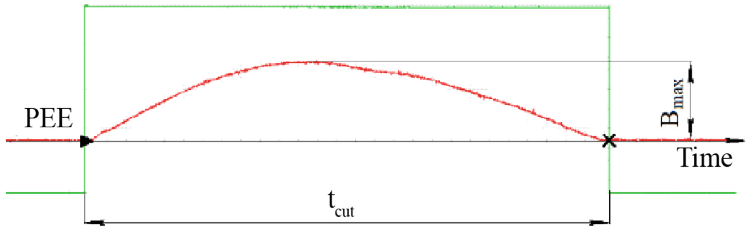

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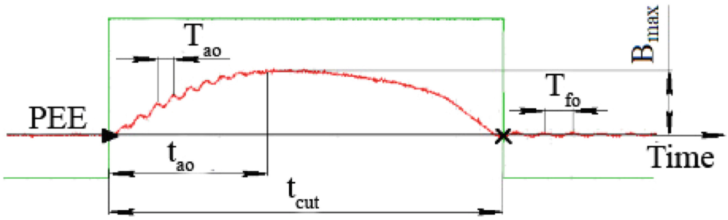
Fig. 3. Fragments of oscillograms of sample oscillations during up- (a) and down (b) end-milling with a spindle rotation frequency of n = 120 rpm.

a spindle rotation frequency of n = 200 rpm do not occur. When cutting, the most significant thickness of the sheared layer creates such properties of the TC that dampen these oscillations. After the cutter exits the cutting zone, the free oscillations of the sample with the period of T_{ao} ($t_{ao} = 1.95 \cdot 10^{-3}$ s, $f_{ao} = 512$ Hz) act, which also decays. The cutter cuts into the sample, which does not oscillate.

Figure 5 shows fragments of oscillograms of sample oscillations during up- and down milling with a spindle rotation frequency of n = 700 rpm.

An increase in the initial cutting speed increases the amplitude of the accompanying free oscillations. When milling with a spindle rotation frequency of n = 700 rpm, these oscillations are superimposed on forced oscillations, both during up-milling at the beginning of cutting (Fig. 5, a) and during down-milling at the end of cutting (Fig. 5, b). The occurrence of free oscillations and their damping during end-milling is associated with a change in the thickness of the cut layer. The fundamental thing here is that there is not enough cutting time for self-oscillations characterized by stability.

The obtained results allow a different look at the speed zones of oscillations, which were considered in the paper [20]. Without changing the boundaries of these zones, it is necessary to correct the use of the term "self-oscillation". Instead, the term "accompanying free oscillations of the TS" should be used when considering speed zones.



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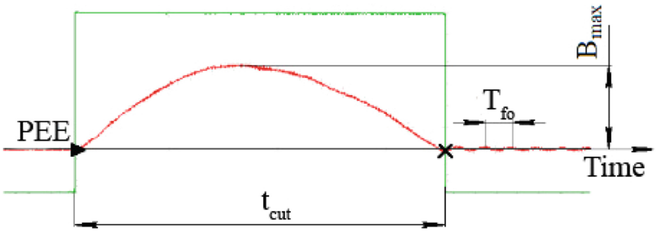

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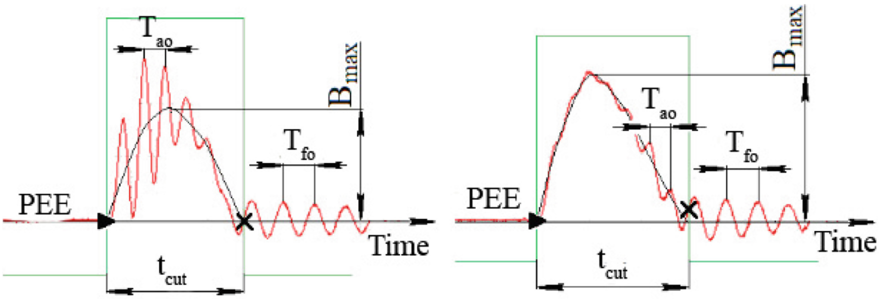
Fig. 4. Fragments of oscillograms of sample oscillations during up- (a) and down (b) end-milling with a spindle rotation frequency of n = 200 rpm.



a b

Fig. 5. Fragments of oscillograms of sample oscillations during up- (a) and down (b) end-milling with a spindle rotation frequency of n = 700 rpm.

5 Conclusions

The regularities of the action of various types of oscillations during cutting have been determined. First, forced oscillations act, and the accompanying free oscillations of the vehicle are superimposed on them. After their damping, the sub-adjustment of the TS occurs, and stable self-oscillations occur.

The possibility of different types of oscillations depends on the cutting time.

When turning, when the cutting time is extended, there are conditions for the action of all kinds of oscillations.

The cutting time limitation does not allow stable self-oscillations in the end-milling of thin slices. During end-milling, the amplitude of the accompanying free oscillations of the TS depends on the initial conditions. Therefore, as the cutting speed increases, it also increases.

The obtained results allow a different look at the speed zones of oscillations, which were considered in the paper [20]. Without changing the boundaries of these zones, it is necessary to correct the use of the term “self-oscillation”. Instead, the term “accompanying free oscillations of the TS” should be used when considering speed zones.

Further research should be planned to determine the influence on the dynamic properties of the TS and the amplitude of the accompanying free oscillations of the cutting modes and the geometry of the tool.

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