Self-oscillation regeneration control by irregular tooth pitches

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Abstract— **Machining of workpieces under low rigidity of equipment is often accompanied by excitation of self-oscillations impeding the technological process. Among the causes of self-oscillations, there is their regeneration on the cutting surface. Self-oscillation regeneration can be controlled by target impacts on changes of phase shifts between mark oscillations and current system oscillations. These impacts can be exercised by choosing a cutting speed or its modulation or using irregular teeth pitches. The latter method is more promising for practical application. Therefore, the article describes the results of experimental studies on the influence of the difference of adjacent alternate teeth pitches on the efficiency of self-oscillation control when boring holes, turning non-rigid shafts and end-milling non-rigid workpieces.**

The designs of experimental multi-tooth boring and turning heads and end mills which can randomly adjust tooth pitches are described. A step-by-step discrete increase in the difference of tooth pitches decreased the self-oscillation amplitude in all experiments where these tools were used. Near self-oscillation suppression was at the value of pitch difference close to a half self-oscillation wave-length. In a wide range of this value, self-oscillations can be controlled as well but the result is rather worse. The experimental data are interpreted in terms of the theory of regenerative self-oscillations.)

Keywords— regenerative self-oscillations; control; difference of tooth pitches

I. INTRODUCTION

Edge cutting machining of low rigid workpieces is accompanied by excitation of intensive self-oscillations aggravating the accuracy and quality of machined surfaces, tool life, machine tool lifecycle and machining performance. Traditional methods for controlling self-oscillations (improvement of the rigidity of low rigid elements of the technological system, variation of the cutting scheme and edge geometry, decrease in machining modes, etc.) are not efficient and difficult to apply or decrease machining performance. To this end, development and analysis of efficient self-oscillation control methods are a crucial task for various machine building industries.

Self-oscillation regeneration trends can solve the task. The studies have been carried out since 1937 when N.A. Drozdov published his work [1] where he showed that vibrations of cutting tools have self-oscillation properties and a mark on the cutting surface is important for their development and maintenance. In the second half of the last century due to the increase in applied cutting speeds and use of hard-to-machine materials in machine designs, the issue took on particular significance [2…13 et al.].

Based on the results of studies on the turning process, I.S. Amosov [3] found that regeneration provides 85% of self-oscillation excitation energy. The same estimation of regeneration was given by I.I. Ilnytskiy [4], N.D. Reshetov and Z.M. Levin [5], and V.S. Zars [11]. The observations showed that the vibration mark on the cutting surface moves forward at each rotation of the workpiece at a quarter wave-length, i.e. at a phase angle of 90±25º by L.K. Kuchma's estimation [6] or from 50 to 80º by I.I. Ilnitskiy's estimation [4] forming a screw pattern from residual ridges inclined to the workpiece axle at a certain angle determined by the self-oscillation wave-length and the value of cutter feed in one workpiece rotation.

Spontaneous and independent self-oscillation phase displacement at about +90° to mark oscillations under almost free regeneration speaks for their self-organization aimed at minimizing energy consumption for oscillation [14]. On the other hand, this displacement creates conditions for delivering portions of energy into the oscillation system due to different values of thickness of the layer cut when putting the tool in

and out of the workpiece. If the initial shift of current oscillation phases is not equal to +90° at the moment of regular contacts with the mark from the previous workpiece rotation or pass through the previous tooth, self-oscillation regeneration is constrained. It causes a transition process in which the system adapts to mark oscillations during one or two periods. The frequency of self-oscillations increases or decreases and their amplitude decreases. System adaptation consumes some portions of energy. This is the first method of self-oscillation regeneration control involving the choice of cutting speeds corresponding to the initial self-oscillation phase shift at the level of −90°. Increasing chatter stability of the technological system is presented in a radar diagram proposed by N.E. Merrit [10]. However, in practice this method can be used only for high speed machining when there are no more than two self-oscillation waves on the cutting surface of one workpiece rotation or a pass of adjacent tool teeth. When using widely applied tools made from high speed steel and hard materials, more than two self-oscillations waves can be located on the cutting surface. After completion of the short transition process, self-oscillation regeneration becomes uncontrollable.

The second method applied to control the self-oscillation regeneration process involves the use of modulated cutting speeds [14]. To apply this method correctly, it is necessary to choose such values and depths of cutting speed modulations at which its value differs significantly during mark formation and mark cutting. It leads to continuous changes of phase shifting between mark oscillations and system oscillations impeding its adjustment and consuming energy reserves for self-oscillations. Special technological equipment transforming the uniform spindle rotation into the non-uniform workpiece or tool rotation can be used to modulate cutting speeds [14]. However, the equipment overcharges the working zone of the machine. For CNC-based machines, spindle movements are programmed to modulate cutting speeds [15]. However, a high response rate of the spindle restricts the application of this self-oscillation control method. The method is accompanied by an additional oscillation impact on the tool for active dampening of the cutting process [16]. For practical application, the most promising self-oscillation regeneration control method is the third one which involves the use of tools with an irregular tooth pitch. It can be useful for various multi-tooth tools whose teeth cut facings step-by-step: mills, drills, reamers, heads for turning internal and external surfaces, etc. In Russia, the irregular tooth pitch has been applied since the 1950s to dampen self-oscillations when using face, end and side mills [17]. The area of application of these tools is expanding. Sandvik Coromant, a leading tool manufacturer, offers a wide range of face and end mills with irregular tooth pitches [18].

It is crucial to choose a correct type and value of changes of tooth pitches. A pitch variation can be alternate, increasing, increasing-decreasing, etc. To minimize forced oscillations, it is better to alternate low and high tooth pitches. According to many researchers [8, 9, 11, 12, 13, 14, 19, 20, 21, 22], to dampen self-oscillations, the difference of adjacent tooth pitches has to be equal to a half wave-length on the cutting surface. V.G. Shalamov [23] argues that this difference can be

0,5; 1,5; 2,5 wave-length, but the first value is more efficient. There are other opinions about value of the pitch difference. For example, S.G. Cherezov [24] argues that it has to be equal to one self-oscillation wave-length. This contradiction can be solved by experimental methods.

Among the described self-oscillation regeneration control methods, the latter is more appropriate for industrial application. Therefore, the present article deals with this method. The article aims to identify the influence of the difference of adjacent alternate teeth pitches on the efficiency of self-oscillation dampening when boring holes, turning shafts and face milling under low-rigidity of the technological system. To this end, some experiments were carried out.

II. EQUIPMENT AND RESEARCH METHODS

Boring experiments were carried out using a threading lathe 1M63 (Fig. 1). A pipe section (D=176 mm, d=158 mm, L=137 mm) made from steel 20 (HB=163) was fixed in a three-jaw self-centering chuck and supported by a steady rest. A device holding as tick for supporting a boring head was fixed on the tool support instead of a common tool holder. The length of the stick length was 403 mm. There are two circular T-slots on the front side of the special boring head. Bolt head holding two cutters are inserted in these slots (Fig. 2). Bolt heads are equipped with T5K10 brazed carbides. They have the following parameters: $\gamma = 0°$, $\alpha = 12°$, $\lambda = 0°$, $\varphi = 45°$, $\varphi_1 = 45°$, r =1 mm.

To record lateral oscillations of the boring head, 1PA-6 piezo sensors were installed on its body in two mutually perpendicular threaded sockets. The signals entered a PC through an AD convertor and a processing block. Vibration records of boring head oscillation accelerations in vertical and horizontal directions were presented on-screen. To determine a frequency spectrum, the amount of data of each vibration record was subjected to the Fourier analysis using MatLab. Shifting amplitudes were calculated by acceleration amplitudes and oscillation frequencies.
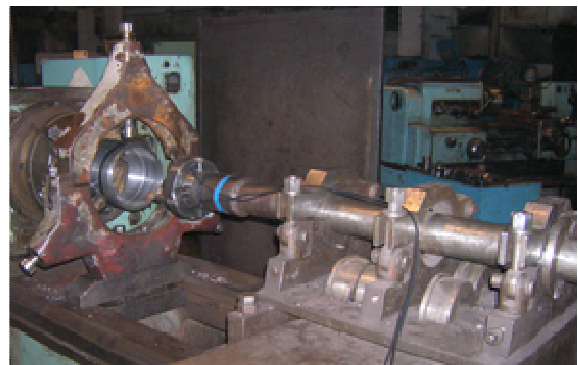

Fig.1. Example of a figure caption.

To study a dynamic stability-boosting feature of the technological system when boring with a multi-tooth head, a set of 13 experiments were repeated twice under different tooth pitches (Table 1). The difference of adjacent pitches was created by shifting one of the uniform angular positions from −3° to +3° in 0,5° increments. The radial (by a machining

diameter of 159 mm) and mutually angular positions of cutters were adjusted using a special device. Dry machining of the workpiece was carried out at the following cutting parameters: a_p=1,0 mm, f_n=0,305 mm/rev (f_z=0,1525 mm/tooth), n=125 rev/min. The spindle rotation frequency was n=128,194 rev/min (V_c=64,035 m/min=1,067 m/sec).

Fig. 2. Boring Head.

The experiments on low-rigid shaft turning were carried out using a 16B25PSp lathe. On its support, instead of a cutter holder, a four-teeth head was installed on a special bracket (Fig. 3). The head (Fig. 4) consists of flange 1 with four holders 2 which circle due to a circular flange slot. Four cutting inserts 3 equipped with four-sided cutters made from T5K10 (φ=45°, α=6°, γ=–6°). Holders 2 are fixed on flange 1 with bolts 5 and 9. Cutting inserts were set for the required diameter with a sample part fixed in a chuck and a set of plain probes. The radial position of inserts was adjusted with bolts 11, and the axial position was adjusted with screws 10. Cutters were fixed with cams 8. The tooth pitch was varied by shifting two horizontally located cutters in a horizontal direction.
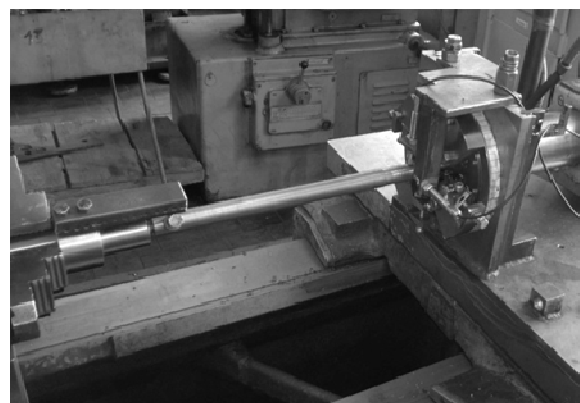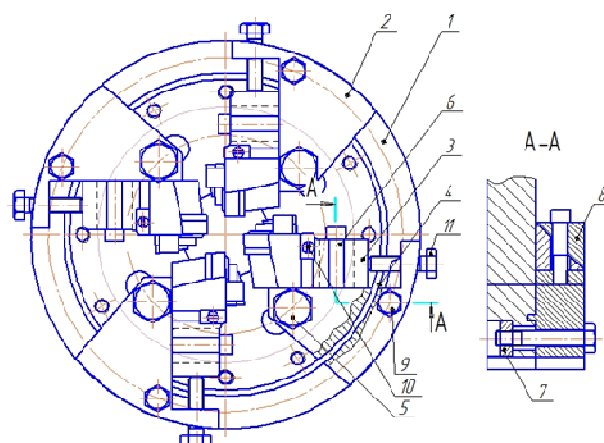

Fig. 3. Experimental turning unit

Fig. 4. Multiple cutting turning head

TABLE I. IMPACT OF THE DIFFERRENCE OF BORING HEAD TOOTH PITCHES ON THE AMPLTUDE AND FREQUENCY OF ITS NATURAL SELF-OSCILLATIONS

№	Angular displacement of the cutter №2, deg	Pitch difference of adjacent teeth, deg	Frequency of dominant mode f, Hz	Self-oscillations amplitude A, μm	
				horizontal	*vertical*
1	-3	6	330	3	4
2	-2,5	5	288	6	9
3	-2	4	159	100	20
4	-1,5	3	168	11	18
5	-1	2	173	15	14
6	-0,5	1	161	97	54
7	0	0	162	142	77
8	+0,5	1	165	93	37
9	+1	2	166	25	18
10	+1,5	3	168	18	16
11	+2	4	173	51	42
12	+2,5	5	146	10	7
13	+3	6	157	8	6

TABLE II. IMPACT OF THE DIFFERRENCE OF TURNING HEAD TOOTH PITCHES ON THE AMPLTUDE AND FREQUENCY OF WORKPIECE SELF-OSCILLATIONS

№	Angular displacement of the horizontal cutter, deg	Pitch difference of adjacent teeth, deg	Frequency of dominant mode f, Hz	Self-oscillations amplitude A, μm	
				horizontal	*vertical*
14	0	0	580	39	60
15	0,8	1,6	578	13	15
16	1,5	3	537	14	15
17	2,5	5	368	4	4
18	3,4	6,8	368	27	21
19	4,2	8,4	367	13	15
20	5,1	10,2	325	33	54
21	5,9	11,8	322	68	83
22	6,8	13,5	323	26	29,5

The workpiece was fixed in front drive and rear rotating centers. When cutting, its horizontal and vertical oscillations were measured with two contactless AE108 eddy current displacement sensors. The signals were recorded and processed in a way which is similar to the one in boring experiments. Before carrying out the experiments, damped vibrations of the workpiece were recorded. Their frequency was 270 Hz.

The workpiece is a shaft made from steel 45 (NV = 197) of 24 mm in diameter and 425 mm in length. It was machined at the following cutting parameters: a_p=0,5mm, f_n=0,375 mm/rev (f_z=0,09375 mm/tooth), n=630 rev/min. The real spindle rotation frequency was n=653,594 rev/min, and the real cutting speed was V_c=49,28 m/min=0,821 m/sec. Nine experiments were repeated twice. The difference of adjacent alternate tool teeth pitches was changed discretely from zero to one wave-length on the cutting surface (See Table 2).

Fig. 5. Experimental face milling unit

№	Angular displacement of the even cutters, deg	Pitch difference of adjacent teeth, deg	Self-oscillations dominant mode		Peak-to-peak R, мкм
			amplitude A, µm	frequency f, Hz	
23	0	0	352	159	1700
24	1	2	40	157	900
25	2	4	22	163	450
26	3	6	22	161	300
27	4	8	20	163	300
28	5	10	17	158	350
29	6	12	12	159	200
30	7	14	47	163	250
31	8	16	11	169	300
32	9	18	34	164	350
33	10	20	89	165	400

To carry out milling experiments, special equipment was used: a face mill with spontaneous tooth pitch adjustment and a device changing the rigidity of the machined workpiece in a feeding direction. The experimental mill has a diameter of D_c=125 mm and 8 teeth. Mill teeth equipped with inserts of T5K10 hard material have the following parameters: φ=75°; γ=−5°; α=16°; λ=15°. The angular position of teeth was adjusted on ODG-2 optical dividing head. A special device creating adjusted rigidity of the workpiece in a feeding direction was made from an elastic inverted U-shaped holder fixed in yews (Fig. 5). A workpiece made from steel 45 (HB=207) 150x90x10 in size is fixed with bolts on the holder flange. Device rigidity was adjusted by changing holder lengths.

Experiments on milling low-rigid workpieces with an irregular tooth pitch were carried out using a horizontal milling machine tool 6M82 under the following cutting parameters: n=400 rev/min, V_f=500 mm/min (f_z=0,156 mm/tooth), a_p=2 mm, a_e=90 mm. The milling process is conventional, symmetrical, dry. The real spindle rotation frequency was n=419,58 rev/min, and the real cutting speed was V_c=164,77 m/min=2,746 m/sec. To produce an alternate irregular pitch, even teeth were displaced in one direction to their uniform position from 0° to 10° in 1° increment. The position of uneven teeth was constant. Thus, 11 experiments were repeated twice (Table 3). The holder length was 140 mm, and the workpiece oscillation frequency in a feeding direction was 151 Hz. Workpiece oscillations in a feeding direction were recorded with a contactless eddy current sensor in a similar manner to the above-described experiments.
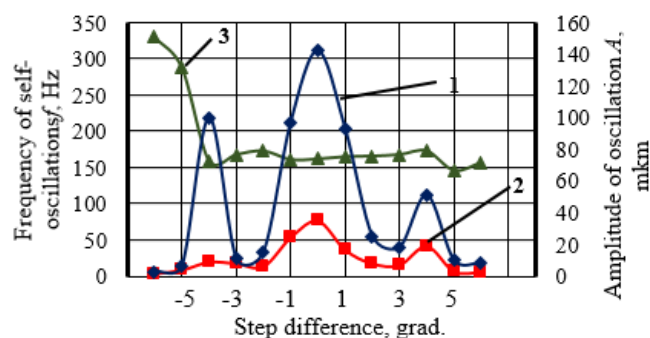

Fig. 6. Influence of the angular shift Δ of cutter 2 on the amplitude A of self-oscillations of the boring head (1 – horizontally, 2 - vertically) and frequency f of their dominant mode (3)
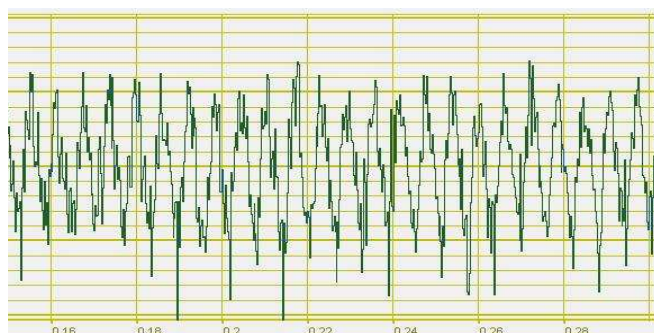

Fig. 7. Vibration record of horizontal oscillations of the two teeth head at uniform spacing of cutters

III.   RESULTS AND DISCUSSION

The results of boring experiments using a two-tooth head are presented in Table 1 and Figure 6. When the tool teeth are evenly positioned (experiment 7), intensive bending vibrations with an amplitude of 142 µm in a horizontal direction and 77 µm in a vertical direction were observed. They are self-oscillations as confirmed by the vibration record (Fig. 7) and spectrum (Fig. 8) of these oscillations with a pronounced dominant harmonic at a frequency of 162 Hz. Displacement of cutter 2 by 1…1,5° in both circular directions (experiments 4, 5, 9, 10) decreased the amplitude by times. A further increase in displacement up to 2° (experiments 3 and 11) increased vibrations but to a lesser degree than at a uniform position of

cutters. Displacement by 2,5…3° (experiments 1, 2, 12, 13) contributed to the smoothest cutting conditions. The machined surface under smooth and dynamically unstable cutting conditions is shown in Fig. 9. In experiments 3-13, the frequency of bending head oscillations was almost equal to the frequency of the first head oscillation. In experiments 1 and 2, it was equal to the frequency of the second head oscillations.
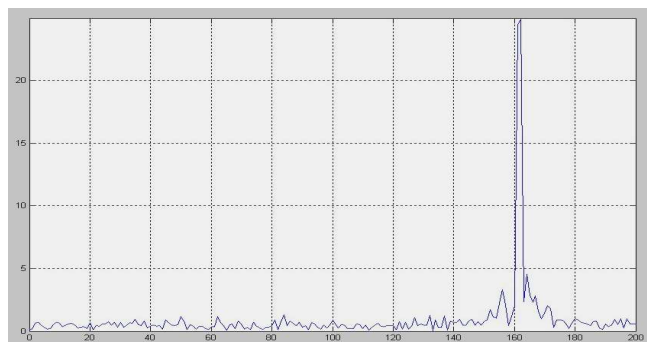

Fig. 8. Spectrum of acceleration of horizontal oscillations of the head at uniform spacing of cutters

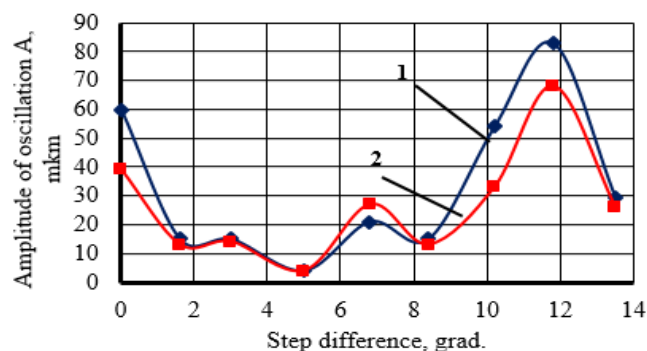Fig. 9. Machined surface during smooth and dynamically unstable boring

Fig.10. Impact of differences of pitches of adjacent teeth of the turning head on the workpiece self-oscillation amplitude: 1–vertical oscillations, 2 – horizontal oscillations

The results of turning experiments for a low-rigid shaft are presented in Table 2 and Figure 10. When turning head teeth are evenly positioned (experiment 4), on a frequency of 580 Hz, intensive bending self-oscillations with an amplitude of 39 µm in a horizontal direction and 60 µm in a vertical direction were observed. They are accompanied by specific noise and mark formation (Fig. 11a). The comparison of workpiece oscillation frequencies (see Table 2) with the natural frequency of oscillations (270 Hz) shows that in the first three experiments the workpiece oscillations were close to the second workpiece oscillations, and in the other experiments – to the first ones. A discrete increase in the teeth pitch difference changed the intensity of oscillations (see Fig. 10). In the range of 0,25 to 1,3 wave-length (experiments 15-19), the difference of teeth pitches dampened self-oscillations, and at 0,75 (experiment 17) wavelength, it eliminated them (see Fig. 11b). A further increase in the pitch difference caused a new increase and decrease of the self-oscillation amplitude. At the pitch difference of 1,75 wave-length (experiment 21), the self-oscillation amplitude increased 1,5-fold as compared to uniform teeth spacing which influences the surface quality (see Fig. 11c).
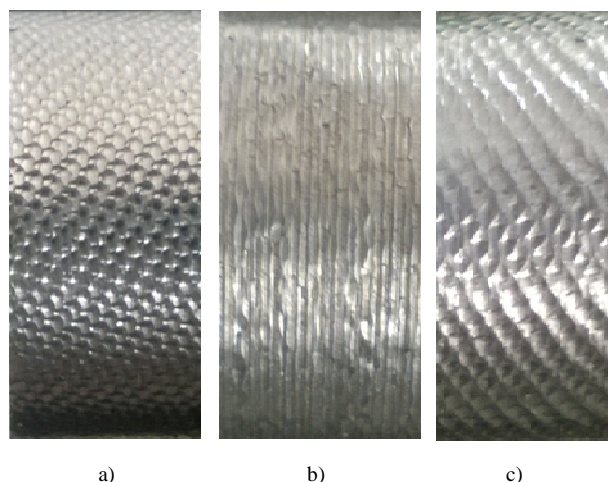

| a) | b) | c) |

Fig. 11. Photos of turned surfaces: a – at a constant tooth pitch (experiment 14), b – at pitch difference of 0,75 wave-length (experiment 17), c – at pitch difference of 1,75 wave-length (experiment 21)

The milling results are presented in Table 3 and Figure 12. When the tool teeth are evenly positioned (experiment 23), intensive self-oscillations of the low-rigid workpiece with an amplitude of 352 µm and peak-to-peak of 1700 µm were observed on a frequency of 159 Hz which was close to the frequency of natural workpiece oscillations of 151 Hz. The difference of adjacent teeth pitches decreased the intensity of oscillations. The best results were obtained when displacing even teeth in the range of 3 to 6°: The peak-to-peak decreased from 1700 µm to 288 µm, i.e. six times. The amplitude of the dominant harmonic of self-oscillations decreased to 18 µm, i.e. by 20 times (Fig. 12b). An increase in the tooth pitch difference changed the frequency of self-oscillations.

Dynamic behavior of technological systems in all three sets of experiments can be interpreted in terms of the theory of regenerative self-oscillations [14]. At an even position of tool teeth (experiments 7 and 14), there is a large number of self-oscillation waves between them: 37,91 waves when boring, and 13,32 waves when turning. It creates conditions for their free regeneration under which current oscillations of the system advance vibration mark oscillations by 0,25 wave-length, ensuring energy supply into the system for supporting

intensive self-oscillations. Uniform spacing of face mill teeth (experiment 23) ensures 2,84 wave-length between them creating initial phase shifting close to +90° and contributing to self-oscillation development. After relative turning of the tool and workpiece at an angular distance between the teeth, the latter meet the mark of the previous pass with a different phase angle. It causes simultaneous short transition during 1-2 oscillations for all teeth. After completion of the process, a less desirable phase angle of +90° supporting self-oscillations is set between current system oscillations and mark oscillations.
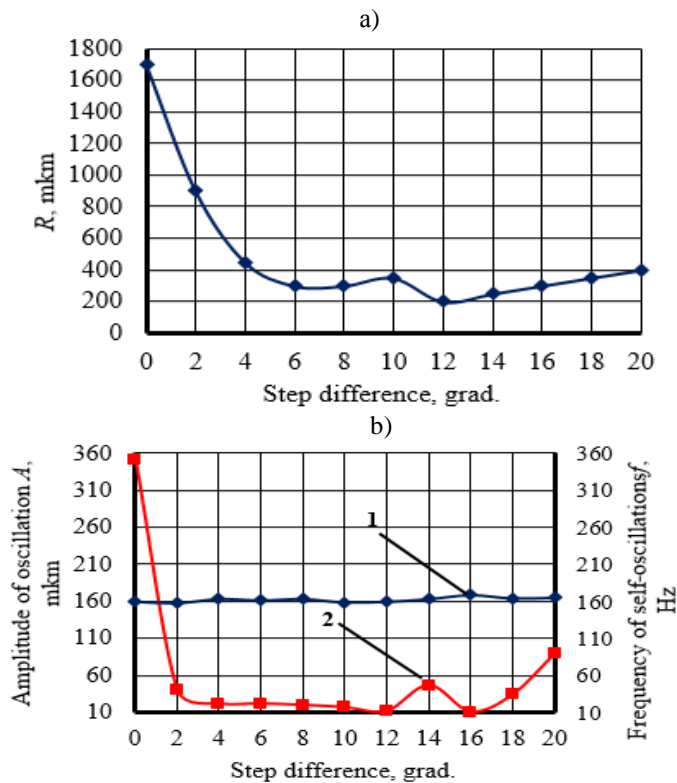

Fig. 12. Impact of differences of pitches of adjacent teeth on the range R of workpiece oscillations (a), amplitude A (1) and frequency f (2) of its self-oscillations (b)

A similar situation holds when the difference of tooth pitches is equal to an integral number of self-oscillation waves on the cutting surface (experiments 3, 11, 18, 22). Lower intensity of self-oscillations in these experiments in comparison with experiments 7 and 14 can be due to the non-synchronism of adjustment resulted from asymmetrical spacing of teeth. For the face mill (experiment 31), the non-synchronism effect due to a smaller number of waves between teeth is stronger than for boring and turning heads. It dampens self-oscillation regeneration. Besides, adjacent teeth pitches can hold 2,34 and 3,34 oscillation waves creating initial phase shifting close to 90° which dampens self-oscillations.

When the difference of pitches is equal or close to a half wave-length (experiments 4, 5, 9, 10, 16, 27), current oscillations of adjacent teeth develop in a reversed phase which is impossible due to their position on the common tool body. The teeth prevent each other from adapting to mark oscillations at a phase angle of +90°. It dampens regenerative self-oscillations and the cutting process occurs under smooth

conditions. It should be taken into account that adjacent teeth are mutually perpendicular on the turning head and their oscillation path is almost circular. Thus, the difference of adjacent teeth pitches of 0,75 wave-length corresponds to the largest degree of self-oscillation regeneration control. It was confirmed by experiment 17 in which pronounced self-oscillations were not observed.

IV. CONCLUSION

The research results show that in order to control the intensity of self-oscillations, it is necessary to understand the physical nature of their regeneration mechanism. Correct identification of the difference of adjacent teeth pitches ensures almost complete self-oscillation dampening. To increase the efficiency, the method can be combined with other ones (e.g., additional dampening in the cutting zone). The use of the method for improving the vibration stability of technological systems sets a task to develop new designs of tools with smooth adjustment of angular teeth spacing

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