

Features of Peripheral End milling: Formation of Machined Surface Profile

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Abstract—The profile of the machined surface at the peripheral end milling is made when various types of fluctuations occur. At milling under self-excited oscillations, the machined surface, in addition to traces from cutting in with each tooth, has a wavy profile. The purpose of the article is to consider the peculiarities of the mechanism for making the profile of the machined surface under up and down peripheral end milling in case of chatter appearance. The experiments have been carried out on a special bench, using a technique that allows estimating the law of the vibrational motion of a part in the milling process by recording oscillograms of part fluctuation. The profile of the machined surface was evaluated by strip chart recording. The basic fragments of the oscillograms were used to determine the values of the parameters, which made it possible to establish the relationship between the waviness on the machined surface and the oscillatory movements of the part during milling with different feed directions. On the basis of the conducted experimental research, the mechanisms of surface finish formation during the up and down peripheral end milling in the third velocity zone have been determined. The height of the waviness during the cut-up milling with self-excited oscillations is formed by cavities, the depth of which is determined by the deviation of the part from the elastic equilibrium line on the first wave of auto-oscillations. The number of cuts determines the waviness stroke. At the cut-down milling, shaping cavities are formed by the part deviation from the elastic equilibrium line when the tool leaves the cutting zone. The waviness stroke on the machined surface depends on the change in the length of the cutting surface.

Keywords—*profile; number of cuts; oscillogram; the vibrational motion, waviness; profilogram*

I. INTRODUCTION

Cost efficiency of milling process is highly dependent upon its stability, which determined by the dynamics of the machine-tool/tool/workpiece system and in turn limits the cutting parameters, which may be chosen [1]. Solving of such problem attracted a lot of attention of scientist who prefer numerical prediction of the machining process using simulation models rather than experimental investigation [2-4]. It is generally believed that the major problem which prohibits obtaining desirable efficiency and quality is the regenerative effect (chatter) that causes the chatter marks. The basic principles of chatter theory have been developed in 1960s by Tobias [5] and Tlustý [6], Tlustý and Poláček [7]

and Merritt [8]. These scientists presented stability theory for orthogonal turning and developed a stability lobe theory for the system with two degrees of freedom. The aim of stability lobe theory is to calculate the critical axial depth of cut at the highest available spindle speed. The developing of this theory was proposed by Altintas [9] who presented a new analytical form of the stability for milling. Further Bravo et al. [10] proposed a method of the stability lobes calculation when both the machine tool and workpiece have similar dynamic behavior. Seguy et al. [11] calculated the dynamic of part by final element method, and the 3D stability lobes for thin-wall components.

Davies and Balachandran [12] noticed that numerous types of nonlinearities can affect the dynamic behavior of milling processes. However, the effect of nonlinearities associated with the intermittency have been virtually ignored in the literature. They showed that impact dynamics is likely to dominate vibrations in milling operations where the cutter rotation can excite flexible modes in the workpiece. Further Davies et al. [13] concluded that the assumptions of this Traditional regenerative stability theory became invalid for highly interrupted machining and they proposed a first direct analytical solution to the problem.

Milling of thin-walled components with complex shape always occurs under interrupted cutting conditions [14], which significantly complicate prediction of the stability, especially at low spindle speed.

At the peripheral end milling of thin-walled components, there are five velocity zones of oscillations [15], each of which has its own modes of oscillation and, as a result, its own features of making the profile of the machined surface [16].

The profile of the machined surface at the peripheral milling is made in the form of a combination of protrusions and cavities from cutting in with each tool tooth, repeated with a period equal to the feed per tooth – S_z [17 – 19].

Cavities are formed when the cutter's tooth cuts into the machined surface, and the height of the protrusions is Δh , is related to the tool radius – R_c , and feed rate per tooth – S_z (Fig. 1).

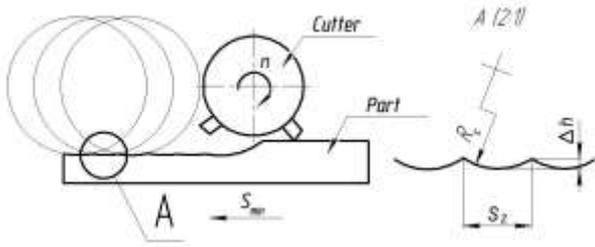


Fig. 1. The scheme of making the surface profile at the peripheral milling

At milling of thin-walled components when chatter take place, the machined surface, in addition to traces from cutting with each tool tooth, has a wavy profile with a stroke – S_w , unequal feed per tooth – S_z , and depth – W_z , both with cut-up and cut-down directions (Fig. 2).

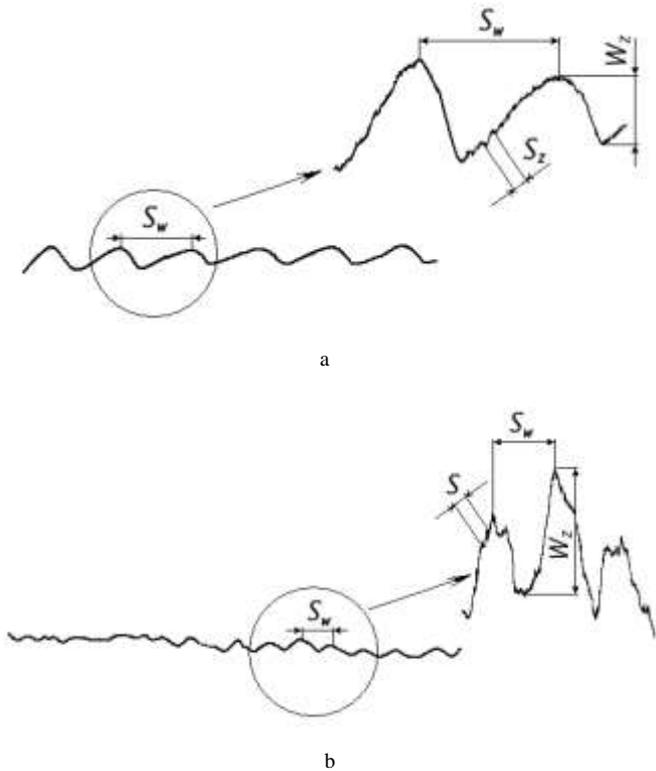


Fig. 2. Profilograms of the surface after the cut-up (a) and cut-down (b) end peripheral milling with auto-oscillations

The research work [16] shows that making a wavy profile on the machined surface is due to the influence of vibrations, but the mechanism for forming cavities of different depths has not been revealed.

The article [20] explains this is due to different positions of the cutting points and the tool exit at milling under the conditions of forced vibrations, but chatter have not been considered.

II. THE RESEARCH OBJECTIVES

Taking into account that the effect of auto-oscillations is most evident in the third velocity zone, in which the rough and semi-finishing milling of parts from hard-to-cut materials is most often carried out, the aim of the present work is to reveal the peculiarities of the mechanism for making the machined surface profile when the chatter occur.

III. PRESENTATION OF THE MAIN MATERIAL AND ANALYSIS OF THE RESULTS

The research has been carried out on a special bench [22, 23], the design of which allows recording oscillograms of part oscillations during milling. Oscillograms were divided into basic fragments, allowing to evaluate the law of oscillatory movement of a part when cutting with each milling tooth and the shape of the cutting surface [20]. A profilogram of the machined surface was recorded after milling.

Milling was performed on a vertical milling machine of FWD-32J, model with a single-tooth, straight flute, special milling cutter of $\varnothing 55$ mm with an adjustable position of the cutting tooth. The material of the cutting edge of the tooth mill is a carbide alloy; the frequency of free oscillations is 833 Hz. The sample size is $50 \times 25 \times 34$ mm. The sample material is St.3 according to GOST 380-2005. The cutting conditions were set for milling when auto-oscillations arise: the spindle rotation speed is $n = 280$ rpm; the radial cutting depth is $a_e = 0.5$ mm; the axial cutting depth is $a_p = 3.4$ mm; the feed per tooth is $S_z = 0.1$ mm. The feed direction is up and down milling with oblique cutting.

To determine the stroke – S_w and the height of the waviness – W_z of the machined surface, formulas (1) and (2) have been obtained from the profilogram:

$$S_w = t \cdot v, \quad (1)$$

where t is the recording time of the signal between the similarly-named protrusions on the profilogram of the machined surface, s ;

v is the signal recording velocity determined by the feed of the machine table, mm/s .

$$W_z = k \cdot V, \quad (2)$$

where k is the calibration value for XS1M18AB120 inductive proximeter used when recording the profilogram, mm/V ;

V is the largest deviation of the recorded signal from the position of elastic equilibrium (PEE), V .

To determine the relationship between the waviness on the machined surface and the oscillatory movements of the part at milling according to the basic fragments of the oscillogram (BFO), the values of the following parameters have been defined:

– for up milling: the deviation of the part from the position of elastic equilibrium (PEE) when the tooth is cut in – Δ_{enter} , the chatter range – R_2 , the chatter period – T_{ao} , the cutting time – t_{cut} , the maximum deviation of the part under the action of the driving force – Δ_{max} , the deviation of the part from PEE at the exit of the milling tooth – Δ_{exit} , the amplitude of the first wave of free damped oscillations – A_1 , the deviation of the first wave of chatter of the part from PEE is Δ_{prof} (Fig. 3, a);

– for down milling: the deviation of the part from PEE at the milling tooth cutting in – Δ_{enter} , the range of chatter – R_2 , the period of chatter – T_{ao} , the cutting time – t_{cut} , the maximum deviation of the part under the effect of the driving force – Δ_{max} , the deviation of the part from PEE at the milling tooth exit – Δ_{exit} , the amplitude of the first wave of free damped oscillations – A_1 . (Fig. 3, b).

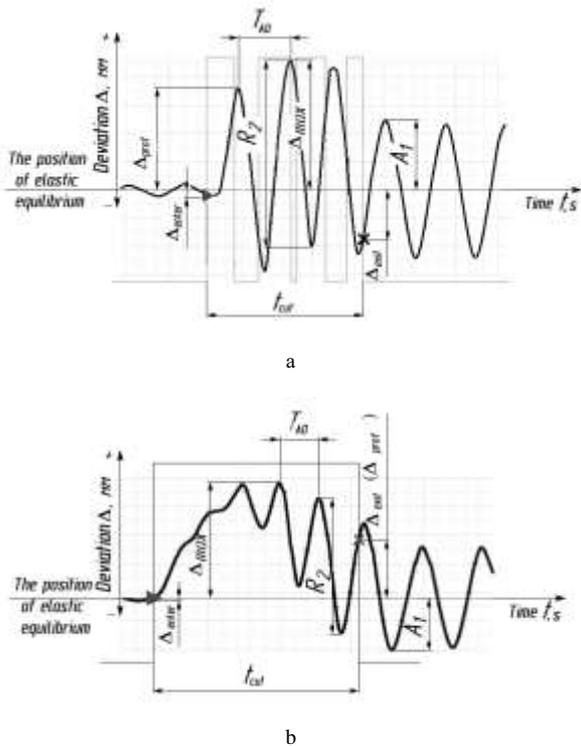


Fig. 3. Fragments of the oscillogram with an indication of the measured parameters in the up (a) and down milling (b)

Fig. 4 shows the profilograms of the machined surfaces after the up and down milling with chatter and the movement direction of the tool and part.

The evaluation of the parameters measured according to BFO showed that for up milling only the change in the deviation of the first chatter wave on the part from PEE is Δ_{prof} , both in height and in stroke, corresponds to the law of waviness change on the machined surface. This is clearly shown by the values in tables 1 and 2, where the strokes and heights of the waviness of the machined surface, measured on profilograms and determined according to BFO, are given.

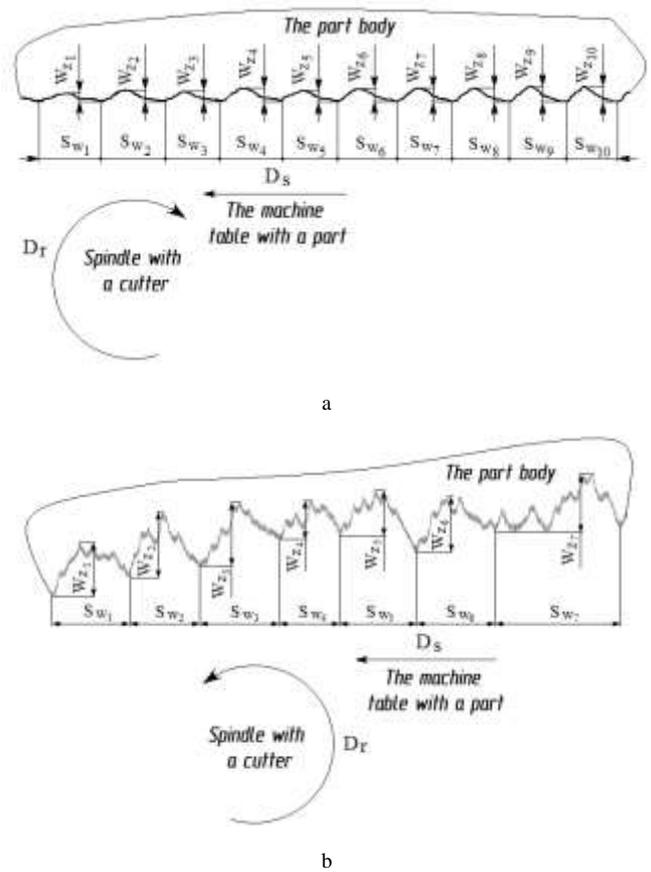


Fig. 4. Fragments of the profilogram of the machined surface after the up (a) and down (b) end milling

TABLE I. COMPARISON OF THE WAVINESS STROKE OF THE MACHINED SURFACE MEASURED ON THE PROFILOGRAM WITH THE STROKE DETERMINED ACCORDING TO BFO

The section number on profilogram	3	4	5	6	7
Waviness stroke S_w on the profilogram, mm	2.54	2.65	2.57	2.65	2.49
The number of cuts with the mill tooth n_{cut}	25	26	26	27	24
Feed per tooth S_z , mm	0.1				
Waviness stroke S_w , determined by the number of cuts ($S_w = n_{cut} S_z$), mm	2.5	2.6	2.6	2.7	2.4
Margin of error, %	1.57	1.89	1.15	1.85	3.61

The comparison shows that the error margin of the stroke and the waviness height measured on the profilogram and determined according to BFO do not exceed 4% and 5%, respectively. Based on this, we can say that the waviness height at the up peripheral milling with self-excited oscillations

is formed by cavities remaining from the cutting surface, the depth of which is determined by the deviation of the first wave of chatter from PEE. The waviness stroke is determined by the number of tool cuts at which the deviation of the first chatter wave from PEE – Δ_{prof} , varies from the maximum to the minimum.

TABLE II. COMPARISON OF THE HEIGHT OF THE WAVINESS MEASURED ON THE PROFILOGRAM AND DETERMINED ACCORDING TO BFO

The section number on profilogram	3	4	5	6	7
Waviness height on W_{zi} profilogram, mm	0.083	0.091	0.083	0.107	0.082
The waviness height determined according to BFO W_{zio} , mm	0.081	0.095	0.081	0.102	0.078
Margin of error, %	2.4	4.2	2.4	4.67	4.88

The evaluation of the measured parameters characterizing the oscillations of the part during milling has showed that they all change periodically. The change in the cutting time, period and range of auto-oscillations suggests that the length of the cutting surface, height and waviness stroke on it change periodically.

The change in the cutting time is affected by the shift of the wave phase of auto-oscillation at each subsequent cut (Fig. 5), which corresponds to a similar shift of the waves on the cutting surface and leads to a change in its length (Fig. 6).[20]

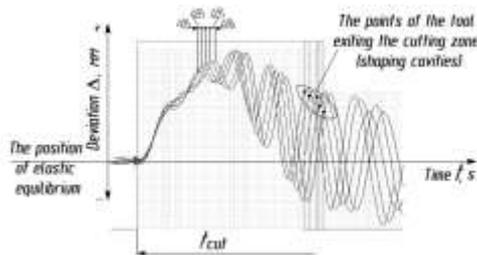


Fig. 5. The shift of the wave phase on the oscillogram on each subsequent cut

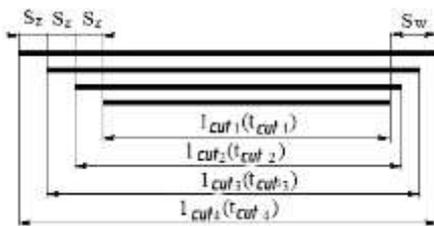


Fig. 6. The diagram of the cutting time effect on the change in the length of the cutting surface and the formation of the waviness stroke on the machined surface

With the down milling, as well as with the up milling, each subsequent cutting in of the tool into the part occurs after its movement by the value of feed per tooth – S_z . Since each

subsequent cutting surface is longer than the previous one, the remaining cavity from the next cut is ahead of the previous one. This order for making cavities periodically repeats. As a result, a wavy profile is formed on the machined surface. The formula for calculating the wavy stroke – S_w at the down milling is:

$$S_w = \sum_{i=1}^{n-1} (l_{i+1} - l_i - S_z) \quad (3)$$

where l_i and l_{i+1} – are the lengths of the cutting surfaces on the previous and subsequent cuts, mm;

S_z is feed per tooth, mm;

n is the number of cuts made in the period of the cutting time change (lengths of the cutting surface).

Table 3 shows the values of the waviness strokes determined by the profilogram and calculated by the formula (3).

TABLE III. THE VALUES OF THE WAVINESS STROKES MEASURED ON THE PROFILOGRAM AND CALCULATED FROM THE CHANGE IN THE LENGTH OF THE CUTTING SURFACES AT CUT-DOWN MILLING

The section number on profilogram	1	2	3	4	5	6	7
The waviness stroke on the profilogram, S_{wi} , mm	0.847	0.808	0.866	0.664	0.904	0.845	1.49
The waviness stroke calculated S_{wi} , mm	0.861	0.808	0.835	0.652	0.887	0.834	1.46
Margin of error, %	1.6	0	3.6	1.8	1.9	1.3	2.0

The values of the waviness strokes for the similarly-named sections taken from the profilogram and from the oscillogram, given in Table 3, have close values with an error margin within 4%.

At the down milling, the cavities making the machined surface remain at the exit of the milling tooth. Therefore, it can be assumed that its depth is determined by the deviation of the part from PEE at the tool exit. Different depth of the cavities makes the waviness on the machined surface.

The waviness height according to BFO for each period is defined as the difference between the highest and the lowest values of Δ_{exit} in this section:

$$\delta = \Delta_{exit \max} - \Delta_{exit \min}, \quad (4)$$

where δ is the waviness height determined by the oscillogram, mm

For comparison with the waviness height determined by the profilogram, the height determined by the oscillogram is calculated by the formula:

$$W_{zi} = -17.387 \cdot \delta_2 + 2.9825\delta - 0.071. \quad (5)$$

Table 4 shows the values of strokes determined by the profilogram and calculated by the formula (5)

TABLE IV. THE VALUES OF THE WAVINESS HEIGHT MEASURED ON THE PROFILOGRAM AND CALCULATED BY THE FORMULA (5)

The section number on profilogram	1	2	3	4	5	6	7
Waviness height on W_{zi} profilogram, mm	0.047	0.055	0.058	0.034	0.040	0.044	0.054
The waviness height calculated, W_{zi} , mm	0.049	0.057	0.057	0.032	0.041	0.044	0.049
Margin of error, %	4.1	3.5	1.7	5.9	2.4	0	9.2

IV. CONCLUSIONS

On the basis of the conducted research, the peculiarities of the mechanisms for making the profile of the machined surface during the up and down peripheral end milling have been established.

1. At the up and down peripheral end milling in the third velocity zone the mechanism for forming the machined surface is different.

2. It has been established experimentally that the waviness height at the up milling when chatter take place is formed by cavities, the depth of which is determined by the deviation of the parts from the PEE on the first wave of auto-oscillations. This depth varies periodically from the highest value to the lowest one. The number of cuts at which this change occurs, with a known feed per tooth, determines the waviness stroke.

3. At the down milling, shaping cavities on the machined surface are formed by the deviation of the part from the PEE when the tool exits the cutting zone. The waviness stroke on the machined surface depends on the change in the cutting surface length, which is influenced by the wave stroke from the chatter on the cutting surface and the phase shift between them occurring at each subsequent cut of the milling tooth.

References

- [1] Dalton, H., Byrne, G. and Steinicke, M. 'Evaluation of a model for the prediction of milling stability for thin-walled components', *Int. J. Manufacturing Technology and Management*, Vol. 15, No. 2, 187–196, (2008).
- [2] Ratchev, S., Liu, S., Huang, W. and Becker, A. A. A flexible force model for end milling of low-rigidity parts, *Journal of Materials Processing Technology*, vol. 153-154, no. 1–3, 134–138, (2004).
- [3] Budak, E. Analytical models for high performance milling. Part I: cutting forces, structural deflections and tolerance integrity, *International Journal Machine Tools & Manufacture*, vol. 46, 1478–1488, (2006).
- [4] Rai, J. K. and Xirouchakis, P. Finite element method based machining simulation environment for analyzing part errors induced during milling of thin-walled components, *International Journal of Machine Tools and Manufacture*, vol. 48, no. 6, 629–643, (2008).
- [5] Tobias, S. A., 1965, *Machine Tool Vibration*, Wiley, N.Y.
- [6] Koenigsberger, I. and Thusty, J. *Structures of Machine Tools*, Pergamon Press. (1971).
- [7] Thusty, J. and Polacek, M. The stability of machine Tools against self excited vibrations in machining, *Proceedings of the ASME Production Engineering Research Conference*, 465–474, (1963).
- [8] Merritt, H. E. Theory of self-excited machine-tool chatter: contribution to machine-tool chatter research, *Journal of Engineering for Industry*, vol. 87, no. 4, 447–454, (1965).
- [9] Altintas, Y. *Manufacturing Automation-Metal Cutting Mechanics, Machine Tool Vibrations and CNC Design*, Chemical Industry Press, (2002).
- [10] Bravo, U.; Altuzarra, O.; López De Lacalle, L.N.; Sánchez, J.A.; Campa, F.J. Stability limits of milling considering the flexibility of the workpiece and the machine. *International Journal of Machine Tools and Manufacture*, 45(15): 1669–1680, (2005).
- [11] Seguy, S.; Campa, F.J.; de Lacalle, L.N.L.; Arnaud, L.; Dessein, G.; Aramendi, G. Toolpath dependent stability lobes for the milling of thin-walled parts. *International Journal of Machining and Machinability of Materials*, 4(4): 377–392, (2008).
- [12] Davies, M, Balachandran, B Impact dynamics in the milling of thin-walled structures. In: *Proc. Nonlinear Dyn. Control. Symp.* 12–22, (1996).
- [13] Davies MA, Pratt JR, Dutterer BS, Burns TJ The stability of low radial immersion milling. *CIRP Ann Technol* 49: 37–40, (2000), doi: 10.1016/S0007-8506(07)62891-1.
- [14] Germashev, Anton & Logominov, Viktor & Anpilogov, Dmitri & Vnukov, Yuri & Khristal, Vladimir. Optimal cutting condition determination for milling thin-walled details. *Advances in Manufacturing*. 6, (2018), doi: 10.1007/s40436-018-0224-y.
- [15] Dyadya, S., Kozlova, E., Kondratyuk, E.: Systematization of Oscillations at the End Milling of Thin-Walled Elements of Parts. *Engine Engineering Bulletin* 1, 68 –71 (2016).
- [16] Logominov, V. (2013) Formation of Roughness of the Machined Surface at the End Peripheral Milling of Thin-Walled Elements of Parts. Dissertation, Zaporozhye.
- [17] Granovsky, G., Granovsky, V. : A textbook for the Machine Building and Instrument Engineering Specialised Universities. Higher School, (1985).
- [18] Rosenberg, Yu.: *Cutting of Materials*. Kurgan: Publishing House of OJSC: Trans-Urals, (2007).
- [19] Kashirin, A.: *Investigation of Vibrations at Metal Cutting*. Publishing House of the Academy of Sciences of the USSR. (1944).
- [20] Dyadya, S.: Study of the Formation of the Machined Surface of a Thin-Walled Part Element at End Peripheral Milling with Auto-Oscillations. *Modern Technologies in Machinery Building* 12, 5 –18 (2017).
- [21] Gubanova, A. (2016) Improving the Surface Quality at Cut-down Milling with End Mills on the Basis of Controlling the Dynamics of the Process. Dissertation, Rostov-on-Don.
- [22] Logominov, V.: Methodology for Researching Regenerative Auto-Oscillations by Cut-Grams at Milling Thin-Walled Parts. *Modern Technologies in Machine Building: Collection of Scientific Works* 9, 176 – 182, (2014).
- [23] Vnukov, Yu., Logominov, V., Kamorkin, P.: The Bench to Study Mechanical Vibrations at Milling Low-Rigid Parts with End Milling. *Cutting and Tools in Technological Systems: The Collection of International Scientific and Technical Works* 80, 32 –37 (2011).