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RESEARCH

Kinematic, Dynamic and Tribological Aspects of Up and Down Milling Processing

This paper consists partly of large scale theoretical investigation concerning up and down milling from the aspect of kinematics processing and dynamic tool stability. The objective of the study is to determine theoretical parameter dependencies influencing the processed area quality, with respect to milling treatment and corresponding kinematics and dynamic relations to the tools used in the process conduct. Based on the obtained results from kinematics and especially dynamic modeling treatment of milling processing, it can be concluded that from the aspect of processed area quality advantage is given to down milling.

Keywords: up and down milling, kinematics modeling, and dynamic modeling

1. INTRODUCTION

Processed area quality is one of the basic technological optimizing and processing supervision criteria. Processed area assessment is performed via asperity parameters and structural and mechanical characteristics of the surface layer. Condition recognition in which processed areas of requested quality can be obtained is of special interest. Primarily that requires skill in determining factors influencing the processed area quality. Quality of the processed area depends on several factors related to:

- mechanical, tribological, structural and adiabatic characteristics of the processed material in question.,
- processing mode parameters,
- mechanical, tribological, geometrical, structural and adiabatic tool characteristics machine status characteristics which can be partly realized over dynamic machine stability parameters,
- coolant and lubricant,
- holding circuit tool,
- other processing conditions.

Bibliography contains great number of informations related to certain parameters impact on processed area quality [4], [5], [7]. One can say that nowdays all major factors are known. However, the extent of other factors impact, especially when speaking of factors related to older machines, has not yet been studied sufficiently and it still stands as a subject of interest of large number of authors [1], [2], [3].

Especially current problems are theoretical investigations of up and down milling techniques from the aspect of processed area quality. These investigations are initiated by the fact that during down milling better processed area quality is achieved, and regardless this procedure is far less used in industry compared to up milling procedure. According to available literary data, from the time frame in which these investigations were conducted, author has not succeded to theoretically clarify this phenomenon. Based on surveying literary resources the conclusion that theoretical explanation should be looked for in areas of kinematics and dynamics of up and down milling processes was imposing. In following discussion abbreviated summary of the performed theoretical investigations is given.

2. MILLING KINEMATICS

Milling process is performed, from the kinematric point of view, using main tool rotary motion (flux line cutter) and auxiliary, most frequently straight gear line motion of the processed object.

During down milling horizontal velocity vector projection along the collective trajectory of the

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teeth and processed object is in an allignment, according to direction and lie, with auxiliary movement velocity vector. In case of up milling projections of the abovementioned vectors differ in lie. Curve AB (figure 1), formed during teeth movement from point A to point B with velocity *v* and processing object moving with velocity v_p is a part of cycloidal trajectory, most frequently replaced with circular curve. Completely identical curve will be formed when cutter performs the auxiliary movement in counter clock wise direction as seen in figure 1.

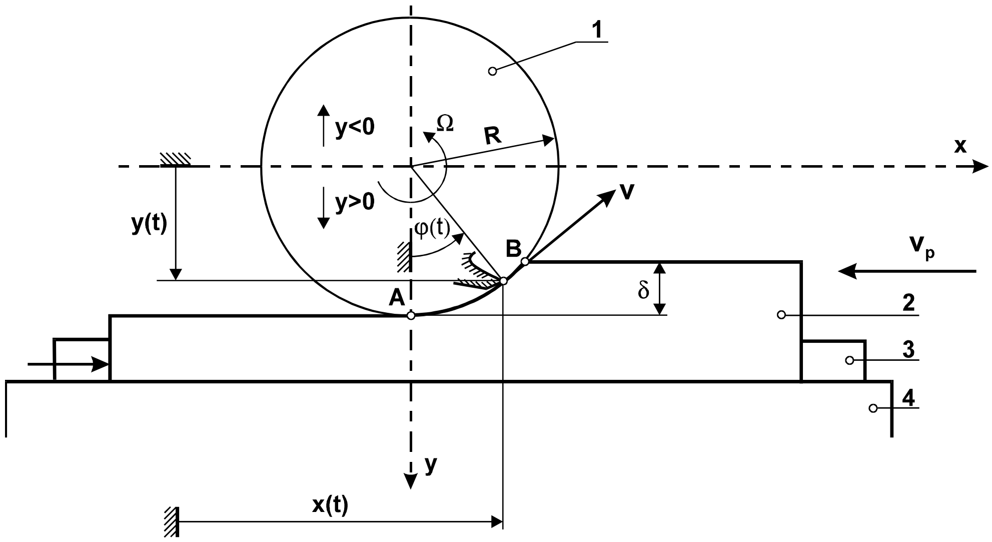


Figure 1. Schematic illustration of milling process treatment
1 -cutter; 2 – processed object; 3-holding circuit tool; 4 – cutter worktable

Cutter teeth trajectory can be determined based on coordinates of the position of cutting teeth top *x* (*t*) and *y* (*t*). According to figure 1 coordinates are

$$x = R \cdot \sin\varphi(t) + v_p \cdot t$$
$$y = R \cdot \cos\varphi(t)$$

Angle change φ(*t*) is defined with expression:

$$\varphi(t) = \Omega \cdot t,$$

after substitution in coordinate equation:

$$\boxed{\begin{aligned} x &= R \cdot \sin\Omega t + v_p \cdot t \\ y &= R \cdot \cos\Omega t \end{aligned}} \qquad (1)$$

the following being :

R - cutter radius
Ω - cutter angular velocity
v_p - auxiliary movement
t - time

Teeth trajectory equation is produced by eliminating time *t*. Therefore from the second system of equations follows:

$$y = R \cdot \cos\Omega t \Rightarrow \cos^2\Omega t = \frac{y^2}{R^2} = 1 - \sin^2\Omega t \Rightarrow$$

$$\sin\Omega t = \pm\sqrt{1 - \frac{y^2}{R^2}}$$

$$t = \frac{1}{\Omega} \cdot \arcsin\sqrt{1 - \frac{y^2}{R^2}}$$

By substituting in first equation of system 1 teeth trajectory equation is produced:

$$\boxed{x = \pm R\sqrt{1 - \frac{y^2}{R^2}} \pm \frac{v_p}{\Omega} \cdot \arcsin\sqrt{1 - \frac{y^2}{R^2}}} \qquad (2)$$

Up milling is carried out in the area: $0<y<R$, in other words, $0<\delta<R$,
Whereas the area of down milling is defined by condition:

$-R<y<0$, in other words odnosno $-R<\delta<0$.

Ratio (v_p/Ω) with appropriate transformations can be expressed over auxiliary and main movement velocity ratio:

$$\frac{\nu_p}{\Omega} = \frac{\nu_p \cdot R}{1000 \cdot \nu}$$

The following being:

ν_p - auxiliary movement velocity mm/min
R - cutting radius mm,
ν - main movement velocity m/min.

By substituting this ratio in equation 2 the expression defining teeth trajectory for both milling processes is gained:

$$\boxed{x = \pm R\left[\sqrt{1-\frac{y^2}{R^2}} \pm \frac{\nu_p}{1000\cdot\nu}\arcsin\sqrt{1-\frac{y^2}{R^2}}\right]} \quad (3)$$

Sign mark (–) in equation 3 corresponds to down milling process, whereas sign mark (+) corresponds to up milling process.

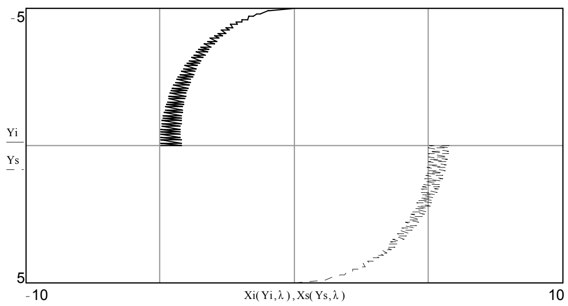


Figure 2. Schematic illustration of cutter teeth trajectory dependency from ratio λ_b (λ_b – auxiliary and main movement velocity ratio changed in time interval λ_b=0÷0.1)

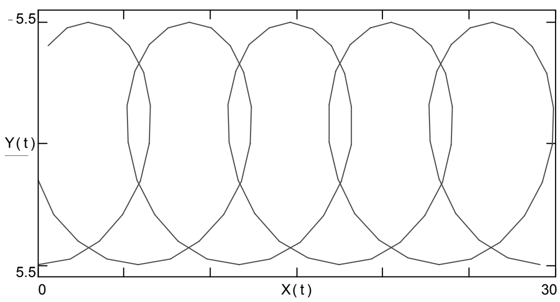


Figure 3. Schematic illustration of cycloid cutter teeth trajectory. Processing parameters: d=10, mm; Ω=6.28, s^{-1}; v_p=350, mm/min; t=0÷5, s

By equation 3 analysis it can be concluded that differences in teeth trajectory in up and down milling impact main and auxiliary movement velocity ratio.

Should (ν_p/1000·v) be designated as λ_b depending on λ_b magnitude, kinematics differences in up and down milling processes can be analyzed.

Figure 2 shows teeth cutter trajectory for both processing treatments and parameter λ_b value in terms 0 ÷ 0.1.

One can say that differences in up and down milling processes, from kinematics point of view have greater theoretical than practical significance. In purpose of realizing these differences figure 3 illustrates cutter teeth trajectory for practically unrealistic main and auxiliary movement velocity ratio (angular speed Ω=6.28, s^{-1} for 10 mm cutter radius, corresponding speed is ≈1.8 m/min). Figure 4 illustrates velocity distribution for processed area for approximately border case processing parameters from the aspect of main and auxiliary movement velocity ratio.

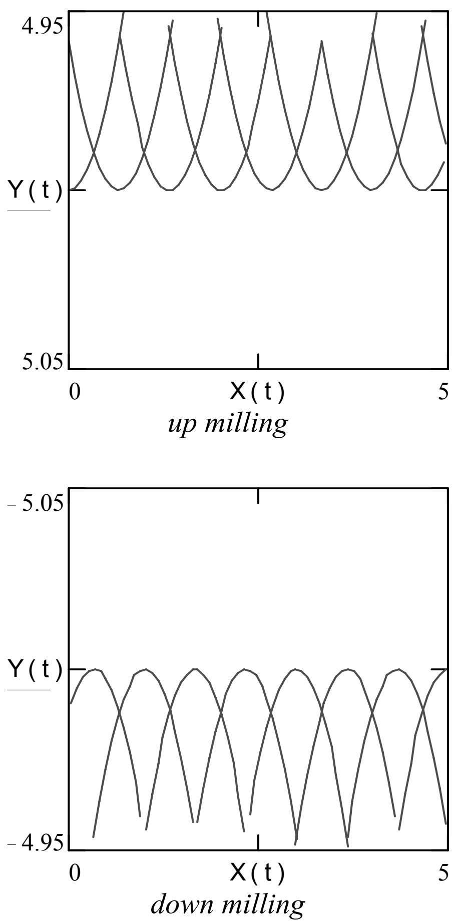


Figure 4. Schematic illustration cutter teeth trajectory and side view of processed area using down and up milling treatment. Processing parameters: d=10, mm; v=9.4, m/min; v_p=200, mm/min; x (t), mm; y (t), mm.

Theoretically speaking, from kinematics standpoint, up milling provides less height roughness. However, for realistic processing conditions, in most of analyzed cases differences in maximum height roughness are less than 1 μm, therefore there is no sense talking about kinematics differences in up and down milling processes.

Realistic milling manufacturing conditions are characterized by certain radial deviation of certain teeth. These differences are result of manufacturing error and cutter sharpening as well as deviation of kinematics and geometrical cutter axis. In such processing conditions cutter teeth position is defined (figure 5) by different vector radius and angle β_u=*const*. position coordinates $x(t)$ and $y(t)$ of certain cutter teeth are defined by equations:

first tooth:

$$x_1(t) = |R_1| \cdot \sin\Omega t + v_p \cdot t \;\text{ i }\; y_1(t) = |R_1| \cdot \cos\Omega t$$

second tooth:

$$x_2(t) = |R_2| \cdot \sin(\Omega t + \beta_u) + v_p \cdot t \;\text{ i }\; y_2(t) = |R_2| \cdot \cos(\Omega t + \beta_u)$$

n tooth:

$$x_i(t) = |R_i| \cdot \sin[\Omega t + (i-1)\beta_u] + v_p \cdot t \;\text{ i }\; y_i(t) = |R_i| \cdot \cos[\Omega t + (i-1)\beta_u]$$

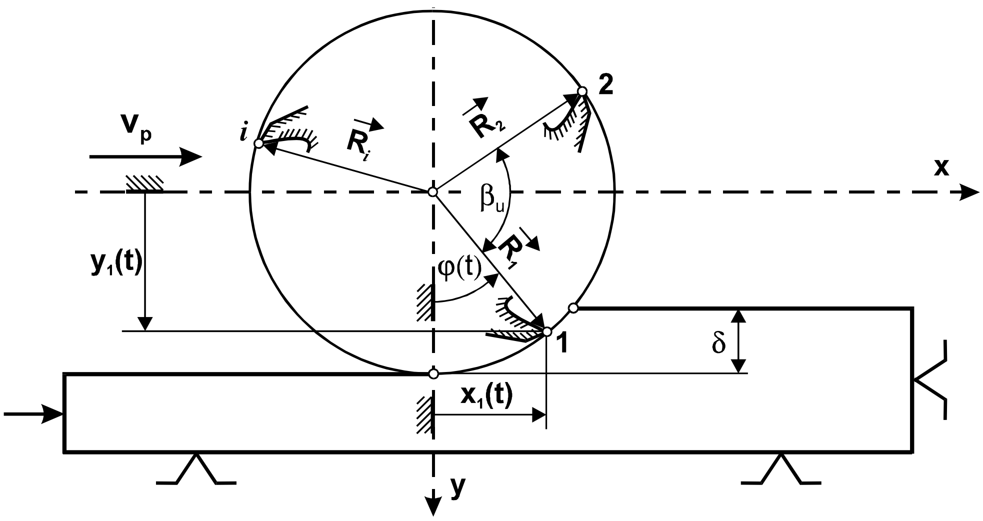


Figure 5. Cutter tooth position

Angle between cutter tooth is defined via expression: $\beta_u = \frac{2\pi}{z}$.

z being number of cutter teeth, so it can be written as follows

$$\begin{aligned} x_i(t) &= |R_i| \cdot \sin\left[\Omega t + (i-1)\frac{2\pi}{z}\right] + v_p \cdot t \\ y_i(t) &= |R_i| \cdot \cos\left[\Omega t + (i-1)\frac{2\pi}{z}\right] \end{aligned} \qquad (4)$$

Positional radius of n tooth, in kinematics point of view, is not a time function, but it primarily depends on eccentricity, thence it can be determined from the expression

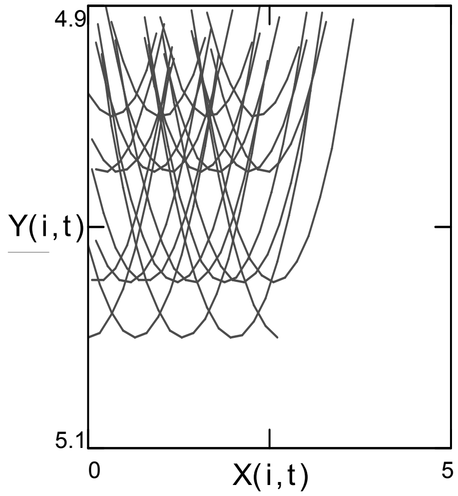
$R_i = R_0 + \varepsilon_z \cdot \cos\left[(i-1)\frac{2\pi}{z}\right]$, or it can be selected in terms:

$R_i = R_0 \pm \Delta R_0$, where the following are

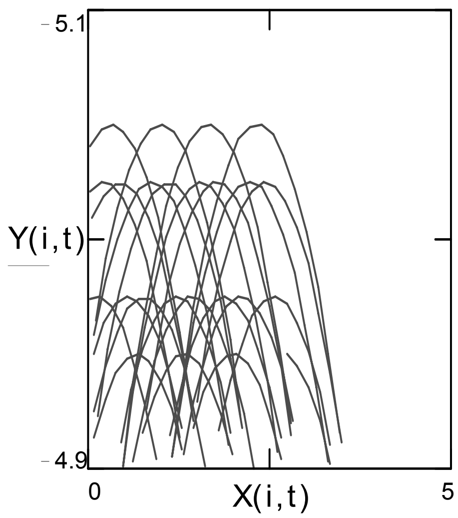
ε_z - cutter eccentricity,
ΔR - adopted or measured vector radius deviation
R_0 - cutter radius nominal value

On the basis of given expressions it is possible that with appropriate computer support, much realistically simulate milling process treatment. By analyzing both processes, while varying parameters in wide area of possible modes, it can be concluded that processed area is formed by tooth with greatest vector radius, which is illustrated in scheme in figure 6. Teeth size radial deviation has large impact on even distribution in side view milling chip between certain cutter teeth, in other words the load they are taking. Figure 7 illustrates side view shape of processed area and side view chip size cut using cutter teeth of different vector radius while performing down and up milling treatment process.

According to shown diagrams (figure 7) larger uneven load distribution is marked while using up milling treatment. However, generally, even load distribution depends on size and distribution of cutter teeth radial deviation and not from process treatment. Theoretically observed, it is possible that for defined processing conditions, from the aspect of even load distribution to select process treatment. However, it should be emphasized, that optimizing from kinematics aspect cannot have practical significance, given the dynamic character of load.



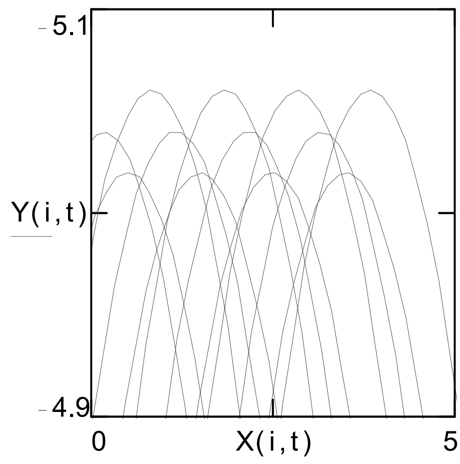
up milling



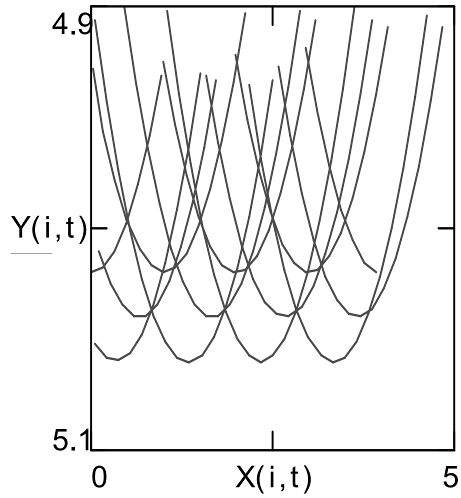
down milling

Figure 6. Schematic illustration cutter teeth trajectories and side view of processed area in down and up milling process treatment.

Treatment parameters: d=10 mm; v=9.4 m/min; v_p=200 mm/min; z=6 cutter teeth; ε_z=0.05 mm; R_o=5 mm



down milling



up milling

Figure 7. Schematic illustration of side view of milling chip of the processed area using down and up milling treatment process.

Processing parameters: d=10, mm; v=9.4, m/min; v_p=300, mm/min; z=3; R_1=5.02, mm; R_2=5.04, mm; R_3=5.06, mm; X(i,t), mm; Y(i,t),

3. MILLING DYNAMICS

Milling treatment process is characterized by varying loads. At the moment of tool teeth ingression in the material of the processed object, while using down milling, the highest maximum value of resistance to milling will occur, which will in time of order of magnitude of 0.01 seconds drop at zero value. During cutting and teeth egression from the material of the processed object loads of transmission elements for main and auxiliary movement are changing. Dynamic effects of their oscillation have negative effect on processed area quality, tool steadiness and other output magnitudes of treatment process.

Impact impulses transferred from tool cause oscillation of the whole system of transmitters for main movement. Transmitter elements for auxiliary movement oscillate so as to arouse forces transferred from processed object and holding circuit tool.

Oscillating principles of both transmitters are described via systems of differential equations with ten and more degrees of freedom.

Author, has in his investigations, related to this problem, performed dynamic modelling of tool conduct while performing down and up milling treatment.

According to [6], [7] equations used to describe tool movement and oscillation velocity have the following form:

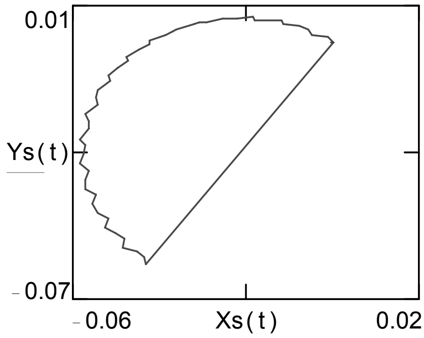
$$\begin{array}{|l|}\hline x_{zi}(t) = v_p \cdot t + x_i(t) + R \cdot \sin[\varphi_{1i}(t)] \\ y_{zi}(t) = y(t) - R \cdot \cos[\varphi_{1i}(t)] \\ x_{zs}(t) = v_p \cdot t + x_s(t) + R \cdot \sin[\varphi_{1s}(t)] \\ y_{zs}(t) = y(t) - R \cdot \cos[\varphi_{1s}(t)] \\ \hline \end{array} \qquad (5)$$

$$\begin{aligned} v_{xzi}(t) &= v_p + v_{xi}(t) + R \cdot \frac{d[\varphi_{1i}(t)]}{dt} \cdot \cos[\varphi_{1i}(t)] \\ v_{yzi}(t) &= v_{yi}(t) + R \cdot \frac{d[\varphi_{1i}(t)]}{dt} \cdot \sin[\varphi_{1i}(t)] \\ v_{xzs}(t) &= v_p + v_{xs}(t) + R \cdot \frac{d[\varphi_{1s}(t)]}{dt} \cdot \cos[\varphi_{1s}(t)] \\ v_{yzs}(t) &= v_{ys}(t) + R \cdot \frac{d[\varphi_{1s}(t)]}{dt} \cdot \sin[\varphi_{1s}(t)] \end{aligned} \qquad (6)$$

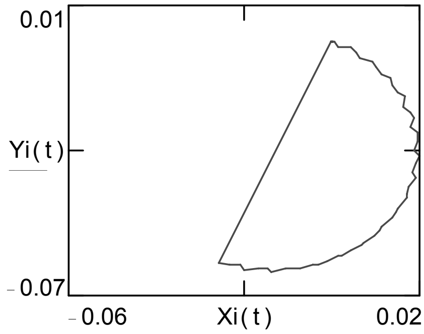
The complex functions dominating expressions 5 and 6 are described in detail and defined in frame of literary quote.

On basis of defined principles of cutter teeth movement (cutter teeth oscillation) and cutter teeth oscillation velocity, for different values arousing forces and cutter characteristics factor analysis impacting processed area quality has been performed, which is illustrated in schemes in figures 8-10. Based on shown diagrams it can be noticed that essentially oscillating shape and cutter center movement significantly differ in process of up milling than of that in down milling.

Alongside with teeth movement velocity change (figure 10) in diagrams are shown the functions $f_i(t)$ and $f_s(t)$ as well. These functions presents resulting cutting forces during down and up milling multiplied by certain constant (f=0.01·F).

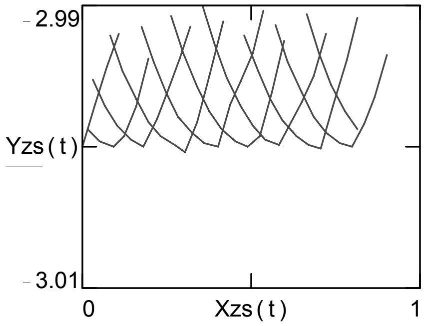


up milling

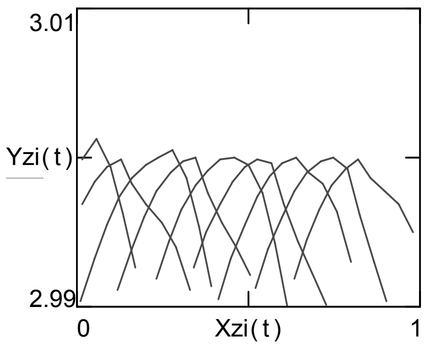


down milling

Figure 8. Cutter center movement due to elastic deformations while processing using down and up milling at angular speed Ω=314 s^{-1}; X(t) mm; Y(t) mm.



up milling



down milling

Figure 9. Side view of processed area obtained while processing using down and up milling (δ=3 mm; Ω=314, s^{-1}); X(t) mm; Y(t) mm.

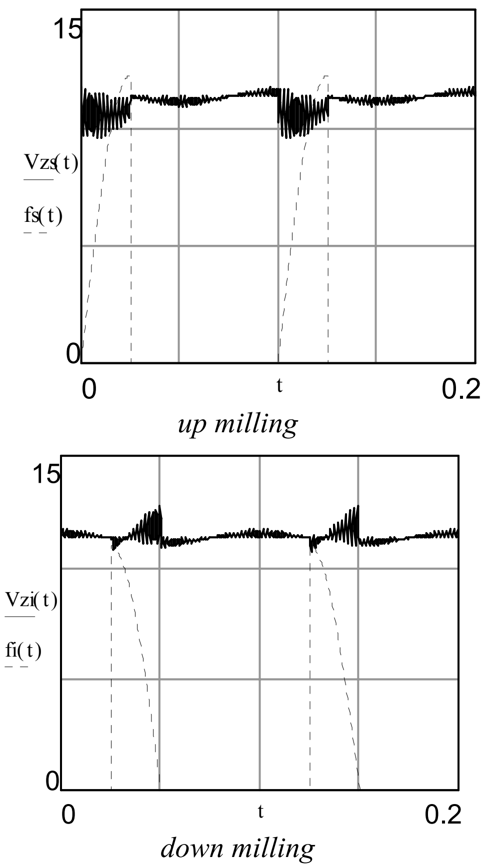


Figure 10. Cutter teeth velocity change while processing using down milling and up milling at angular speed Ω=62.8 s^{-1};t, s; v_z m/min; f(t) N.

From the aspect of teeth movement in dynamic conditions of processing there are no significant differences in treatment of down and up milling. However, average oscillation velocity (figure 10), calculated for teeth cutting time, is always higher in down milling processing, whereas speed dispersion, calculated for the same time, higher in up milling, which by all means gives advantage to down milling.

For previously defined processing conditions and angular cutter speed Ω=125.6 s^{-1}, figure 11 contains diagram illustration of power used for cutting one chip. In this diagram it can be clearly perceived that average teeth movement velocity is much higher than of that in down milling processing. For given realistic cutter rigidness, for down milling, bigger side view chips correspond to lower cutting velocity values. Higher velocity dispersion occurs for low force values, in other words, in the zone where the processed area is formed. For up milling velocity dispersion is significantly higher in areas of higher side view chips. This fact contributes down milling process as well.

Combined work performed by resulting force while cutting a chip can be determined over integral in case of down and up milling

$$A_i = \int_0^{0,05} F_i(t) \cdot v_{zi}(t) \cdot dt$$

$$A_s = \int_0^{0,05} F_s(t) \cdot v_{zs}(t) \cdot dt \ .$$

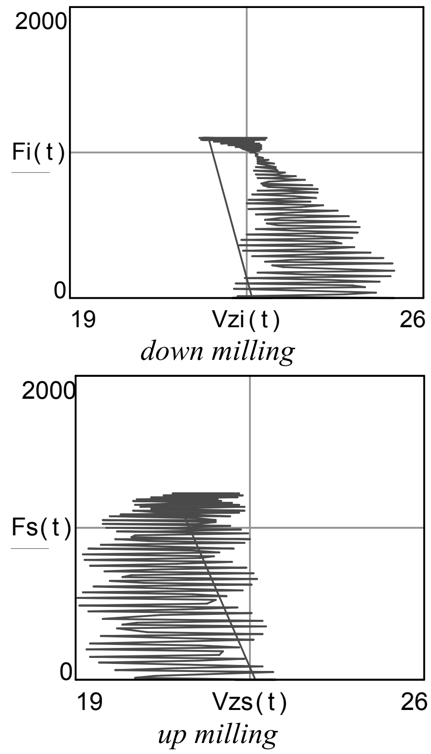


Figure 11. Diagram illustration of power used on cutting of a chip for down and up milling at angular speedΩ=125, 6 s^{-1} F_i (t) N; F_s (t) N; V_z (t) m/min

Cutting time of 0.05 second corresponds to one cutter rotation.

Magnitude of A_i and A_s obtained via corresponding computer software, for given processing conditions are:

A_i=3,324, J A_s=3,415, J

Figure 12 shows diagram illustration of power used for cutting a chip at far lower value of cutting resistance compared to previous example. Other conditions are completely identical.

Based on diagram (figure 12) it can be concluded that velocity magnitudes are approximately the same for both treatment processes, if the cutter load is small compared to its rigidness. Calculated magnitudes of work in these conditions are:

$\boldsymbol{A_i}$=0,328, J i $\boldsymbol{A_s}$=0,365, J.

From the aspect of resulting cutting force of works in large number of analyzed cases the advantage is given to down milling process. Differences of these works depend on conditions under which processing treatment is carried out and usually it is in time interval from two to ten percent.

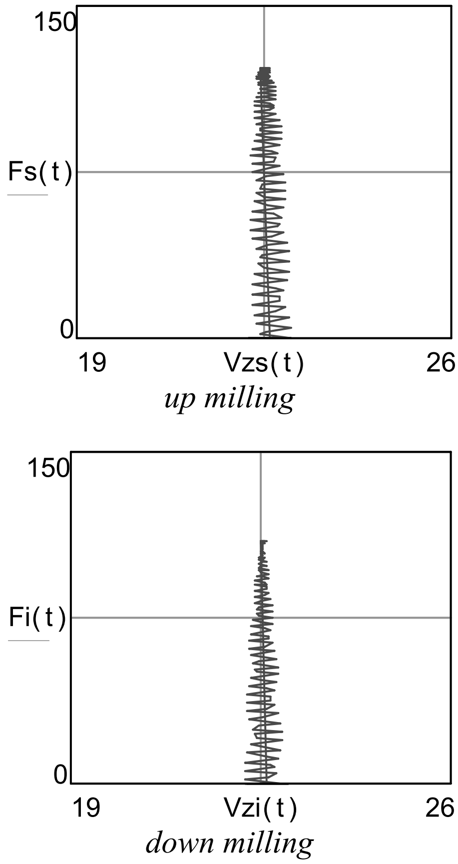


Figure 12. Diagram illustration of power used for cutting a chip for down and up milling at maximum load F_{omax}=100, N

4. CONCLUSIONS

Based on the performed analysis it can be concluded:

1. From theoretical aspect, in kinematics sense, up milling process provides lower roughness values, in other words, better processed area quality. However, for large number of analyzed cases, in practices, differences in theoretical height of roughness are irrelevant and realistically it cannot be talked about advantages of up milling compared to down milling from the aspect of kinematics treatment process.
2. Down milling treatment process, from dynamic aspect shows certain advantages. According to author's opinion, one of the basic reasons for better quality of processed area for down milling compared to up milling is optimal tool oscillation character for down milling, which is demonstrated via real cutting velocity values and energy spent in treatment process. Namely, real cutting velocity values, considering tool oscillation, are higher for down milling compared to up milling regardless the milling process simulation being carried out for identical main and auxiliary velocity, for both processes. Magnitude of works consumed for cutting a chip are lower up to ten percent for down milling as well, in the same timeframe simulation for loads for both processes
3. Theoretical modelling treatment has not taken into consideration transmitter oscillation for auxiliary movement which is according literary resources, and in the contex of the previous discussion, a factor impacting processed area quality.

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