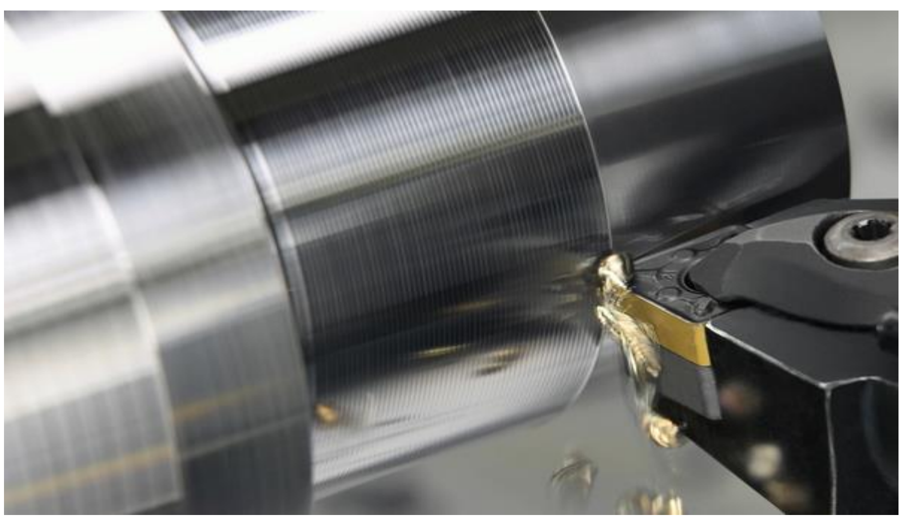
TDK THESIS

RECONSTRUCTION OF SURFACE ROUGHNESS IN TURNING PROCESS



MTA-BME Lendület Machine Tool Vibration Research Group

Department of Applied Mechanics

Consultant: Dr. Dombóvári Zoltán

Done by: Nahid Salayev

Contents

Introduction

Nowadays, it is undeniable that machining is one of the most important technologies of manufacturing operations. It is impossible to imagine the current industry without machining operations.

Turning is one of the forms of machining, material removal process, in which cutting tool describes a helix toolpath given by the feed and cuts away unwanted material while the workpiece rotates. This process is one of the widely used metal cutting operations in industry. In most cases machining the parts gives a final shape to them, which means the quality of the products are based on these cutting operations.

There is a vital role of surface roughness in determining how the real machined object will interact with its environment. Surface roughness is a major indication of product quality which is considered as one of the most specified customer requirements for machined parts. Due to the high demand for quality products, currently, manufacturers face a difficult problem of increasing productivity without compromising quality.

Regardless their wide use in entire world industry, such machining operations as turning, milling and drilling still have unresolved problems. Thus, they influence the quality demands of the product. This project deals with the problem occurring during the turning process that decreases the quality of the product and does not meet the requirements of customers.

Approach to the problem

The surface profile of a machined part changes based on dynamic conditions, tool geometry, workpiece material and other factors as tool wear, vibrations, machine dynamics and cooling fluid.

On one hand, machine vibration has been an issue to overcome for manufacturers which has not been fully recognized yet. As the industry has grown, the demand for precision increased as well as the speed of the process. New problems have arisen with the advancement of technology, such as tool vibration. The consequences of vibration, beyond manufacturing, can damage the tool of machine or even the machine itself.

On the other hand, cutting parameters of the process such as cutting speed, feed rate, depth of cut, nose radius and boundary conditions of the workpiece will be taken into account. The aim of this research to investigate the possibility of surface profile prediction. As the fact is that surface profile is usually obtained after the machining operation, it takes a significant role in avoiding of a waste of machined workpiece due to unsuitable cutting parameters.

Hence, the algorithm created will be more efficient for manufacturers and it will be more significant to predict surface profile before machining operation rather than obtaining after machining process.

The table shown below which provides with factors that affects the surface profile and roughness.

classificaton	factors affecting surface profile and roughness
cutting parameters	feed rate, cutting speed, depth of cut, process kinematics
tool properties	tool wear, tool nose radius, tool shape
workpiece properties	workpiece diameter, length, defect in material
machining equipment	chatter, vibrations, noise, cutting forces
machining environment	cooling fluid, friction in cutting zone, temperature

Table 1. *Factors affecting surface profile and roughness*

Here, all factors affecting surface finish quality are listed as in **Table 1**.

Comparing with many referenced works that take into the consideration the dynamic behavior of machining process and aggregate in process features (such as vibration, cutting force, tool wear, etc. measured during or after the process) into surface quality prediction, my research hopes to investigate the possibility of surface profile prediction (pre-evaluation) and preview using some input parameters such as cutting speed, feed velocity, depth of cut and nose radius.

Geometry of turning process

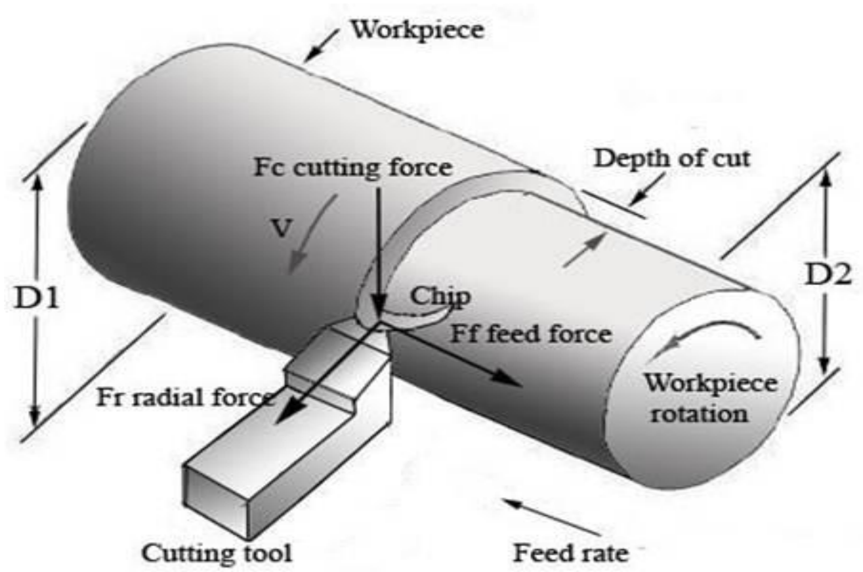


Figure 1.illustrates the geometry of turning process, where the cutting parameters, feed velocity V_f, cutting speed V_c, The frequency n, the rotational frequency Ω, depth of cut d, are shown. [8]

Clearly, the process of turning operation taking place as following: while the workpiece is rotating along its own axis, the tool edge with rounded insert in turning process is cutting unwanted material and describes a helix pattern on workpiece.

The pattern created by tool edge geometry can be seen after the operation.

The input data before the start of machining operation is the rotational frequency Ω, the feed velocity V_f, feed f, the depth of cut d, and the nose radius of tool r

- As the first step, the dependence function of an angle of rotation φ on the length of the workpiece L has been determined.

To express an angle of rotation φ, the spindle speed n that obtained from rotational frequency Ω (given as an input data) is needed.

Cutting speed V_c of the tool during the machining a cylindrical part with diameter D and spindle speed n, is following:

$$V_c = \pi D n, \tag{1}$$

while the constant feed velocity V_f is obtained as next:

$$V_f = \frac{L}{\triangle t} \tag{2}$$

, where L is the workpiece length and $\triangle t$ is the time duration of the process.

Hence, the relation of an angle of rotation (φ) with machined workpiece length the angle of rotation can be described as:

$$\varphi = \Omega\, t \;\; , \;\; z = V_f\, t \tag{3}$$

It is apparent that there exists a linear proportionality between angle of rotation φ and the axial displacement z, which can be given for each period of time while the workpiece is rotating, as the length of workpiece L, the diameter D and π value are constant values.

Far from the reality as the motion is vibration-free, yet. The lines showing the dependence of an angle of rotation on the length of the workpiece, further will occur on the surface profile. The generated lines, so-called feed lines, are illustrated in the following figure.

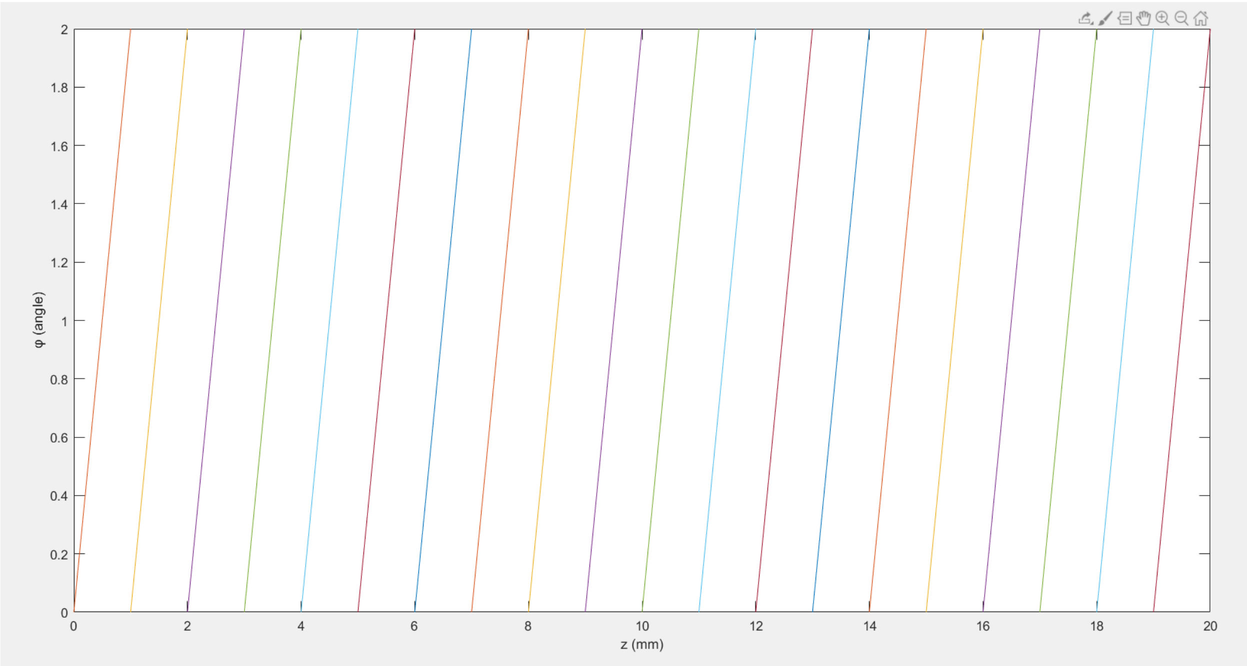


Figure 2. Feed lines, illustrates the obtained dependence of an angle of rotation on the length of turned part.

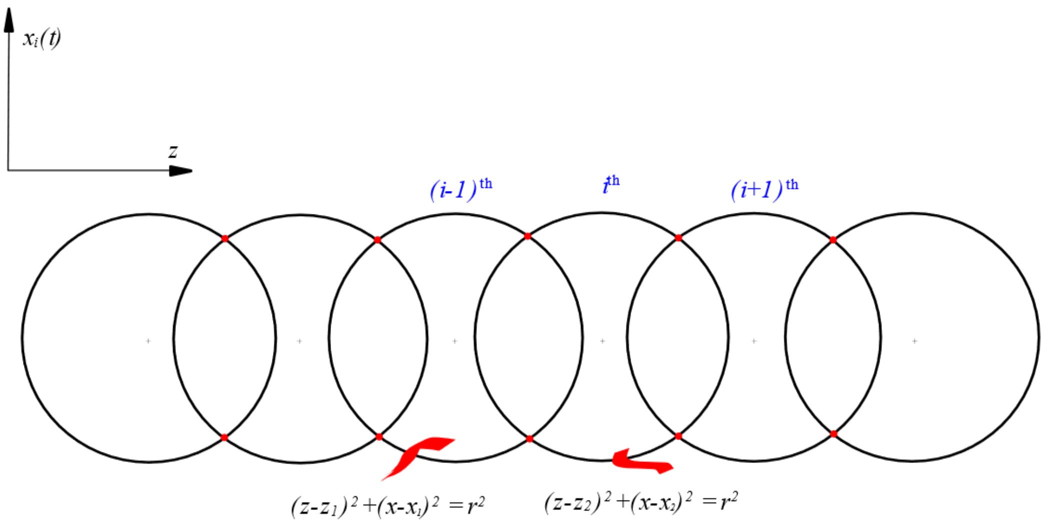
Considering the more or less linear motion of the tool with nose radius r, the graph shows the path of machine tool with cylindrical geometry.

Surface generation

In this chapter the surface generation of the workpiece material is discussed. It is obvious that the pattern implemented by tool of machine is made by circles, since the edge geometry of the tool has circular insert. Hence, the lines, shown in an aforementioned Figure 2**,** left by the edge of tool is actually made by intersection points of circles.

1. Intersection of circular edge geometry.

- As the next step, the intersection points marked with red dotes in *Figure 3* of the circles must be determined and the minimum values of '*x*' coordinate must be taken into consideration due the maximum values are not taking a role on surface.



The Figure 3. illustrates the path generated by circular tool geometry with nose radius r in (*z*, *x*) *coordinate system. The index i denotes the circle of corresponding time period* t_i.

As shown in the *Figure 3*, from the basics of mathematics, we know that the equations of circles with same radiuses r and with center points at (z_1, x_1) and (z_2, x_2), respectively, are described as:

$$\begin{aligned}(z-z_1)^2+(x-x_1)^2 &= r^2,\\ (z-z_2)^2+(x-x_2)^2 &= r^2.\end{aligned} \tag{4}$$

Since the machine tool edge is identical, the radiuses of circles are equal. Thus, to equalize the equations of circles leads us to obtain the intersection points of circles in (*z*, *x*) coordinate system. As we have many circles the obtained values of '*z*' and '*x*' create a matrix. After simplification, parametric equations are given as following:

$$\begin{aligned} z_{i\pm} &= \frac{z1+z2}{2} \pm \frac{(x1-x2)\sqrt{((x1-x2)^2+(z1-z2)^2)(-4r^2+(x1-x2)^2+(z1-z2)^2)}}{2((x1-x2)^2+(z1-z2)^2)},\\ x_{i\pm} &= \frac{(x1+x2)((x1-x2)^2+(z1-z2)^2)\pm(z2-z1)\sqrt{-((x1-x2)^2+(z1-z2)^2)(-4r^2+((x1-x2)^2+(z1-z2)^2))}}{2((x1-x2)^2+(z1-z2)^2)}.\end{aligned} \tag{5}$$

We have set of points $(z_{i\pm}, x_{i\pm})$ obtained from intersection of circles, which are the path left by circular tool geometry. These points are creating $[z_{i1}\ z_{i2}]_{2\text{xNr}}$ and $[x_{i1}\ x_{i2}]_{2\text{xNr}}$ matrices, respectively. Hence, the minimum values of 'x_i' coordinates of intersection points are needed to be derived from

$[x_{i1}\ x_{i2}]_{2xNr}$ matrix due corresponding arcs (a_i), which merge them, are making the surface of workpiece. Moreover, regardless the complex solutions, the real solutions must be selected.

Considering that the tool of machine is moving along 'z' direction with constant feed f in (z, x) coordinate plane, where 'i_r' is the rotation index. The motion can be described as:

$$z_i = i_r f, \tag{6}$$

while the radial motion of the tool with amplitude of motion A, vibration frequency ω and time duration t_i of i^{th} edge can be described as following:

$$x_i(t) = A \sin(\omega t_i)\ . \tag{7}$$

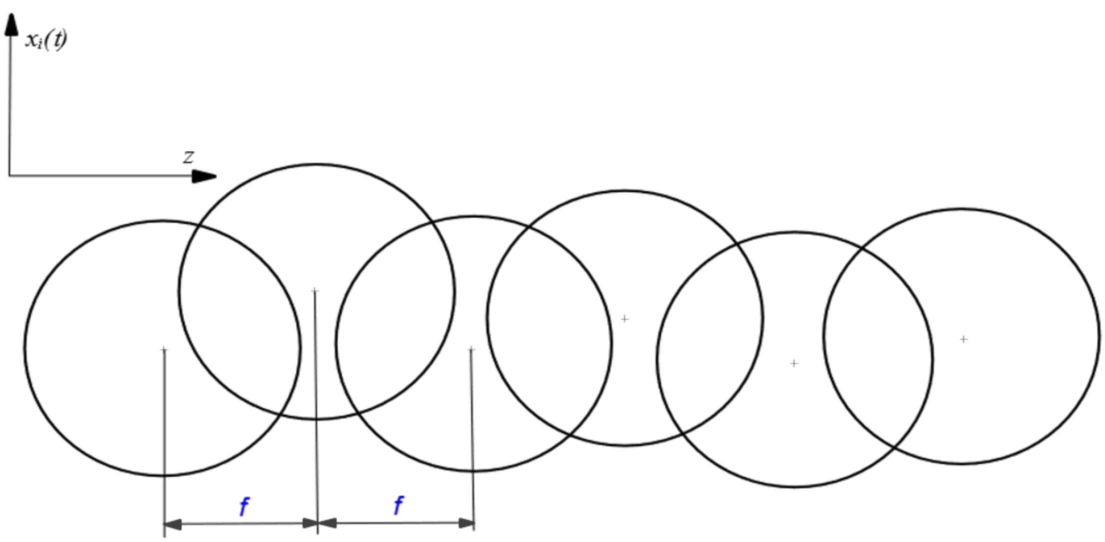
It is apparent that the equation of radial motion is time-periodic in the sense $t_i = T(i-1)$, where the period $T = \frac{2\pi}{\Omega}$.

Accordingly, substituting T into the equation of motion, we get:

$$x_i(t) = A \sin(\omega t_i) = A \sin(2\pi \frac{\omega}{\Omega}(i-1)). \tag{8}$$

Obviously, the radial motion of the tool based on the input data of rotational frequency (Ω) assigned before the process and the index of the happening circle at that time period.

As the tool of machine oscillates along 'x' direction of coordinate system making a radial motion, the circles generated by tool edge will look as shown in the following *sketch 1:*



Sketch 1. The exaggerated vibration on the idealized circle edges.

Each of circles left by tool edge have past intersection with the circle occurred one period earlier and future intersection with circle occurred one period later. All of these intersection points must be evaluated (details discussed further). The corresponding arcs which merge the past and future intersections of are making surface. Thus, these arcs must be estimated.

From the background of geometry, all arcs are evaluated according to corresponding angles between radiuses which connect the center of circle with its past backward and future forward intersections, respectively.

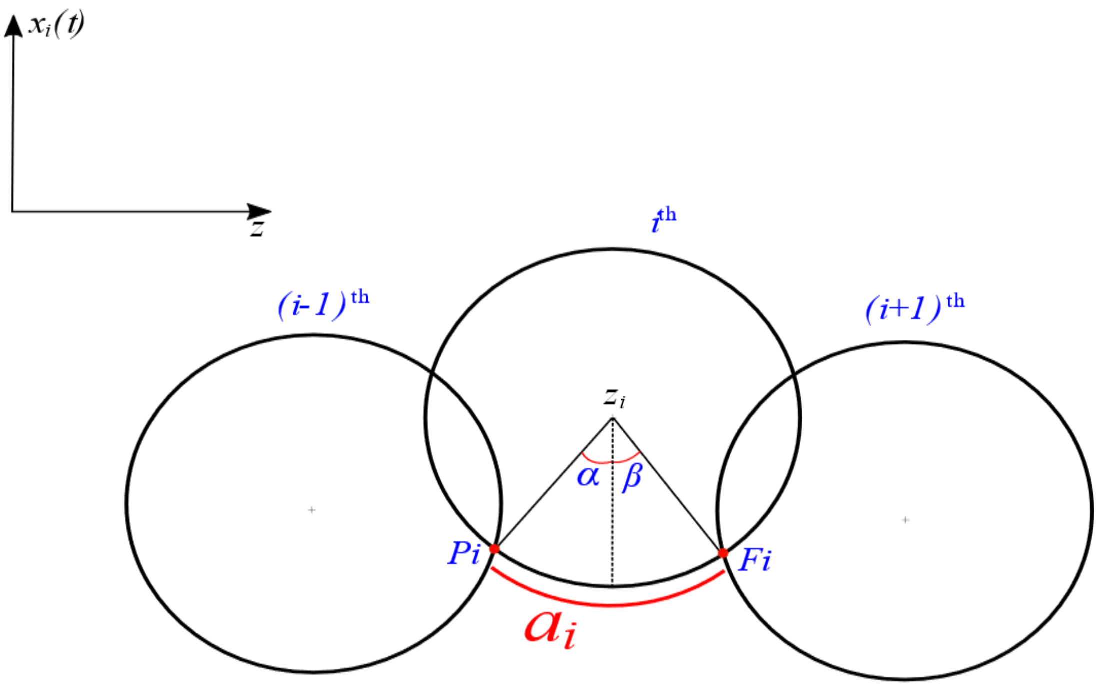


Figure 4. illustrates the arc which is pattern left by tool that makes the surface merging the past backward intersection of circles 'i' with 'i–1' and future forward intersection with 'i+1'.

Approaches to evaluate the arcs are needed to be introduced, since we use the entry and exit angles divided into infinite parts which are involved into matrices to be calculated.

The corresponding arcs which merge the forward F_{iz} and past P_{iz} intersections in 'z' direction described as:

$$a_i = F_{iz} – P_{iz}. \tag{9}$$

and can be obtained from entrance angle α and exit angle β whose sum are creating an angle θ corresponding to required arc, as following:

$$\tan \alpha_i = \frac{z_i - P_{iz}}{x_i - P_{iz}}, \quad \tan \beta_i = \frac{F_{iz} - z_i}{x_i - F_{iz}}, \tag{10}$$

where $\theta \in [\frac{3\pi}{2} - \alpha_i; \frac{3\pi}{2} - \beta_i]$.

The evaluation of arcs a_i is vital and leads us to predict the surface made by them.

1. Conditions of evaluated arcs.

There are 3 conditions to be taken into consideration, occurred after the evaluation of arcs. These cases based on the values obtained from corresponding arcs a_i merging the intersection points. Acquired results have to be checked during implementation

The tool of machine making following cuts on the workpiece:

- pure cutting,
- fly-over effect,
- partial cutting.

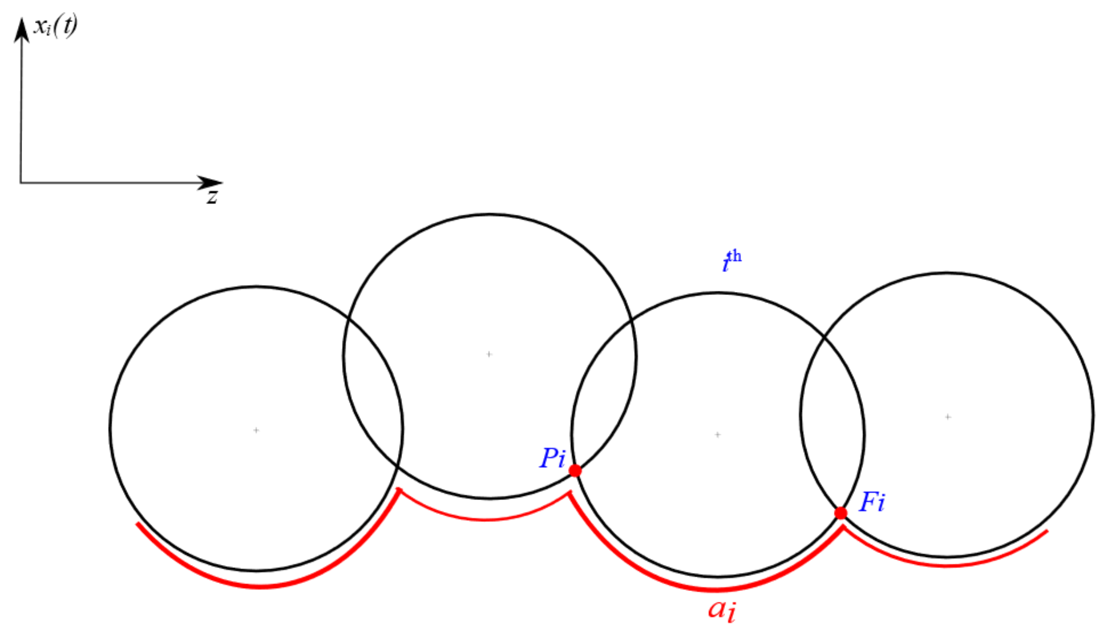
All cases were discussed due making a better prediction of surface roughness before the process.

2.1 Pure cutting

The condition for pure cut requires the corresponding arc to be:

$$a_i > 0,$$

which means that the difference between future forward intersection point of i^{th} with $(i+1)^{th}$ circles and past backward intersection point of i^{th} with $(i-1)^{th}$ circles must be greater than zero. Thus, all the arcs left by edge of tool at any period of time take a place in surface cutting and make the surface. This is the ideal case of all considered conditions.



The Figure 5 illustrates the pure cutting condition during the turning process.

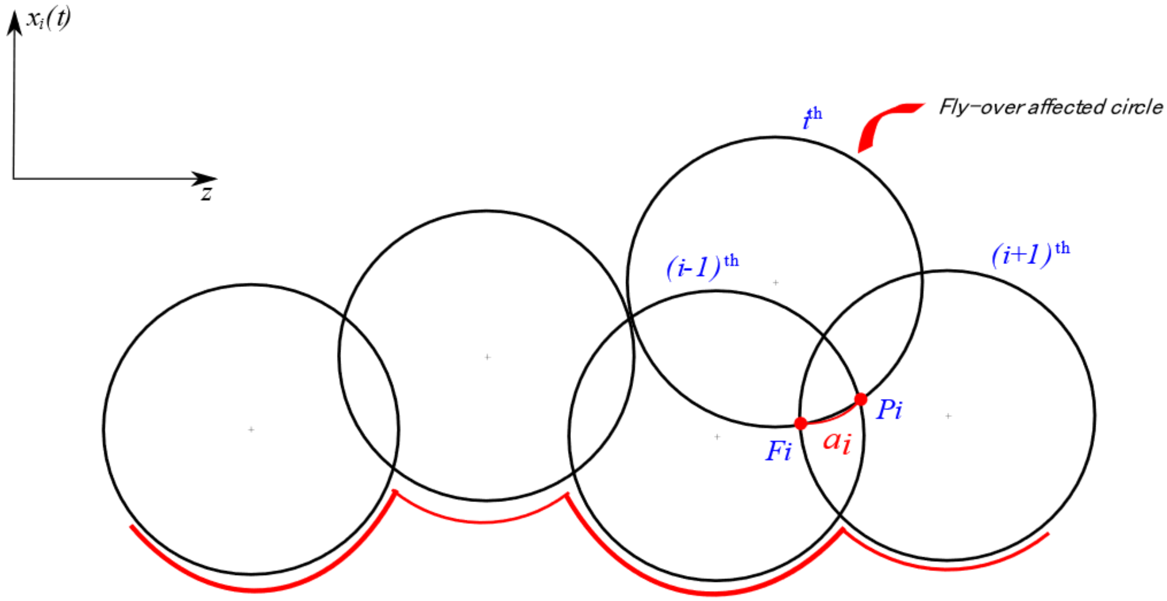
2.2 Condition for fly-over

As the tool of machine is vibrating, these oscillations cause difficulties and big problems, which manufacturers still face.

The algorithm created for this project has taken the condition of fly-over into account to discard it in the final result. The simulation can be done even for high amplitudes which may result high vibrations.

When the fly-over occurs during the process, the tool leaves the workpiece surface and remains on it a missed-cut. This leads the problem to be more complicated.

So, the corresponding circle of this period of time is not taking a role of making surface. Thus, this means the surface to be cut formed by circle another circle which is discussed next.



The Figure 6 shows the missed cut occurred by fly-over effect during the turning process.

As you can see in the *Figure 7*, the past intersection of i^{th} and $(i-1)^{th}$ circles happens one step ahead than the future intersection of i^{th} and $(i+1)^{th}$ circles. Thus, during the turning process, the i^{th} circle left the surface and remained a missed cut on it, which means it did not make a surface at all. Obviously, the surface made by circle passed through one period earlier.

Hence, there is a condition occurs for fly-over effect as following:

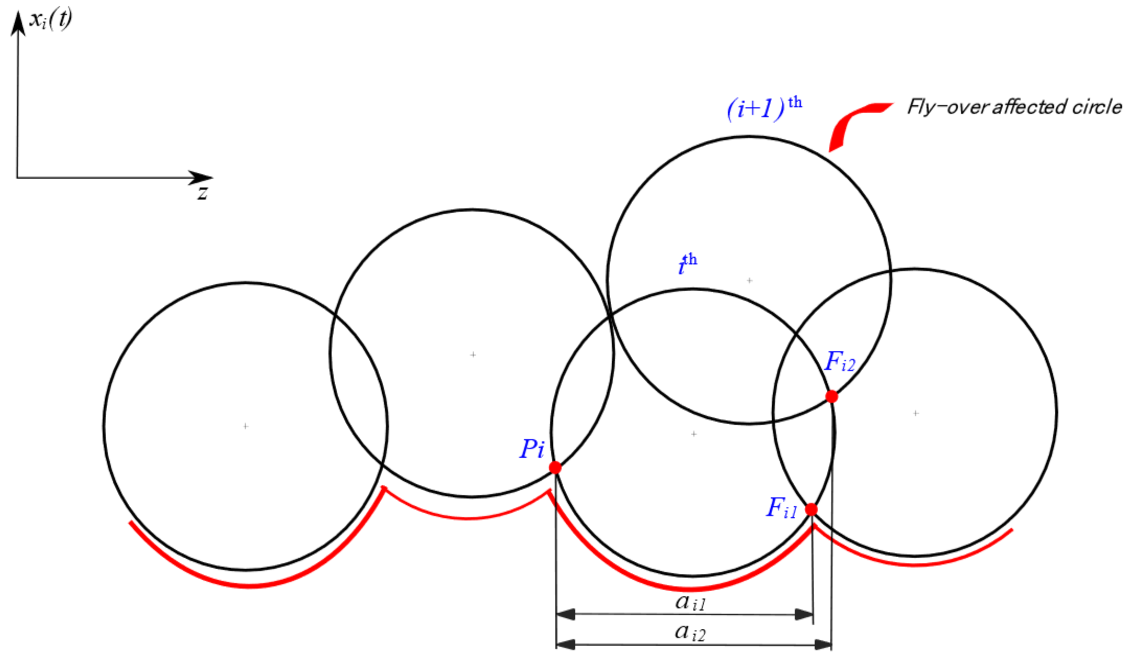
$$a_i = F_i - P_i < 0, \text{ where}$$

F_i is the future forward intersection, and P_i is the past backward intersections.

All arcs less than zero, which are not effective to make the surface must be discarded for further evaluations and simulations.

2.3 Partial cutting

The next condition of cut occurred during the operation is when the tool edge is cutting the material surface partially.



The Figure 7 illustrates the partial cut happened during the process.

Partial cut appears when the intersection of circles 'i' and 'i+2' take place before the future forward intersection of circles 'i' and 'i+1'. So, the corresponding arcs are a_{i2} and a_{i1}, respectively. Basically, for this condition the fly-over effect needs to be occurred.

As you can see in the Figure the circle 'i' with respective arc a_{i2} made the partial cut workpiece surface.

The condition for partial cut is following:

$$a_e > 0.$$

2. Effective surface

Hence, after analyzing the conditions occurred since we obtain the values of a_i arcs, the effective arcs must be evaluated for prediction the surface roughness before the process starts.

The realized arc is:

$$a_i = \min_{l,p=-N_p}^{N_p} a_{i,(l,p)}\ , \tag{11}$$

where the $N_p = \frac{2r}{f}$ is the furthest circle index that actually can have intersection.

The effective arc a_e of surface of workpiece is obtained:

$$a_{i,(l,p)} = F_{i+l} - P_{i+p}, \text{ where} \tag{12}$$

$$p,l \in [-N_{ip}, N_{ip}]$$

Hence,

$$a_i = a_e > 0.$$

These arcs are called effective arcs and, actually, they are taking a role of making the surface discarding the fly-over effect (a_i<0).

Results

Consequently, it is clear that the proposed approach would give a reasonably accurate prediction on surface profile. The algorithm created will give efficient results for profile and surface pre-evaluation.

Here are the results acquired after creating an algorithm for prediction of surface roughness and profile considering the vibration of the tool. The training and simulation were conducted using MATLAB. The data obtained from turning process comprised as next:

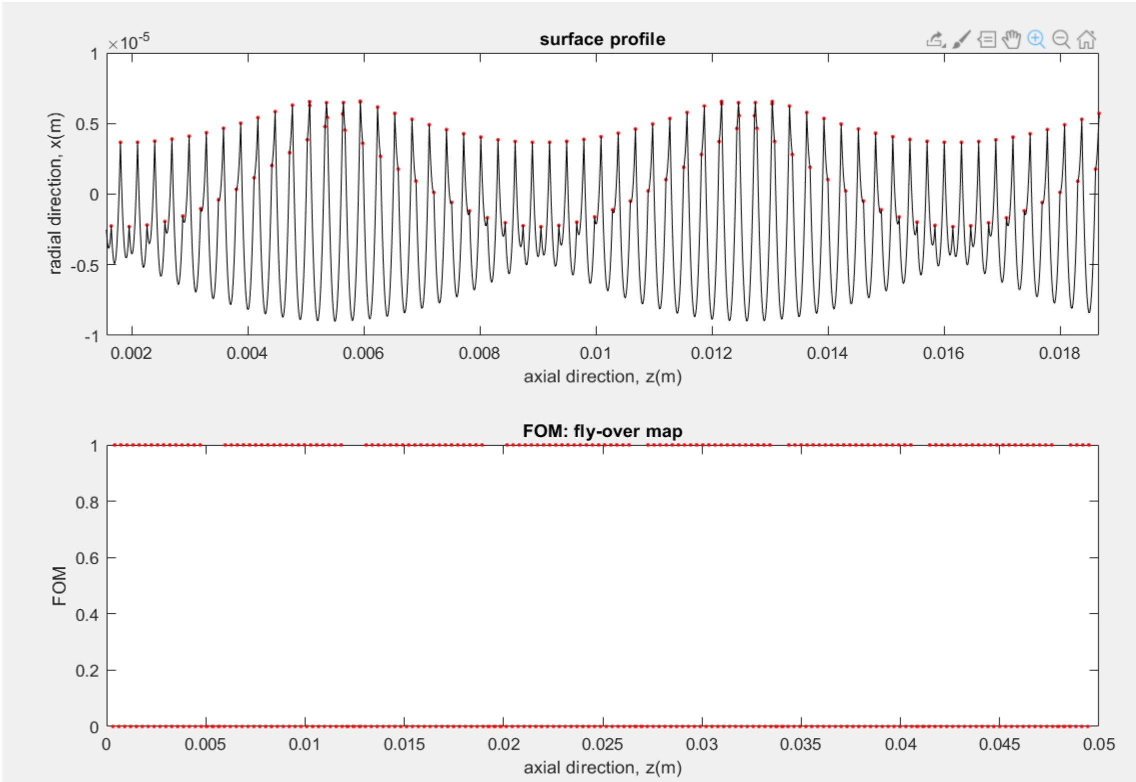
a) Profile

For pre-evaluation of the surface profile the fly-over effected arcs must be discarded.

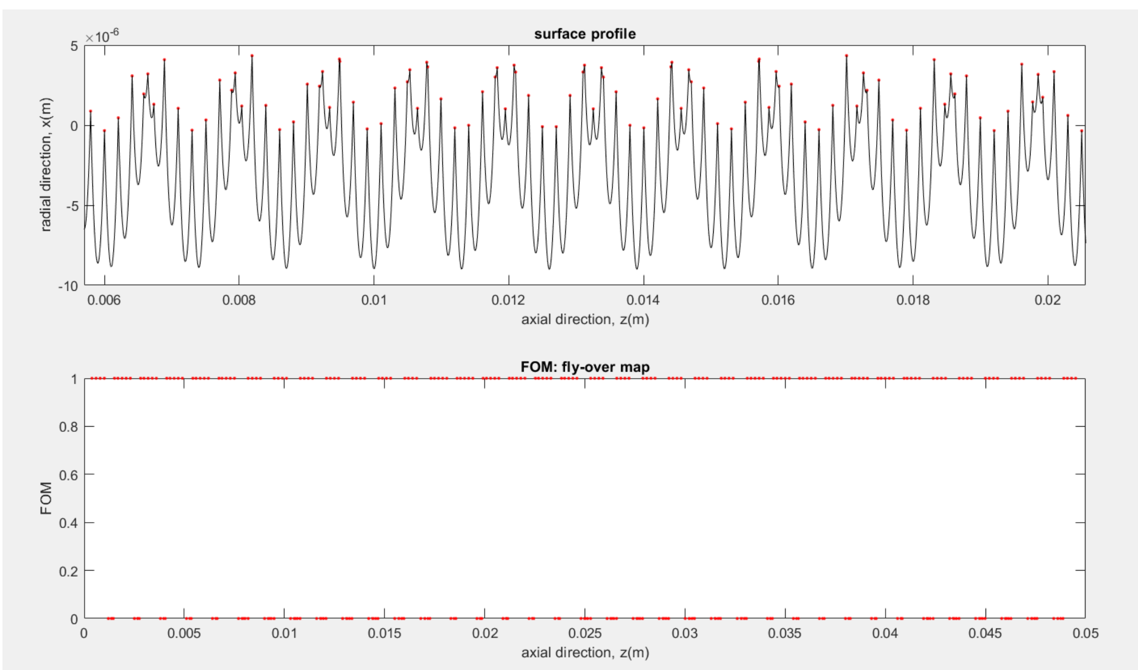
The simulation was proposed for small amplitude of motion and relatively big amplitude, respectively.

To obtain an appropriate surface profile, proper machining parameters were selected. The resulting vibrations were significantly reduced, as the arcs affected by fly-over were deducted as shown in FOM.

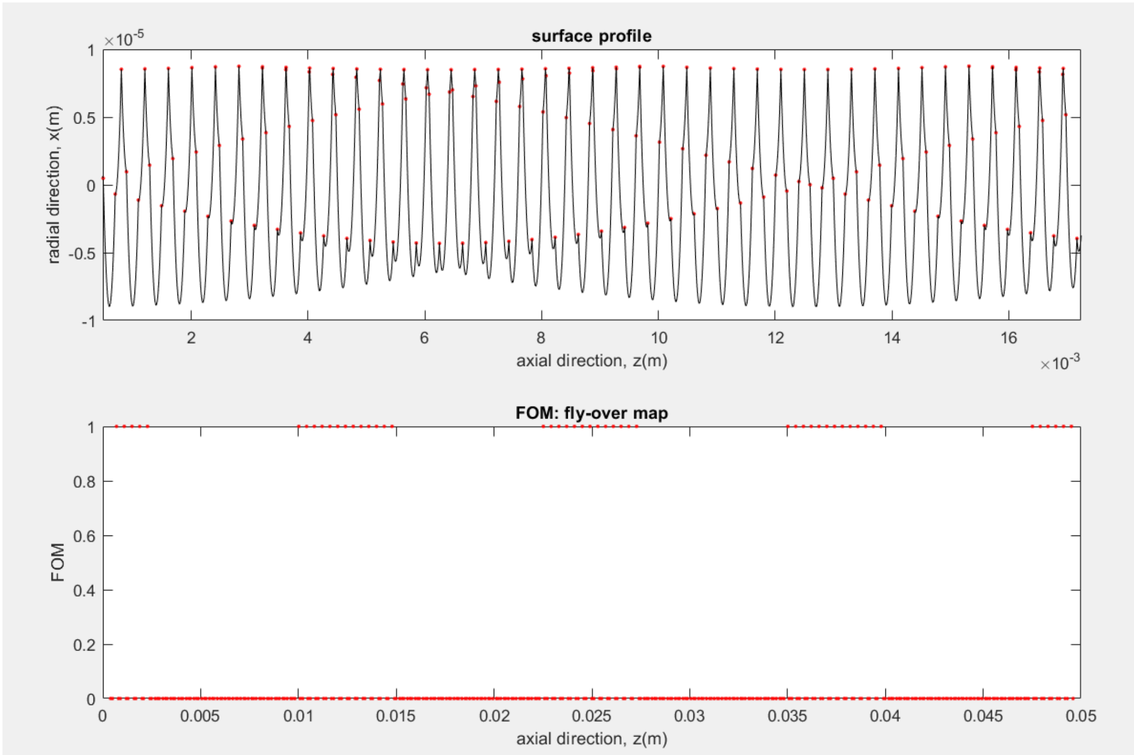
The Figure 8 illustrates the surface profile and the FOM (Fly-Over Map).



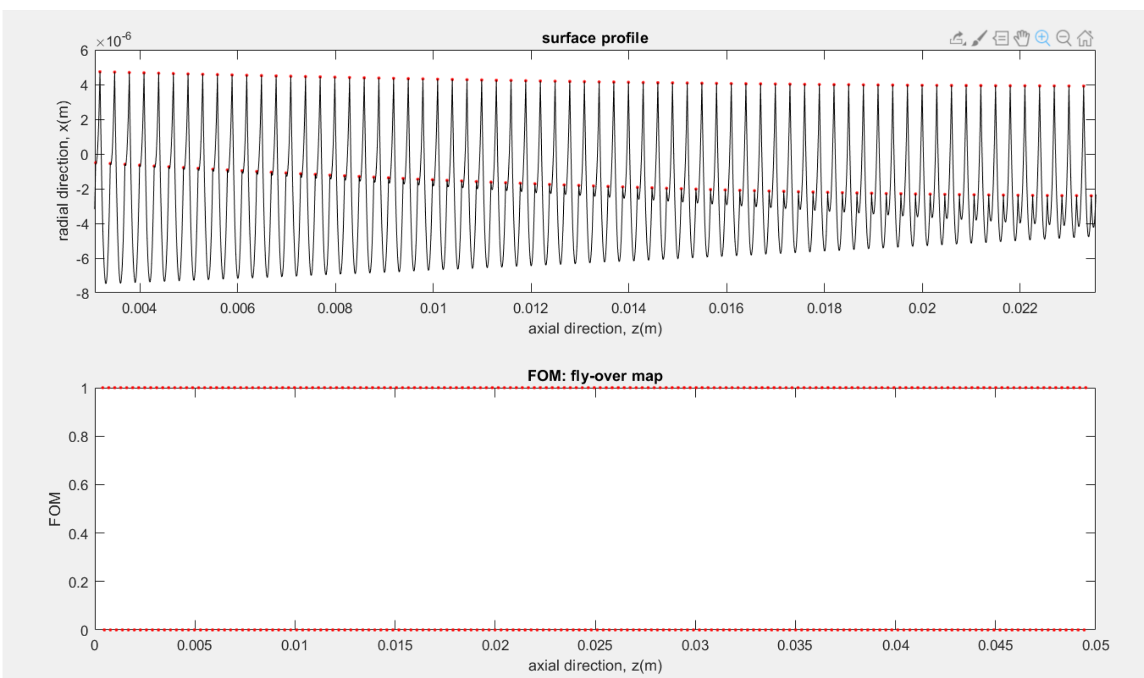
a) The data: A_{max} = 9µm, $\omega = 210\frac{\text{rad}}{\text{s}}$.



b) The data: A_{max} = 9µm, $\omega = 90\frac{\text{rad}}{\text{s}}$.

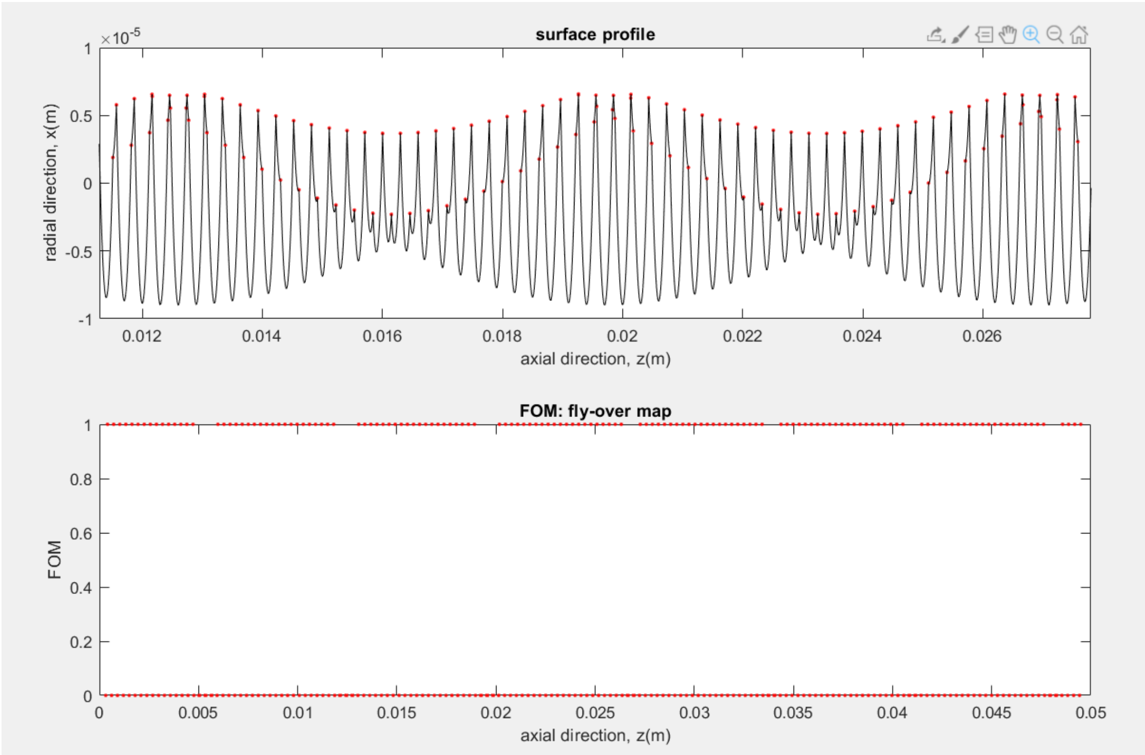


c) The data: $A_{\max} = 9\mu m$, $\omega = 240 \frac{\text{rad}}{\text{s}}$.

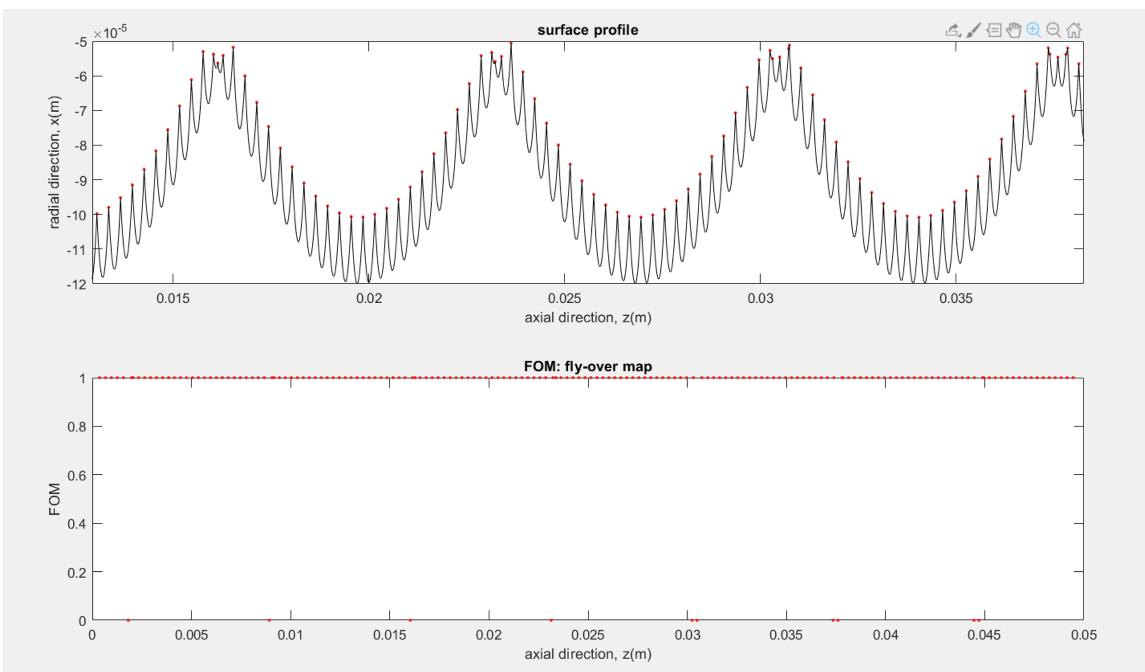


d) The data: $A_{\max} = 9\mu m$, $\omega = 150 \frac{\text{rad}}{\text{s}}$.

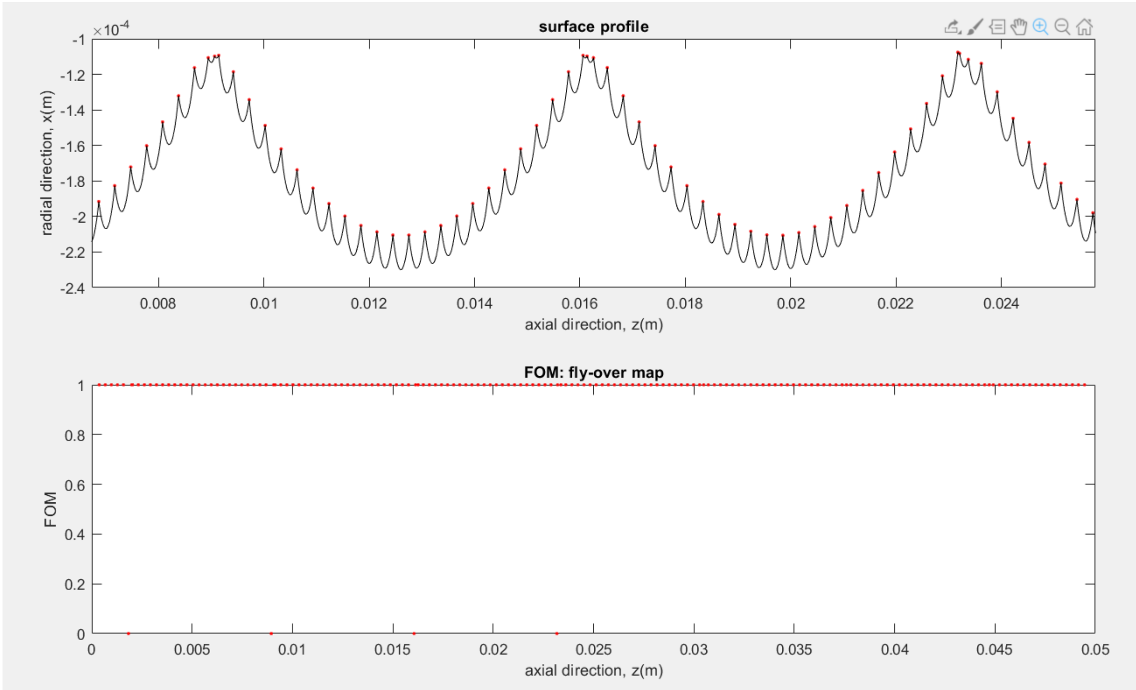
Figure 9 illustrates the simulation done for the process with constant amplitude while the frequency was changing.



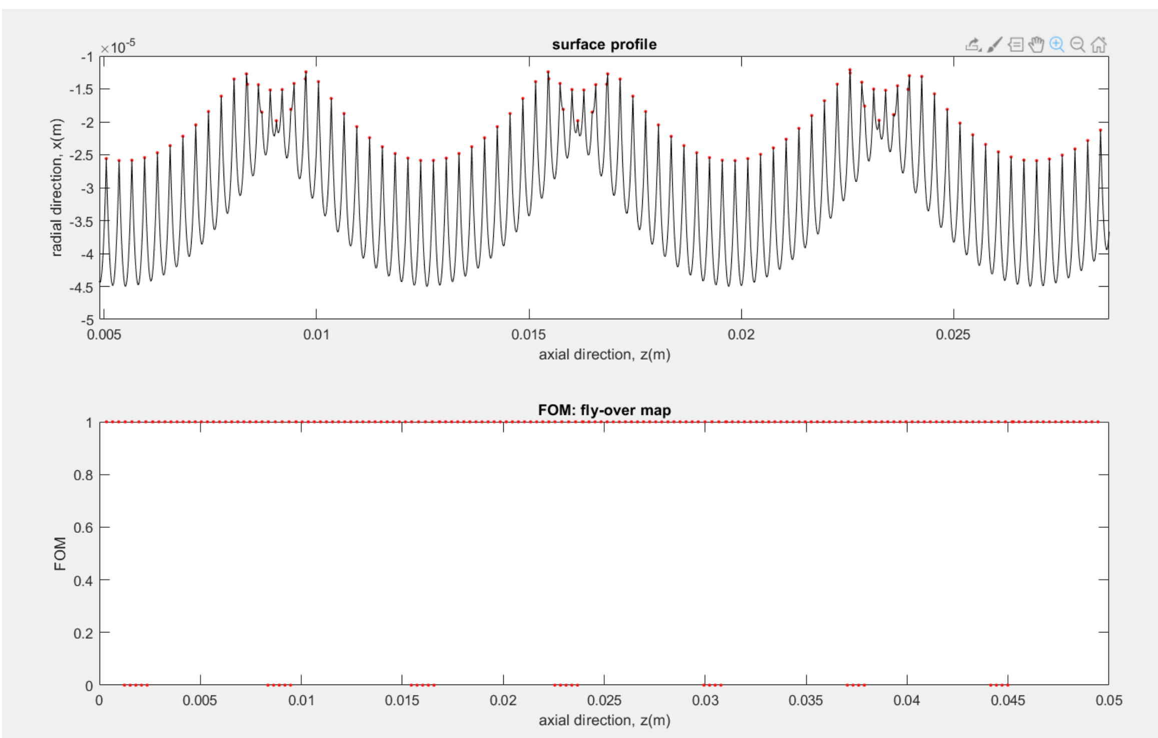
a) The data: A_{max}=90μm, $\omega = 240\,\frac{\text{rad}}{\text{s}}$.



b) The data: A_{max}=500μm, $\omega = 240\,\frac{\text{rad}}{\text{s}}$.



c) The data: $A_{\max}$=230μm, $\omega = 240\,\frac{\mathrm{rad}}{\mathrm{s}}$.



d) The data: $A_{\max}$=45μm, $\omega = 240\,\frac{\mathrm{rad}}{\mathrm{s}}$.

Figure 10 illustrates the simulation done for the process with constant frequency while the amplitude of motion was changing.

In this case, the simulation has been done for the constant frequency while the amplitude of motion was changing.

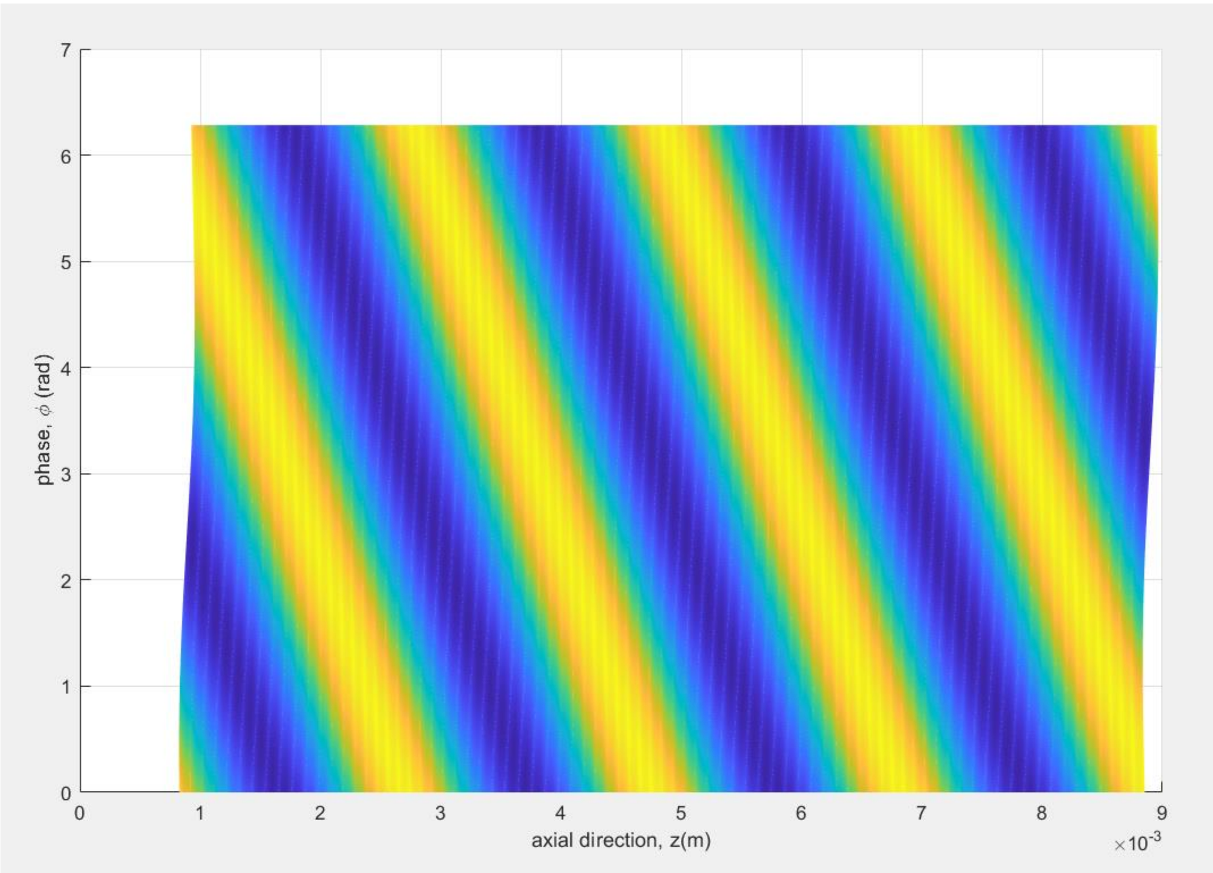
Apparently, it can be noticed that in case when tool is in radial motion with relatively bigger amplitude causes more fly-over effects on the process. Discarding FO effected arcs, effective ones making the surface shown in the figure.

The consideration of actual tool geometry with nose radius (r) is used in a simulation system to achieve the agreement with experimental results.

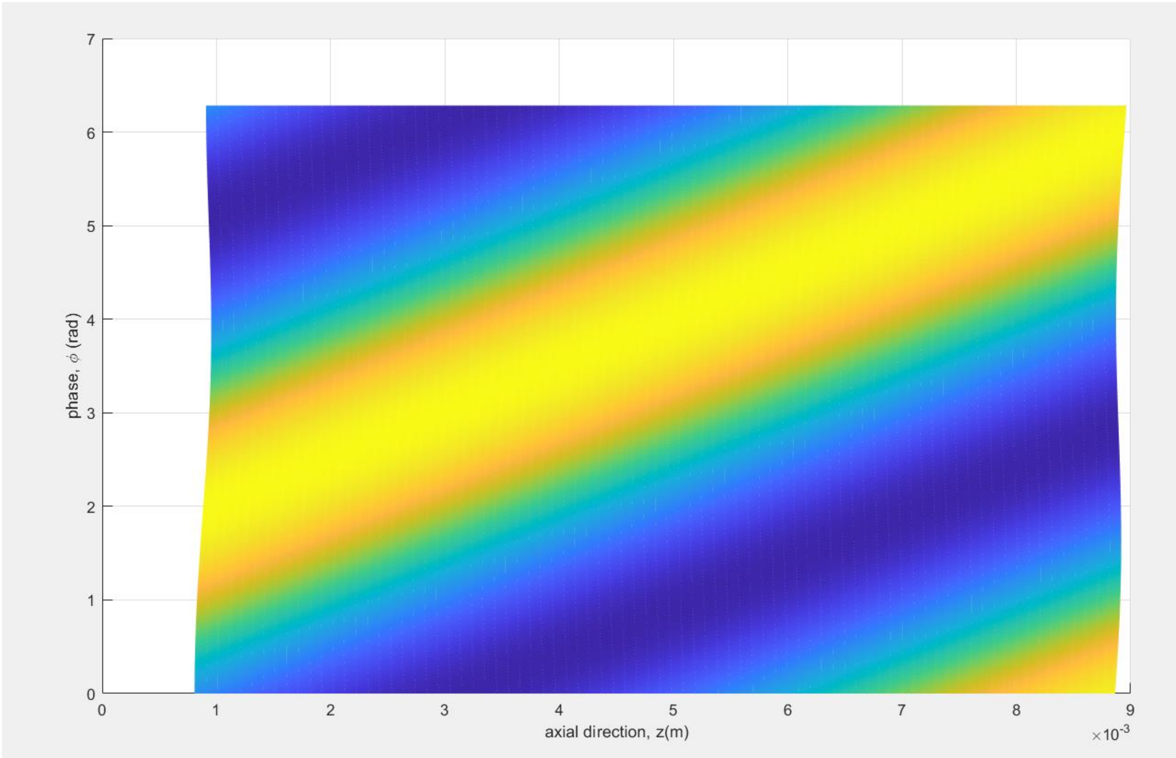
b) Surface

The simulation for pre-evaluation(prediction) of surface finish of workpiece in turning process illustrated in the Figure. The path of the tool edge with rounded insert is visible on the surface.

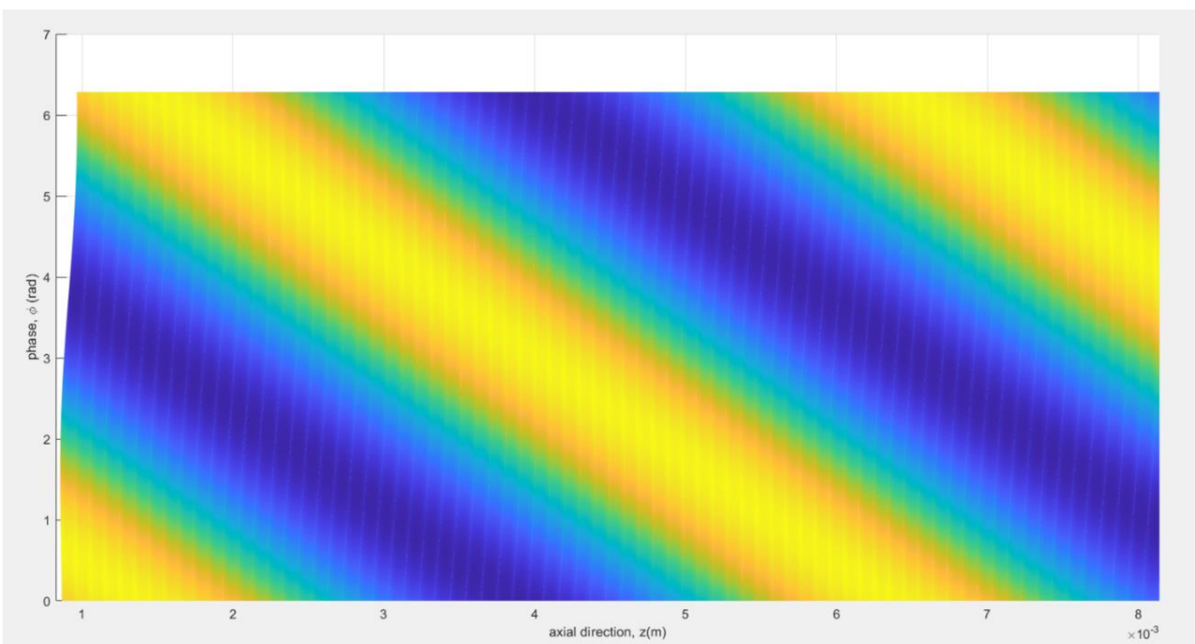
The graph dependence function of an angle of rotation φ on the length of workpiece material L has been simulated.



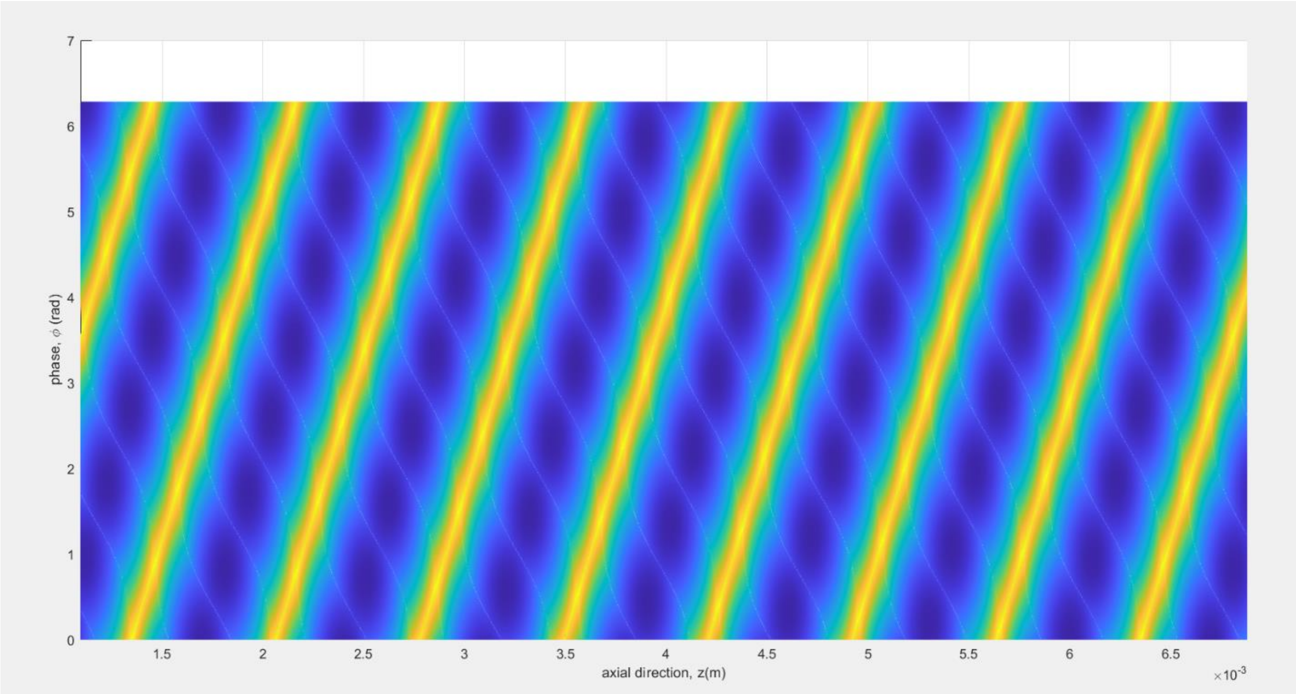
a) The data: A_{max}=20μm, $\omega=15\frac{\text{rad}}{\text{s}}$



b) The data: $A_{\max}$=150μm, ω=300$\frac{\mathrm{rad}}{\mathrm{s}}$



c) The data: A_{max}=70μm, ω=6$\frac{rad}{s}$



d) The data: A_{max}=105μm, ω=270$\frac{rad}{s}$

Figure 11 Illustrates the surface of workpiece material.

The waviness of surface profile can be observed from the figure which interpret the simulated sample characteristics. Moreover, the pattern left by tool is visible in the image. Comparisons between analysis and measurements of 3D surface topography for various parameters assess the proposed simulation.

An efficient algorithm leads to predict the surface finish before the process and provides with to obtain better roughness rather using other (traditional) indirect methods.

Obtained results show that the topography through simulation is quite satisfactory from engineering point of view.

Conclusion

To sum it up, as the technology industry is developing day by day all over the world. My project deals with one of the problems arisen with the advancement of the technology. With my work, not only the customers will meet their expectations for the quality of machining product, but also the machine tool, even the machine itself will be protected what many companies currently face.

The main goal of this project is to create an efficient algorithm, which is able to predict the surface pattern for simple orthogonal turning process with rounded insert. The algorithm relies on the stationary motion of the turning tool and only investigates interactions at intersecting points of the edge geometry. Using this methodology part surface can be predicted even for large vibration amplitude when the edge actually leaves the surface and miss the cut.

The compiled surface then can be used in conventional ray-trace 3D environment, where the appropriate illumination, shading and material properties can be simulated properly. The analysis of parameters on surface topography through simulations should provide a very useful theoretical model linking feed rate, tool vibration, and other cutting conditions to the surface roughness.

References

1. Brown, C.A., Hansen, H.N., Jiang, X.J., Blateyron, F., Berglund, J., Senin, N., Bartkowiak, T., Dixon, B., Le Goïc, G., Quinsat, Y., Stemp, W.J., Thompson, M.K., Ungar, P.S., Zahouani, E. (2018). Multiscale analyses and characterizations of surface topographies. CIRP Annals, 67(2), 839–862. doi.org/10.1016/j.cirp.2018.06.001

2. Thomas, M., Beauchamp, Y, Youssef, A.Y., Masounave, J. (1996). Effect of tool vibrations on surface roughness during lathe dry turning process. Computers ind. Engng, 31(3/4), 637–644.doi.org/10.1016/S0360-8352(96)00235-5

3. Dombovari Z, Stepan G. 2015 On the bistable zone of milling processes.Phil. Trans. R. Soc. A 373: 20140409.http://dx.doi.org/10.1098/rsta.2014.0409

4. Altintas, Y.: Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design. Cambridge University Press, Cambridge. 2000

5. I. Claesson and L. H˚akansson. Adaptive active control of machine-tool vibration in a lathe. IJAV-International Journal of Acoustics and Vibration, 3(4), 1998. Invited.

6. P-O. H. Sturesson, L. H˚akansson, and I. Claesson. Identification of the statistical properties of the cutting tool vibration in a continuous turning operation - correlation to structural properties. Journal of Mechanical Systems and Signal Processing, Academic Press, 11(3), July 1997.

7. Mishra V., Khan G. S., Chattopadhyay K. D., Nand, K., Sarepaka, R. V. (2014): Effects of tool overhang on selection of machining parameters and surface finish during diamond turning. Measurement, 55, 353?361. doi:10.1016/j.measurement.2014.05.019

8. http://article.sciencepublishinggroup.com/html/10.11648.j.ijmea.20160403.12.html