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Dynamic instability of the hard turning process

J. Kopač [a,*], A. Stoić [b], M. Lucić [b]
[a] Faculty of Mechanical Engineering, University of Ljubljana,
Aškerčeva 6, 1000 Ljubljana, Slovenia
[b] Faculty of Mechanical Engineering, University of Osijek,
Trg I. B. Mažuranić 2, 35000 Slavonski Brod, Croatia
* Corresponding author: E-mail address: janez.kopac@fs.uni-lj.si

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ABSTRACT

Purpose: Purpose of this paper is consideration of dynamic behavior of the hard turning process. There are several indicators which could confirm assumption of turning instability (depth of cutting, high ratio of forces Fc/Fp, small tool nose radius, and non-uniform stress distribution over tool/workpiece contact). Lead edge angle and passive force Fp are strongly depend on depth of cutting in hard turning what additionally increase instability.
Design/methodology/approach: Numerical calculation and experimental tests have been done to evaluate the rate of cutting instability while using and comparing different process monitoring sensors, and acquisition techniques based on PC platform.
Findings: It was found that high chip thickness alteration occur because of cutting depth vary for a value of some 60 % and even more if Fp force signal is analyzing when machine tool has inadequate stiffness.
Research limitations/implications: Results and findings presented in this paper are qualitative and might be slightly different in other cutting condition (e.g. if wiper inserts are used). Also there are no experiences with coated workpieces or with workpiece material with low deformation energy.
Practical implications: Assuming that a hard turning is a semi finishing or finishing process, surface finish is of big relevance. Surface roughness is a consequence of both cutting instability and of tool/workpiece loading condition. Results of test indicates an optimal cutting depth for final pass when minimum surface roughness can be achieved what can be valuable for cutting regime determination. Furthermore, more effective use of the machine tool performances might be achieved.
Originality/value: Originality of the paper is in analysis of sources of turning instability (variable depth of cutting combined with side edge angle and tool nose radius) which lead primary to condition where Fp sensing data does not fit to the normal distribution and secondary to cyclic push-offs of the edge.
Keywords: Machining; Mechanical properties; Dynamic properties; Depth of cutting

1. Introduction

Hard turning is continuous process of chip removal according to the tool engagement and thermal loads, but also dynamic undertaking the uncut chip area and depth of cutting in particular.

In contour or outer diameter turning, workpiece geometric variations, and variations in depth of cut (DOC) as a result of prior pass scallops, feedrate, cutting velocity and effective lead angle, along the tool path produce large dynamic force variations, which induce variations in process stability. The evolution of hard turning process, where cylindrical parts are produced, is besides other, associated with the eccentricity of the workpieces, what might lead to self-exited vibration in any component of machine tool. Presence of that kind of vibration can lead to irregularity of machined shape as well as surface damage of machined workpiece. When hard turning process is applied, high precision in dimensions and shape of products is demanded. A lot of factors can affect precision and productivity of machining and one of the most affecting is self-exited vibration. On the other hand vibrations can lead to increased tool wearing and tool breakage as well. Large tool nose radius offer finer surface finish, but also increased specific cutting energy [1]. Nevertheless, circular runouts of spindle should keep low (i.e. for hydrostatic bearings it is set bellow 0,2 μm, and for magnetic bearing even smaller) .

In order to reduce or remove presence of self-exited vibration it is usual procedure to lower cutting width and cutting feed rate or tool geometry. These limitations implicate lower efficiency of machining process. Thereby, it is of great importance to become familiar with dynamic characteristics and to be able to determine at which working conditions and parameters vibrations will occur. If causes are known, and when they occur it is possible to maximize efficiency of machining process itself.

Turn-milling as an alternative process, which reach higher productive rate, still cannot overcome the appearance of vibrations as a result of process kinematics-variations in the chip-cross section, and especially by the entry-exit condition [2].

All the disturbances and instabilities are caused by deflections in machining system (machine-tool-workpiece) [3]. The sources can be one or more of the following [4]:

- machine tool parameters : feed drive instabilities and dynamic behavior of the machine tool
- tool parameters : geometrical variations caused with tool wear,
- workpiece parameters : geometrical deviations (diameter variations) , inhomogenities in workpiece material

It is very difficult to obtain unique separation of the disturbances on its causes but there exists solutions to separate causes e.g. tight and broad measuring signal spectrum.

2. Description of the approach and assumptions

Chip removal rate in hard turning process and appropriate uncut chip area is in the range of $A_c = a_p f - f\,(r_\varepsilon - ((r^2_\varepsilon - f^2/4)^{0,5}/2)$ = 5-60 μm. (a_p =0,05-0,3 mm; f=0,1-0,3 mm). The above model for uncut chip area is provided in terms of tool geometry and the true feed, after the first few revolutions. As shown in fig. 1 tool/workpiece contact is mostly within the tool nose radius.
Tool/workpiece contact is within tool nose radius if :

$$a_p \le r_\varepsilon(1-\cos\kappa_r) \quad (1)$$

For relatively deep cuts in which the depth of cut/ tool nose radius ratio is large (e.g higher than 5), the effective lead angle is approximately equal to the lead angle κ_r. Otherwise in finishing cuts (hard turning), effective lead angle is [5].

$$\tan\kappa_{re} = 0{,}5053 \tan\kappa_r + 1{,}0473\,(f/r_\varepsilon) + 0{,}4654\,(r_\varepsilon/a_p) \quad (2)$$

If variation of depth during cutting exists, effective lead angle will vary too, fig.2.

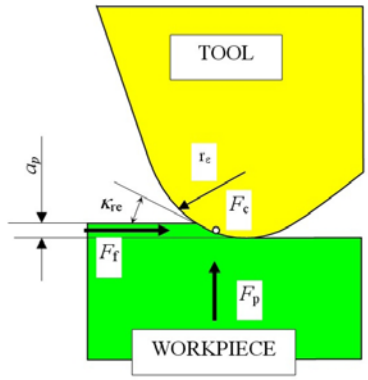

Fig.1. Schematic presentation of tool/workpiece contact geometry

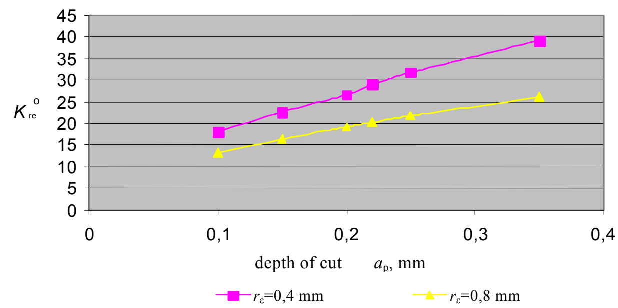

Fig.2. Influence of DOC on effective lead angle

Lowering the depth, lead angle will decrease and passive force should increase but also to decrease because of lower depth. This theoretic consideration is more complicated because of push-off effect derived by Brammertz [6] in terms of surface roughness. Surface roughness is therefore within R_t and R_{tB}.

$$R_{tB} = \frac{f^2}{8 \cdot r_\varepsilon} + \frac{h_{min}}{2}\left(1 + \frac{r_\varepsilon \cdot h_{min}}{2}\right) \quad (3)$$

where h_{min} is minimal chip thichness for push-off free cutting.

As a consequence of uncut chip thickness variation during turning process, which in turn depends on the previous cut profile, variation of cutting force as a result of a nearly subcritical instability in the amplitude versus width-of-cut plane [7]. Hua at all refere the effect of the finishing process on the subsurface residual stress profile related to cutting edge geometry [8].

3. Results of dynamic parameters and instability measurements

The dynamic behavior of the machine tool can be determined before the process (free runs of machines) and mostly can have periodic nature that can be statistically estimate using appropriate data acquisition (vibration, displacement, ...).

Reduction of turning instability is achievable with appropriate understanding of interactions between the dynamic characteristics of machine tool, tool material and workpiece material.

Various methods have been used to decide upon the stability/instability, including examination of the force signals and their Fourier transforms, and of the workpiece surface finish. Force and accelerometer sensors were applied in our tests.

3.1. Natural frequency and damping of system

To be able to identify phenomenon which cause emphasized irregularity on workpiece, measurement of dynamic parameters of machining system is performed. As parts of machining system workpiece, tool, tailstock, slideways, compound rest saddle, carriage and chuck were analyzed. Different types of sensors intended for different levels of measuring precision and parameters to control were analysed ba Y Lee at all [9]

Measurement of dynamic parameters has been done by using accelerometer Hottinger and Baldwin Messtechnik model B12. Tests were applied on bar shaped workpiece with diameter of 40 mm. Total distance from tailstock to headstock was 765 mm, and shape irregularities on machined surface were detected at distance of 190 mm from chuck - chattering was clearly emphasized .

Natural frequencies and damping as one of the most important dynamic parameters were observed and measured. From raw real time measured data, using software package MATLAB, results for natural frequencies and damping of machine tool components were obtained and shown in Table 1. If cutting tool is in contact with workpiece on specific place, and natural frequencies of slideways and workpiece are the same, resonance appears.

That specific place of resonance is right the same as the place where emphasized irregularities are noticed after machining. Very large amplitude close to the natural frequency of the dominant mode very derived in [10] while this resonance is linked with revolution frequency.

Fig. 3. shows results of data signals from force meters and accelerometers with prominent peaks on certain frequencies. First peak correlates with natural frequencies of workpiece, and therefore this value have dominant effect on dynamic behavior during machining. Similar findings were pointed out by Khanfir at all [11].

Table 1. Natural frequencies of parts of lathe TNP 160A

Object	Frequency, Hz	Damping
Chuck	315	0,065
Tailstock	277	0,064
Slideways	163	0,187
Saddle	226	0,132
Headstock	326	0,0708

FEM modeling and frequency analysis

ANSYS software [12] was used to model workpiece with beam elements, and cutting tool was represented with combined elements that include spring rigidity and damping [13]. Both supports are considered as rigid in first analysis and after chuck were considered as elastic support with high rigidity to be able to predict any kind of backlash of chuck. Using calculated rigidity of cutting tool, results of natural frequencies for different positions of cutting tool in contact with workpiece are obtained. These results and results for workpiece without any contact with cutting tool are shown in Table 2. Mahdavinejad reports what natural frequency modes is related to certain machine tool structure component [14].

3.2. Importance of DOC value for cutting stability

To check DOC variation model of tool/workpiece interface was made (walley shown in fig.4), and compute DOC of cutting $a_{min}<a<a_{max}$ in different walley possition according to previous tool pass (p≥0) .Fig 5 shows that variation of DOC is in the range 60%, while in soft steel turning this value is about 10%. In setted DOC of 0,3 mm, these 60 % means roughly ± 0,1 mm.

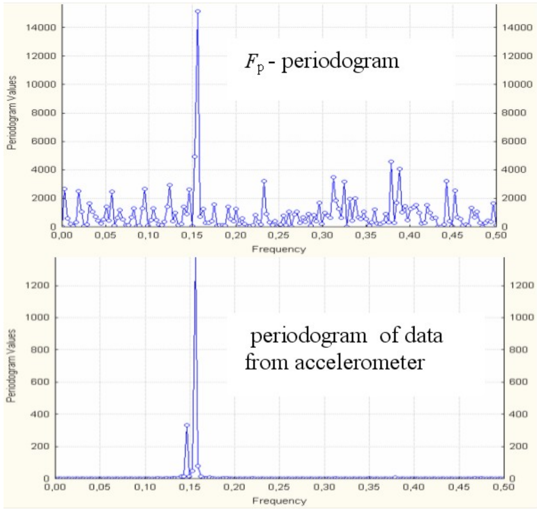

Fig.3. Signals from accelerometers and force meters after FFT (frequency in kHz)

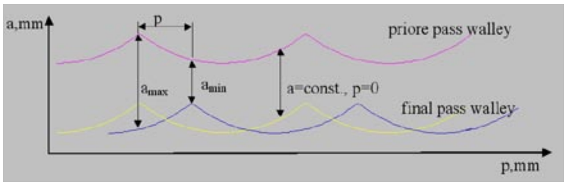

Fig. 4. Parameters for interface modeling and DOC computing

Depth variation in hard turning could be slightly lower 25-30% (for higher nose radius of priore tool pass, and for smaller feed rate), and slightle higher 10-15% (for other p values). This DOC variation can be recorded also by forces measurement. Passive force *F*p is the most sensitive on DOC variation and as a result *F*p force variation over 70% can be established. This value is close to the previous consideration (60% variation of DOC), and confirm assumed facts on dynamic behavior of depth of cutting.

Table 2.
Natural frequencies of workpiece obtained by finite element analysis

	Rigid supports, without contact	One elastic support, without contact with cutting tool	One elastic support, in contact with cutting tool
1. natural frequency, Hz	30,6	29,5	30,8
2. natural frequency, Hz	185,8	149,5	165,8
3. natural frequency, Hz	327	224,4	224,4
4. natural frequency, Hz	652	439,7	445
5. natural frequency, Hz	977	726,1	728,4

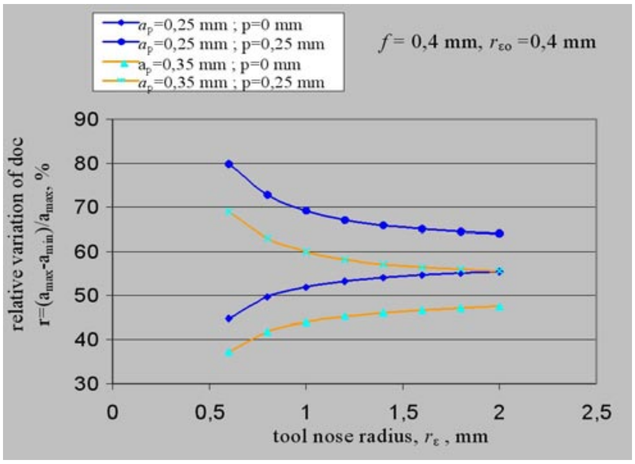

Fig.5. Variation of DOC during hard turning

On accelerometer signal frequency peaks are diversed over range 5 and 45 kHz. This diverse is influenced with cutting speed as well as chip form and segmentation [15].

4. Conclusions

An approach for identification of dynamic instability in hard turning process has been presented. The applied method consists of determination of natural frequencies on different positions in work area and resonance determination by conducting of measurement. This resonance position is confirmed by FEM analysis. It was found DOC variation, by tool/workpiece interface modeling and confirmed with passive force measurement. Since the chip-area geometry vary along the tool path, the tool path for several revolutions is considered when presenting the force/accelerometer sensing data. The achievements can be employed to increase productivity by guiding the judicious choice of cutting conditions and tooling geometry, and/or by regulating the spindle speed.

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