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Vrednotenje stabilnosti pri struženju v trdo

Evaluation of the Stability During Hard Turning

Antun Stoić[1] - Mirjana Lucić[1] - Janez Kopač[2]
([1]University of Osijek, Croatia; [1]Fakulteta za strojništvo, Ljubljana)

Prispevek obravnava vrednotenje stabilnosti pri struženju v trdo. Nestabilnosti se pojavijo zaradi spreminjanja globine odrezovanja, neprimernega razmerja sil Fc/Fp, premajhnega polmera konice orodja in neenakomernih porazdelitev napetosti v materialu na območju stika orodja z obdelovancem. Ta področja nestabilnosti je moč določiti s spremljanjem postopka, npr.: sile, pospeškov, merjenja zvočne intenzivnosti itn., ali po končanem obdelovalnem postopku z merjenjem hrapavosti, temperature, obrabe itn. V primeru nestabilnega odrezovalnega postopka se sile pri odrezovanju povečajo. Poveča se hitrost obrabljanja orodja, kar neposredno vodi do slabše kakovosti obdelane površine. Zato se je treba izogibati nestabilnemu postopku odrezovanja. Za določevanje oz. ocenjevanje stopnje nestabilnosti so bile v delu izvedeni numerični izračuni in pripadajoči preizkusni testi z uporabo in primerjavo različnih zaznaval spremljanja postopka in tehnike zbiranja podatkov na podlagi osebnega računalnika.

V prispevku je prikazano, da se globina odrezovanja med postopkom spreminja za 60 odstotkov v primeru analize geometrijske oblike orodje-obdelovanec. Pri merjenju odrivne sile Fp pa se to nihanje še poveča v primeru premajhne togosti odrezovalnega orodja.

Dosežki in ugotovitve tega prispevka so predstavljeni kakovostno in se lahko rahlo razlikujejo pri drugačnih odrezovalnih razmerah (npr.: pri uporabi rezalnega orodja Wiper). Pri odrezovanju v trdo ne glede na to, ali gre za pol fino ali fino obdelavo, ima kakovost obdelane površine izreden pomen. Kakovost obdelane površine je neposredna posledica stabilnosti postopka in neperiodičnosti obremenitve na stiku obdelovanca in orodja. Rezultati prispevka tako pomenijo določitev optimalne globine odrezovanja pri zadnjem prehodu orodja za zagotovitev najmanjše hrapavosti obdelane površine, kar pa je izredno pomembno za določitev optimalnega režima obdelovanja.

(Ključne besede: struženje, stabilnost, lastnosti dinamične, globina rezanja)

This paper deals with the lack of cutting stability during hard turning (appearing due to cutting-depth variation, unfavorable ratio of forces, Fc/Fp, a small tool-nose radius, and a non-uniform stress distribution over the tool/workpiece contact), which is possible to evaluate with process sensing (e.g., forces, vibrations, sound measurements) or after the process has finished (e.g., roughness, wear measurements). If the cutting process is unstable, the cutting force can become large and the machined surface quality can be poor or the tool can quickly become broken. Therefore, it is desirable to avoid unstable cutting conditions. Numerical calculations and experimental tests were made to evaluate the rate of cutting instability while using and comparing different process monitoring sensors and acquisition techniques based on the PC platform.

It was found that the cutting depth varies by a value of some 60% if the tool/workpiece (T/W) contact geometry is analyzed, and even more if the Fp force signal is analyzed when the machine tool has inadequate stiffness.

The results and findings presented in this paper are qualitative and might be slightly different under other cutting condition (e.g., if wiper inserts are used). Assuming that the hard turning is a semi-finishing or finishing process, the surface finish is very relevant, because it is a direct consequence of both the cutting stability and of the tool/workpiece non-uniform loading distribution. The results of the test indicate an optimum cutting depth for the final pass when the minimum surface roughness can be achieved, which can be valuable for the cutting-regime determination.

(Keywords: turning, stability, dynamic properties, cutting depths)

0 UVOD

Določevanje optimalnih obdelovalnih razmer pri odrezovanju, s tako imenovanimi mejno stabilnostnimi diagrami za vsako od kombinacij orodje - držalo - stroj - material obdelovanca, je običajno zelo neprimerno. Zato so potrebe in interesi industrije določitev območij stabilnosti z uporabo metod, ki ne potrebujejo širokega znanja teorije vibracij. Določevanje stabilnosti s spremljanjem odrezovalnega postopka je v današnjih časih precej preprosto z uporabo hitre Fourierjeve transformacije (HFT) zajetega signala v časovnem prostoru. V preteklosti je bila preizkušena tudi možnost določitve stabilnosti z uporabo variance signala [1] in drugimi preizkusi določitve vpliva geometrijskih lastnosti na stabilnost odrezovalnega postopka. Med drugim tudi vpliv polmera konice rezalnega orodja ([2] in [3]), prostega in cepilnega kota ([2] in [4]) ter usmeritve odrezovanja ([2] in [5]). Pomembnost stabilnosti odrezovalnega postopka je bila v preteklosti predvsem označena s frezanjem, pojavlja pa se tudi pri "prekinjenem" struženju, obdelavi v trdo itn.

Postopek struženja obdelovancev z veliko površinsko trdoto materiala, pri katerem so uporabljene manjše odrezovalne hitrosti in površine odrezkov (v primerjavi s struženjem v mehko), lahko dobro nadomesti dodatni postopek brušenja. To zagotavljanje velike kakovosti obdelane površine vodi do bistveno večje storilnosti pri manjšem obremenjevanju okolja z uporabo manjših količin hladilno-mazalnih tekočin. Poleg vseh teh prednosti tehnologije so opazne tudi negativne lastnosti. Struženje v trdo je nepretrgan postopek odrezovanja in posledično tudi nepretrgan postopek obrabljanja orodja. Obrabljanje je odvisno od mehanskih in toplotnih obremenitev orodja [22]. Tako kakor odrezovanje je tudi obrabljanje orodja dinamično, kar je pričakovano zaradi take dinamike spreminjanja globine odrezovanja. Pri zunanjem struženju spreminjanje globine odrezovanja, zaradi geometrijskih lastnosti obdelovanca in spreminjanja globine odrezovanja (GO) glede na predhodno valovitost obdelane površine, podajanja, rezalne hitrosti in dejanskega nastavnega kota po opravljeni "poti" orodja, lahko povzročajo močno dinamiko rezalnih sil, ki neposredno vplivajo na stabilnost postopka. Poleg vseh teh vplivnih parametrov na stabilnost negativno vpliva tudi izsrednost vpetja obdelovanca, kar se kaže kot samovzbujajoče nihanje katere koli komponente odrezovalnega orodja. Prisotnost takih nihanj se lahko kaže kot nepravilna geometrijska oblika obdelane površine ali celo poškodba obdelovanca.

0 INTRODUCTION

The calculation of the optimum cutting conditions using stability-lobes diagrams for each tool/holder/spindle/machine/material combination on the shop floor is not convenient. The need for rapid identification of the stability behavior using methods that do not require an extensive background in vibration theory increases. A stability-testing technique performed with process sensing is nowadays a rapid job that calculates the fast Fourier transform (FFT) of the time-based signal collected during cutting. There was an attempt [1] in the past to evaluate the instability with signal data variance and other attempts that have been geared towards including the effects of real process-geometry parameters into the stability solution, including tool-nose radius ([2] and [3]), feed rate and lead angle ([2] and [4]), and cutting-mode orientation ([2] and [5]). The importance of the instable behavior of cutting was in previous years associated with milling, but also with interrupt cutting, hard machining, etc.

The turning of parts with a high surface hardness, where small values of cutting speed and chip area in the cross section (compared with soft turning) can be applied, has appeared in the past few decades as a process that substitutes grinding very successfully. This substitution enables higher-productivity machining and reduces the environmental impact (lowering the coolant consumption). However, in addition to these positive effects there are a few negative effects. Hard turning is a continuous process of chip removal according to the tool engagement and thermal loads, but also the dynamic undertaking the uncut chip area and the depth of cutting in particular [22]. In contour or outer diameter turning, the workpiece's geometric variations, and the variations in the depth of cut (DOC) as a result of a prior pass valley, the feed rate, the cutting velocity and the effective lead angle, along the tool path produce large dynamic force variations, which induce variations in the process stability. Besides those already mentioned, cutting instability is also associated with the eccentricity of the workpieces, which might lead to self-exited vibration in any component of the machine tool. The presence of this kind of vibration can lead to irregularity of the machined shape as well as to surface damage of the machined workpiece. The

Vpliv se poveča z večanjem rezalne hitrosti do obdelave z velikimi hitrostmi (OVH). Saj je dejstvo, da so se v zadnjih petdesetih letih odrezovalne hitrosti podvojile. To pomeni, da se je vpliv izsrednih sil v enaki časovni dobi povečal za faktor štiri, kar povzroča izrazitejše probleme z vibracijami.

Veliko je vplivnih parametrov, ki vplivajo na storilnost in natančnost obdelovanja. Najbolj vplivna med njimi so samovzbujajoča nihanja. Poleg tega nihanja, povzročajo hitro obrabo orodja ali celo lom orodja. Velik polmer konice odrezovalnega robu zagotavlja kakovostnejšo obdelano površino na račun povečane specifične energije odrezovanja [6] s povečanjem rezalnih sil.

Za zmanjšanje ali celo odpravo samovzbujajočih nihanj so običajno globine odrezovanja in podajanja manjše, ali je spremenjena celo geometrijska oblika orodja. Te spremembe pomenijo omejitve postopka in s tem slabši izkoristek. Zato je zelo pomembno poznati dinamiko odrezovalnega postopka in biti zmožen določitve obdelovalnih pogojev in parametrov, pri katerih se bodo pojavila ta nihanja. Ob poznavanju vzrokov in mejnih točk, kjer se ta nihanja pojavijo, je to moč izkoristiti za povečanje izkoristka odrezovalnega postopka.

Primerljiv postopek odrezovanja kakor je stružilno frezanje, sicer poveča storilnost, še vedno pa ne odpravi problema nihanj, ki nastajajo zaradi spreminjanja kinematike postopka glede na površino odrezka. Dinamičnost kinematike je najmočnejša zaradi vhodov in izhodov posameznega rezalnega robu v odrezovanje in iz njega [7].

Nestabilnosti postopka so vzrok premiku ali deformaciji posameznih delov obdelovalnega sistema (stroj - orodje - obdelovanec) [8]. Vzrokov za odklanjanje je lahko več: lastnosti odrezovalnega stroja, lastnosti rezalnega orodja in lastnosti obdelovanca [23].

1 NAČINI IN PREDPOSTAVKE VREDNOTENJA

Hitrost tvorjenja odrezka pri struženju v trdo in presek neodrezanega odrezka sta v območju A_c = 5 do 90 · 10^3 μm^2 (a_p = 0,05 do 0,3 mm; f = 0,1 do 0,3 mm). Tak prerez odrezka je zagotovljen z ustrezno geometrijsko obliko orodja, podajanjem itn.

Kakor je prikazano na sliki 1, je stik med orodjem in obdelovancem običajno le na območju polmera rezalnega robu. Tako odrezovanje popisuje razmerje:

problem becomes increasingly important due to the trend for developing high-speed machinery. It is estimated that the speed of operation of machinery has doubled during the past 50 years. This means that the level of unbalance forces may have quadrupled during the same period, causing more serious vibration problems.

A lot of factors can affect the 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. A large tool-nose radius offers a finer surface finish, but also an increased specific cutting energy [6], which means higher forces.

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

Turn-milling as a competitive process, which reaches a higher productive removal rate, still cannot overcome the occurrence of vibrations as a result of the process of kinematics variations in the chip cross-section, and especially with the entry-exit condition [7].

Process instabilities are caused by deflections in the machining system (machine-tool-workpiece) [8]. The sources of deformations and deflection can be one or more of the following [9]: machine-tool parameters, cutting-tool parameters, workpiece parameters [23].

1 APPROACH AND ASSUMPTIONS IN THE EVALUATION

The chip-removal rate in the hard turning process and the appropriate uncut chip area is in the range of A_c = 5 to 90 · 10^3 μm^2 (a_p = 0.05 to 0.3 mm; f = 0.1 to 0.3 mm). The above uncut-chip area is provided in terms of the tool geometry and the true feed, after the first few revolutions.

As shown in Fig. 1, the tool/workpiece contact is mostly within the tool-nose radius. This condition is derived using:

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

Pri konkretnem primeru preizkusov je bilo uporabljeno orodje CNMA in držalo rezalnega orodja PCLNR ($\kappa_r = 97^o$), kar pomeni da mora biti globina odrezovanja (a_{max}) manjša od vrednosti predstavljenih v preglednici 1.

V primeru razmeroma globokih odrezovanj, pri katerih je razmerje med globino odrezovanja in polmerom konice orodja veliko (večje od 5), je dejanski nastavni kot približno enak nastavnemu kotu orodja κ_r. V primerih manjših globin (fina obdelava v trdo), dejanski nastavni kot popisuje razmerje [10]:

Which for the turning condition where the CNMA geometry of the insert and the PCLNR geometry of the holder (while $\kappa_r = 97^o$) are applied, means that the depth of cutting (a_{max}) is smaller than the value given in Table 1.

For relatively deep cuts in which the depth-of-cut/tool-nose-radius ratio is large (e.g., larger than 5), the effective lead angle is approximately equal to the lead angle κ_r. Otherwise, in finishing cuts (hard turning), the effective lead angle is given as in [10]:

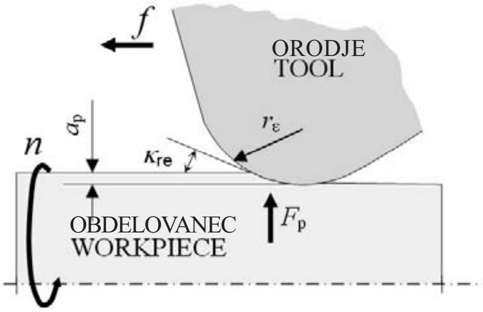
$$\tan \kappa_{re} = 0{,}5053 \ \tan \kappa_r + 1{,}0473\ (f / r_\varepsilon) + 0{,}4654\ (r_\varepsilon / a_p) \qquad (2).$$

Poudariti pa je treba, da se spreminjata globina odrezovanja med samim postopkom, pa tudi dejanski nastavni kot, kakor je prikazano na sliki 2.

Z zmanjšanjem globine (GO) se zmanjša tudi sila odrezovanja. S tem se pomanjša tudi nastavni kot, kar poveča prečno komponento sile odrezovanja. Teoretično je tak postopek zahtevnejši za popis zaradi dodatne odrivne sile ali prečne komponente sile odrezovanja. Ta učinek vpliva na kakovost obdelane površine po Brammerzu [11]. Hrapavost obdelane površine (R_{th}) je lahko opredeljena kot korak med R_t in R_{tB}.

If a variation of the depth of cut during cutting exists, the effective lead angle will vary too, Fig.2.

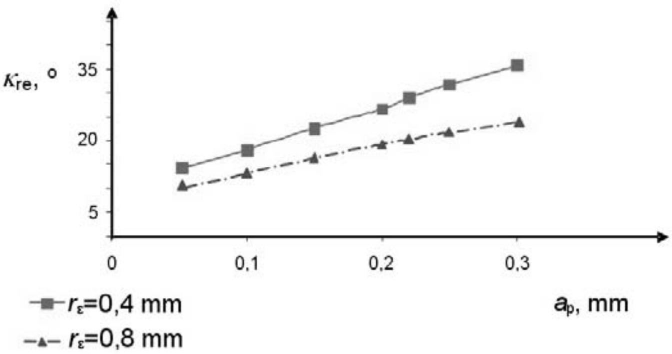
With lowering the depth of cut, the lead angle will decrease (Fig. 2) and the passive force increases. With decreasing the depth of cut, the uncut-chip thickness decreases, as do the forces. This theoretical consideration is more complicated because of the push-off effect (Fig.3) derived by Brammertz [11] in terms of the surface roughness. The surface roughness (R_{th}) is therefore within R_t and R_{tB}.



Sl. 1. *Skica geometriskje oblike stika orodja in obdelovanca*
Fig. 1 *Schematic representation of the tool/workpiece contact geometry*

Preglednica 1. *Pogoji obdelave, kjer odrezovanje opravlja le polmer konice rezalnega robu*
Table 1. *Conditions when the turning is conducted over the tool-nose radius*

r_ε [mm]	a_{max} [mm]
0,4	0,434843
0,8	0,869686
1,2	1,304528



Sl. 2. *Spreminjanje dejanskega nastavnega kota v odvisnosti od globine odrezovanja*
Fig. 2 *Influence of DOC on the effective lead angle*

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

kjer h_{min} pomeni najmanjšo globino odrezovanja brez izrazitejšega učinka odrivne sile.

Kot posledica spreminjanja globine odrezovanja, ki je odvisna od geometrijske oblike obdelane površine v prejšnjem vrtljaju, se pojavi tudi spreminjanje sile odrezovanja. Velikost amplitude odrezovalne sile se spreminja s približevanjem postopka podkritični nestabilnosti zaradi večanja podajalne hitrosti [12].

Hua [13] na primeru finega odrezovanja opozori na nastanek površinskih napetosti, ki so posledica različnih geometrijskih oblik odrezovalnega orodja.

2 REZULTATI VREDNOTENJA STABILNOSTI

2.1 Vpliv globine odrezovanja na stabilnost postopka

Za vrednotenje spreminjanja globine odrezovanja je bil izdelan model orodje/obdelovanec (sl. 4) in določeno spreminjanje globine $a_{min}<a<a_{max}$ glede na valovitost obdelane površine iz prejšnjega vrtljaja (obdelane površine) ($p \geq 0$). S slike 5 je

where h_{min} is the minimum chip thickness for push-off-free cutting.

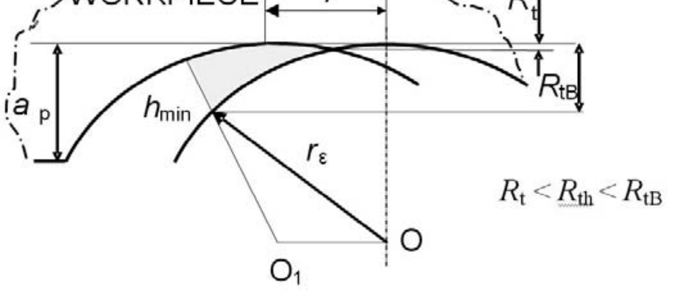
The variation of the uncut-chip thickness during the turning process depends on the previous cut profile. If that variation is significant, the amplitude of the cutting force can increase to a nearly sub-critical instability [12].

Hua at al. [13] suggest that the effect of the finishing process on the subsurface residual stress profile is related to the cutting-edge geometry.

2 RESULTS OF THE STABILITY EVALUATION

2.1 Importance of the DOC value for cutting stability

To check the DOC variation, a tool/workpiece model interface was made (valley shown in Fig.4), and the DOC $a_{min}<a<a_{max}$ computed in a different valley position according to previous tool passes and different displacement values ($p \geq 0$). Fig 5 shows that



Sl. 3. *Hrapavost površine skladno z Brammertzem*
Fig. 3 *Surface roughness in accordance with Brammertz*

razvidno, da je spreminjanje globine odrezovanja okoli 60%, medtem ko je ta vrednost pri struženju mehkega materiala okoli 10%. 60 odstotkov pomeni, da je spreminjanje globine odrezovanja pri nastavljeni globini 0,3 mm, približno ± 0,1 mm.

Spreminjanje globine odrezovanja pri struženju v trdo je lahko zmanjšano za 25 do 30% z večjim polmerom konice rezalnega orodja in zmanjšanim podajanjem. Poveča pa se z od nič različno vrednostjo parametra p za 10 do 15%.

Na račun spreminjanja geometrijske oblike po poti rezalnega orodja izraz za površino odrezka pri struženju [14] vsebuje tudi nelinearno funkcijo globine odrezovanja in podajanja v časovni odvisnosti. Natančni popis dinamike spreminjanja površine odrezka lahko glede na različne vrednosti globine odrezovanja v prejšnjem in trenutnem obratu, podajanju v prečni in vzdolžni smeri, polmera konice rezalnega orodja in nastavnega kota orodja, privede do različnih dinamik. To spreminjanje globine odrezovanja posredno vpliva tudi na silo odrezovanja. Na sliki 6, je prikazan potek odrivne sile F_p, ki se izkaže za najbolj občutljivo za spreminjanje globine odrezovanja. S slike 7a, je razvidno spreminjanje odrivne sile za več ko 70 odstotkov. Ta vrednost je zelo blizu predhodni napovedi (60-odstotno spreminjanje globine odrezovanja) in potrjuje predpostavljeno dinamiko globine odrezovanja.

Odrivna komponenta sile odrezovanja F_p (sl. 7b) v frekvenčnem prostoru (dobljenega iz časovnega poteka sl. 6) prikazuje izrazite amplitude frekvenčnega spektra v območju pod 2 kHz (spremljano je bilo območje do 40 kHz) in veliko amplitudo moči pri frekvenci, ki je frekvenca prečkanja orodja doline/vrha na površini obdelovanca iz prejšnjega vrtljaja.

Pri merjenju pospeškov (merjenih v enaki smeri kakor deluje odrivna sila) se frekvence izrazitih amplitud v frekvenčnem spektru signala pomaknejo v višje

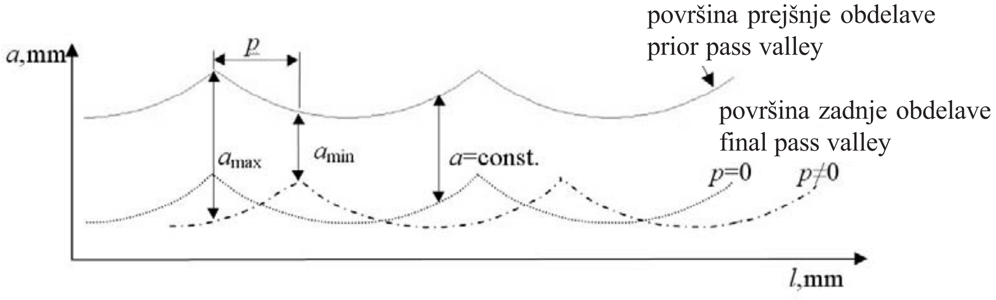
the variation in the DOC is in the range of 60%, while in soft-steel turning this value is about 10%. With a settled DOC of 0.3 mm, this 60% means roughly ± 0.1 mm.

The DOC variation during hard turning could be slightly lower, 25 to 30% (for a higher nose radius of a prior tool pass, and for a smaller feed rate), and slightly higher, 10 to 15% (for valley-displacement values, marked with $p \geq 0$ in Fig.4).

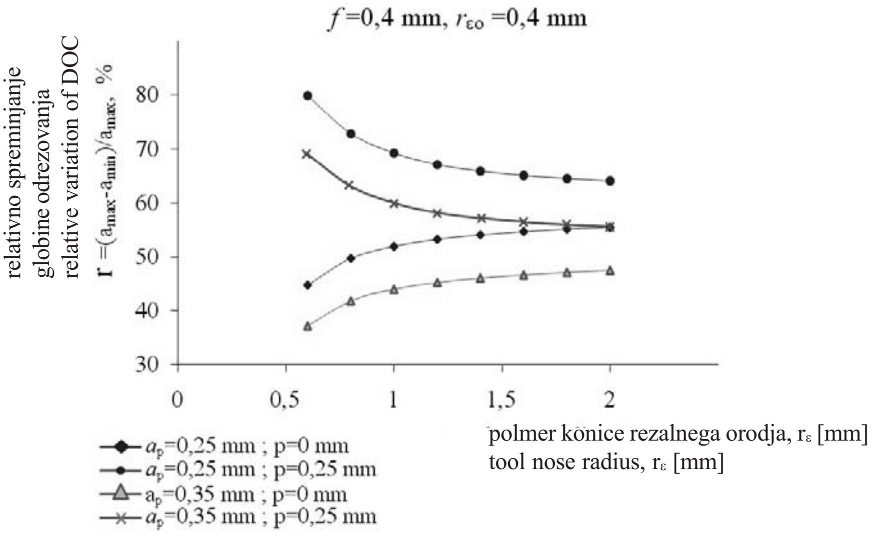
Due to the geometrical variations along the tool path, the chip-area expressions during turning [14] include non-linear functions of the depth of cut and the feed rate vs. time. Determining the dynamic chip-area variations with the exact expressions involves several cases, depending upon the values of the depth of cut in the current and previous tool positions, the feed rates along the axial and radial directions, the tool-nose radius, and the tool lead angle. This DOC variation can also be recorded using a force measurement. Tests were performed on steel for work at high temperatures, 40 CrMnMo7. The specimen was heat treated with hardening at 880°C (100 min) and tempered at a temperature of 440°C. The test sample was a bar with a diameter of 200 mm and a length of 60 mm. The average hardness of the test specimen was 45–47 HRC. As shown in Fig. 6, the passive force, F_p, is the most sensitive to DOC variation and as a result the F_p force variation over 70% can be established (Figure 7a). This value is close to the previous consideration (a 60% variation of the DOC) and confirms the assumed facts about the dynamic behavior of the depth of cutting.

The force-signal data of the F_p component (Fig 7b) in the frequency domain (derived from time-signal data shown in Fig. 6) shows peaks only in the range below 2 kHz (the observed range was up to 40 kHz), and a high power peak at the frequency that corresponds to the frequency when the tool is passing over the valley peaks of the previous pass.

On the accelerometer signal (the sensor was oriented in the same direction as the passive force)



Sl. 4. *Parametri postavitve modela orodje/obdelovanec in izračun globine odrezovanja*
Fig. 4 *Parameters for tool/workpiece interface modelling and DOC computing*



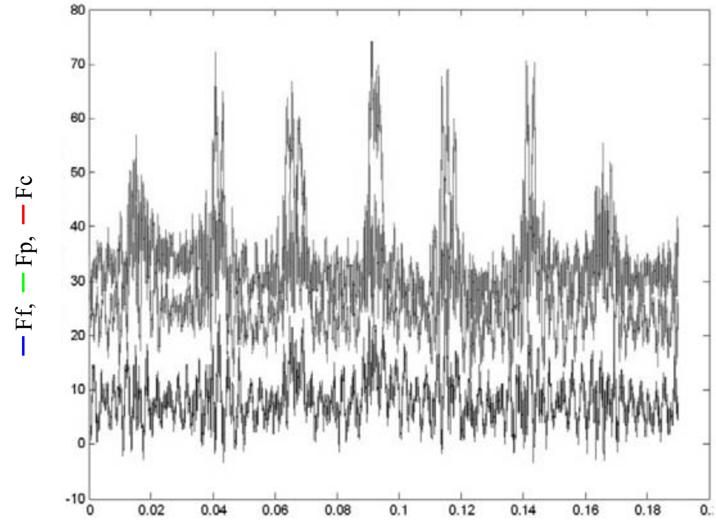
Sl. 5. *Spreminjanje globine odrezovanja pri struženju v trdo*
Fig. 5 *Variation of the DOC during hard turning*

frekvenčno območje, 5 do 45 kHz, z ne prav izrazitima amplitudnima vrhovoma pri frekvencah 17 in 31 kHz. Ta premik frekvenčnega območja je močno povezan z rezalno hitrostjo, nastajanjem odrezka in lomom odrezka [15].

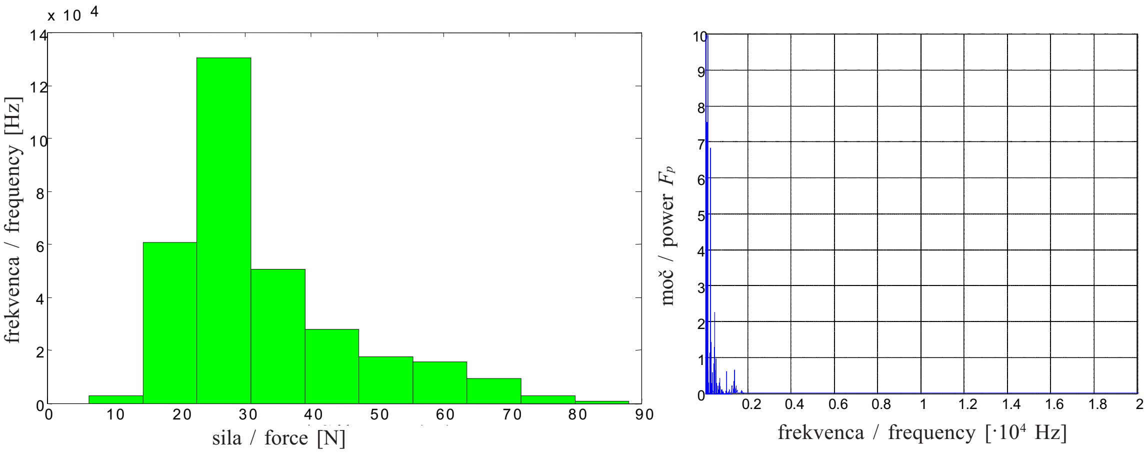
Na sliki 8 sta prikazana frekvenčna spektra signala odrivne sile Fp in pospeškov v tej smeri. Razvidne so izrazite amplitude pri nekaterih frekvencah. Frekvenca prve amplitude se ujema z lastno frekvenco obdelovanca. Tako ima ta vrednost velik vpliv na dinamiko obnašanja obdelovalnega postopka.

the frequency peaks are spread over the range 5 to 45 kHz (with not so high dominant peaks at 17 and 31 kHz). This spread is influenced by the cutting speed as well as the chip form and segmentation [15].

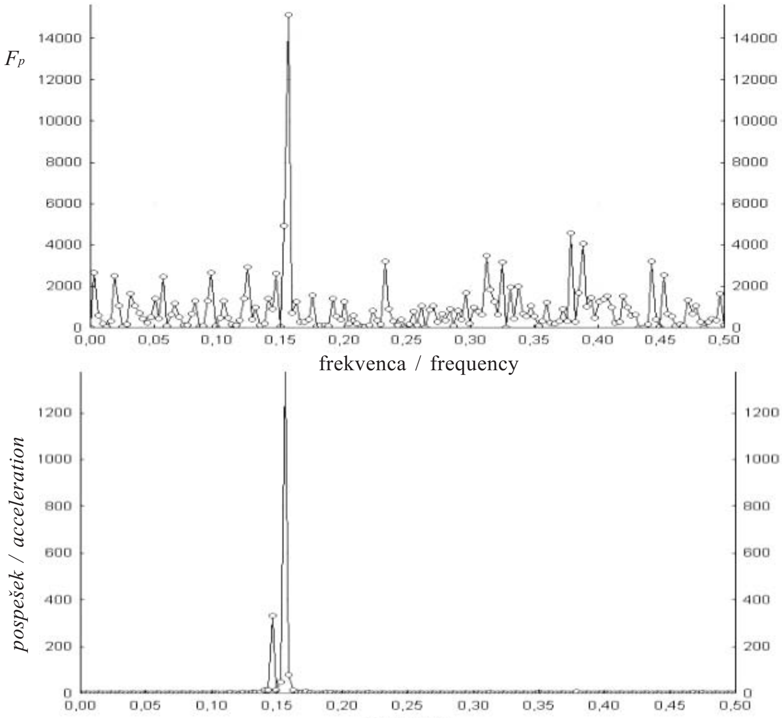
Fig. 8. shows the cutting data signals from the force sensors and accelerometers with prominent peaks at certain frequencies. The first peak correlates with the natural frequencies of the workpiece, and this value has a dominant effect on the dynamic behavior during machining.



Sl. 6. *Signal odrezovalne sile (časovno območje). Pogoji: material 40 CrMnMo7; orodje CBN25 CNMA 120412TN3; suho;* v_c*=500 m/min,* r_c*=1,2 mm,* a_p*=0,2 mm/rev,* f_{old}*=0,2 mm*
Fig. 6 *Cutting-force signal (time domain). Conditions: Material 40 CrMnMo7; Tool CBN25 CNMA 120412TN3; dry;* v_c*=500 m/min,* r_c*=1.2 mm,* a_p*=0.2 mm/rev,* f_{old}*=0.2 mm.*



Sl. 7. *Analiza komponente rezalne sile F_p(levo- histogram; desno: frekvenčni spekter)*
Fig. 7. *Force component F_p data analysis (left- histogram view; right: frequency domain)*



Sl. 8. *Signala odrivne sile in pospeška po HFT transformaciji (frekvenca v kHz)*
Fig.8. *Signals from accelerometers and force sensors after FFT (frequency in kHz)*

2.2 Merjenje dinamičnih parametrov sistema

Povečanje stabilnosti postopka je mogoče doseči z ustreznim razumevanjem odvisnosti med dinamičnimi lastnostmi obdelovalnega stroja, orodja in obdelovanca. Vse te značilnosti sklopa je mogoče določiti pred obdelovanjem. Poleg tega so običajno periodične in jih lahko statistično ovrednotimo in

2.2 Results of the dynamic parameter measurements

Enhancement of the turning-process stability is achievable with appropriate understanding of the interactions between the dynamic characteristics of the machine tool, the tool material and the workpiece material. The dynamic behavior of the machine-tool components can be determined before the cutting process starts določimo na podlagi spremljanja postopka (nihanja, pomiki itn.). Analize so lahko izvedene z različno natančnostjo in različnimi spremenljivkami, ki jih spremljamo [16].

V raziskavi so bile uporabljene različne metode za določitev stabilnosti/nestabilnosti postopka z analizo izmerjenih signalov (HFT) in opazovanjem kakovosti obdelane površine (hrapavost). Za analiziranje obnašanja postopka so bile merjene sile in pospeški.

Za razpoznavo pojava, ki je vzrok izraziti nepravilnosti na obdelovancu, so bile izvedene meritve dinamičnih parametrov obdelovalnega sistema pri vzbujanju z udarnim kladivom. Tipični signal, zajet pri udarnem vzbujanju je prikazan na sliki 9a. Ena od metod za določitev koeficienta dušenja ξ je določitev koeficienta neposredno iz hitrosti zmanjševanja amplitude po številu vrhov n in je prikazana na sliki 9b z upoštevanjem razmerja:

(idle runs of machines) and mostly have a cyclic nature that can be statistically analyzed using appropriate data acquisition (vibration, displacement, etc.). The analysis can be performed with different levels of measuring precision and parameters to be controlled [16].

Various methods have been used to decide upon the process stability/instability, including signal analysis (fast Fourier transforms - FFT), and observation of the workpiece's surface finish. Force and accelerometer data were analyzed in our tests. As parts of the machining system: the workpiece, tool, headstock, slideways, compound rest saddle, and carriage were analyzed.

To be able to identify the phenomenon that causes an emphasized irregularity on the workpiece, measurements of the dynamic parameters of the machining system were performed by impact hammer testing. A typical signal form obtained after the hammer test is shown in Fig. 9a. An approximation of the damping percentage ξ is directly given by the decrease of n consecutive maxima, as shown in Figure 9b:

$$\xi = \frac{1}{2\cdot n\cdot \pi}\cdot \ln\left(\frac{X_1}{X_n}\right) \qquad (4).$$

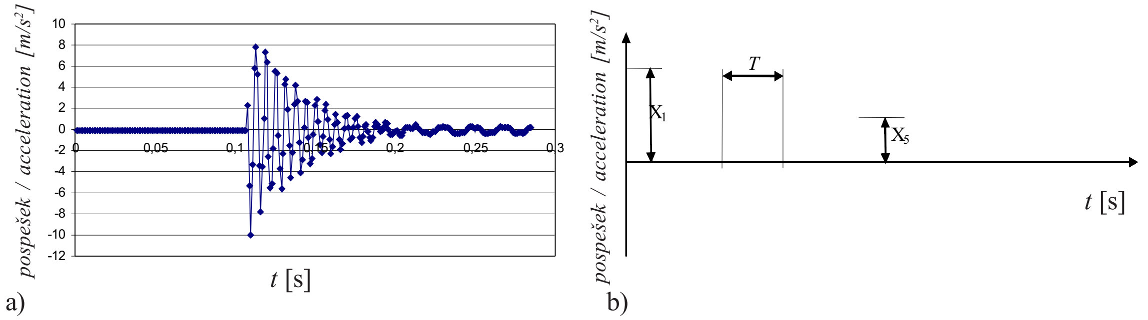
Iz periode prostega nihanja je moč določiti lastno frekvenco dušenega nihanja ω_d sistema, $\omega_d = 2\pi/T$. Iz te pa lahko določimo lastno frekvenco nedušenega nihanja na podlagi razmerja:

The period T of the free oscillations allows one to determine the damped self-frequency ω_d of the structure $\omega_d = 2\pi/T$. The natural self-frequency was then computed using:

$$w_s = \frac{w_d}{\sqrt{1-\xi^2}} \qquad (5).$$

Zaznavanje dinamičnih parametrov (lastnih frekvenc in dušenja) je bilo izvedeno z uporabo merilnika pospeškov Hottinger in Baldwin Messtechnik model B12. Uporabljeni ojačevalnik signala je bil HBM CWS-3082A, A/D pretvornik pa PCI120428-3A. Preizkusi so bili izvedeni na obdelovancu - okrogli konzoli s premerom 40 mm. Celotna razdalja med konjičkom in stružilno glavo je bila 765 mm. Nepravilnost v geometrijski obliki

The sensing of the dynamic parameters (natural frequencies and damping) was made by using a Hottinger and Baldwin Messtechnik model B12 accelerometer. The signal amplifier was an HBM CWS-3082A, and a PCI20428-3A was used as the A/D converter. Tests were applied on a bar-shaped workpiece with a diameter of 40 mm. The total distance from the tailstock to the headstock was 765 mm, and shape irregularities on the machined surface



Sl. 9. *Rezultati vzbujanja z udarnim kladivom; a) vhodni podatki, b) značilni parametri*
Fig. 9. *Impact hammer testing results; a) input data, b) characteristic parameters*

Preglednica 2. *Lastne frekvence komponent stružnice*
Table 2. *Natural frequencies of the lathe components*

Del Object	Frekvenca Frequency Hz	Dušenje Damping
glava/ chuck	315	0,065
konjiček/ tailstock	277	0,064
bočna vodila/ slideways	163	0,187
sedlo/ saddle	226	0,132
vodila glave/ headstock	326	0,0708

obdelovanca in obdelani površini so bile zaznane na razdalji 190 mm od stružilne glave, kjer je dobro razviden pojav drdranja.

Vsi zbrani podatki so bili analizirani s programskim paketom MATLAB. Rezultati so predstavljeni v preglednici 2. Ko je rezalno orodje v stiku z obdelovancem na točno določenem mestu in se lastne frekvence vodil in obdelovanca ujemajo, pride do pojava resonance. To specifično področje pojave resonance se točno ujema z mestom pojave nepravilnosti geometrijske oblike na obdelani površini.

Zelo izrazite amplitude zajetih signalov v frekvenčnem spektru blizu lastnih frekvenc sistema so bile zaznane tudi v delu [19], čeprav je tam resonanca obravnavana le s spreminjanjem frekvence vrtenja obdelovanca.

Do podobnih rezultatov lastnih frekvenc in resonančnih področij je prišel tudi Khanfir [18]. Za vrednotenje preizkusnih rezultatov je bil izveden numerični preračun z metodo končnih elementov, s programskim paketom ANSYS, kakor v primeru [19]. Obdelovanec je bil obravnavan kot konzolni nosilnik, rezalno orodje pa je bilo predstavljeno kot sklop elementov, ki vključujejo togosti in dušenje [20]. Obe podpori sta bili predpostavljeni kot togi v prvem delu analize. V drugem pa je stružilna glava predpostavljena kot elastična podpora z veliko togostjo za zmožnost upoštevanja zračnosti v glavi. Na podlagi izračunane togosti rezalnega orodja so bile določene lastne frekvence pri različnih legah orodja glede na stik z obdelovancem. Ti rezultati in rezultati obdelovanca, ko ta ni v stiku z orodjem, so prikazani v preglednici 3. Lastne frekvence v primeru, ko je obravnavana ena elastična podpora z upoštevanim stikom obdelovanec - orodje (osenčeni del v pregl. 3) se ujemajo s

were detected at a distance of 190 mm from the chuck – chattering was clearly audible.

Raw real-time measured data acquired from the accelerometers were analyzed with MATLAB software (the results are shown in Table 2). If the cutting tool is in contact with the workpiece at a specific place, and the natural frequencies of the slideways and the workpiece are the same, resonance appears. That specific place of resonance is in the same place where the emphasized irregularities are observed after machining.

Very large amplitudes of signals in the frequency domain, close to the natural frequency of the dominant mode were also derived in [17], while this resonance is linked only with the frequency of revolution.

Similar findings for the natural-frequency data and resonance were pointed out by Khanfir at al. [18]. In order to validate the experimental results, a finite-element analysis was performed, and as in [19], ANSYS software was used. The workpiece was modeled as a beam element, and the cutting tool was represented with combined elements that include spring rigidity and damping [20]. Both supports are considered rigid in the first analysis, while in the second analysis the chuck was considered as an elastic support with high rigidity, to be able to predict the backlash in the chuck. Using the calculated rigidity of the cutting tool, the results of the natural frequencies for different locations of cutting tool in contact with the workpiece were obtained. These results and the results for the workpiece without any contact with the cutting tool are shown in Table 3. The natural-frequency data for one elastic support, including contact with the cutting tool, corresponds (shadowed cell in Table 3) with frequency

Preglednica 3. *Analitično določene lastne frekvence obdelovanca z metodo končnih elementov*
Table 3. *Natural frequencies of the workpiece obtained by finite-element analysis*

	Toga podpora brez stika z orodjem/ Rigid supports, without contact	Ena podpora elastična brez stika/ One elastic support, without contact	Ena podpora elastična s stikom/ One elastic support, in contact
1. lastna frekvenca/ natural frequency [Hz]	30,6	29,5	30,8
2. lastna frekvenca/ natural frequency [Hz]	185,8	149,5	165,8
3. lastna frekvenca/ natural frequency [Hz]	327	224,4	224,4
4. lastna frekvenca/ natural frequency [Hz]	652	439,7	445
5. lastna frekvenca/ natural frequency [Hz]	977	726,1	728,4

frekvencami izrazitih amplitud v frekvenčnem spektru na sliki 8. Katerim lastnim oblikam rezalnega orodja pripadajo lastne frekvence, pa obravnava Mahdavinejad [21].

2.3 Vpliv polmera konice rezalnega orodja na stabilnost odrezovalnega postopka

Kakor je omenjeno, ima polmer konice rezalnega orodja velik vpliv na spreminjanje globine odrezovanja (GO) in na dejanski nastavni kot, kar privede do nestabilnosti postopka. Zato je treba določiti vpliv polmera konice rezalnega orodja na dinamiko odrezovanja v frekvenčnem prostoru.

Preizkusi so bili izvedeni pri struženju žarjenega jekla (Č1431 HRN C.B9.021 ali Ck 35 DIN ali C35E EN WNr1.118; trdota HRC=50 ± 2) z rezalnim orodjem (CBN, geometrijska oblika CNMA 1204 TN3), z merjenjem pospeška rezalnega orodja v smeri x (sl. 10).

Zasnova in razporeditev meritev sta prikazani na sliki 10, iz katere je razvidna smer merjenja pospeška. Ta se ujema s smerjo odrivne sile - smer x. Opaziti je moč tudi, da ima uporabljena stružnica z RŠK (Mori Seiki SL-153) razmeroma veliko revolversko glavo, kjer je vpeto držalo z merilnikom pospeškov na eni in rezalno orodje na drugi strani.

Kakor je prikazano na sliki 10 je bila dejanska dolžina obdelovanja obdelovanca pri preizkusih 350 mm. Ta dolžina je bila razdeljena na več področij v enakih obdelovanih razmerah (enakih parametrih odrezovanja). Za vsako od področij je bilo zbranih po deset signalov

periodogram peaks shown in Fig. 8. Mahdavinejad in [21] reports which natural-frequency mode is related to a certain machine-tool structure component.

2.3 Correlation with the obtained results of the tool-nose radius' influence on the cutting stability

The tool-nose radius has, as mentioned above, a strong influence on the DOC variation, and on the lead angle, which suggests cutting instability. It seems reasonable to verify the influence of the nose radius on the cutting dynamic in the frequency domain.

The evaluation was made by turning some heat-treatable steel (Č1431 HRN C.B9.021 or Ck 35 DIN or C35E EN WNr1.118; hardness HRC=50 ± 2) with cutting inserts (CBN, geometry CNMA 1204 TN3), while the acceleration of the tool holder in the x-axis was measured.

The concept and arrangement of the measurements is shown in Fig.10. One can see from Fig. 10 that the direction of the accelerometer sensitivity coincides with the direction of the passive force in the x-axis. It is also evident that the applied CNC lathe (Mori Seiki SL-153) has a relatively large revolver head, where our experimental tool holder with an accelerometer at one end and with a cutting insert (geometry CNMA 1204 TN3) at the other end was fixed.

As shown in Fig. 10, the useful length of a test workpiece (heat-treatable steel Ck35 E) was slightly less than 350 millimeters. This length was divided into several sections, and for each two neighboring sections the machining was performed under the same conditions (the same cutting parameters). For each section 10 single pospeškov v smeri x. Signali so bili povprečeni in preoblikovani v frekvenčni prostor. Tako so predstavljeni rezultati povprečni frekvenčni spektri, dobljeni z diskretno hitro Fourierjevo transformacijo (HFT). Frekvenca vzorčenja postopka je bila 100 kHz ob 8192 diskretizacijskih točkah. Na podlagi razmerja frekvence vzorčenja, števila diskretizacijskih točk in periode zbiranja signala, je ločljivost časovne periode 0,08192 s. To pomeni frekvenčno ločljivost povprečnega frekvenčnega spektra 12.207 Hz.

Slika 11 prikazuje vpliv polmera konice rezalnega orodja (r_ε) na merjene pospeške v smeri *x*. V splošnem manjši ko je polmer r_ε, večje so amplitude pospeška. Tudi iz analize je razvidno, da je amplituda pospeškov v frekvenčnem prostoru pri frekvenci 4 kHz obratno sorazmerna s polmerom r_ε. Na podlagi tega je moč sklepati, da je amplituda pospeška pri frekvenci 4 kHz ustrezna cenilka polmera rezalnega orodja. Poleg amplitude pri 4 kHz je izrazita tudi amplituda pri 10 kHz (sl. 11). Vendar pa se ta amplituda povečuje z večanjem polmera rezalnega orodja. To pa je v nasprotju s prvo določeno cenilko. Tako je moč upravičeno sklepati, da ima le prvi resonančni vrh v frekvenčnem prostoru smiselno fizikalno ozadje: manjši polmer konice vodi do večje nestabilnosti držala orodja (nihanj z večjimi amplitudami) pri tej frekvenci v primerjavi z večjim polmerom konice orodja.

3 SKLEP

Splošne ugotovitve oziroma sklepi analize odrezovanja v trdo (struženja) so:

- Analitično dobljen delež spreminjanja globine odrezovanja - GO je bil 60%. Določen je bil na

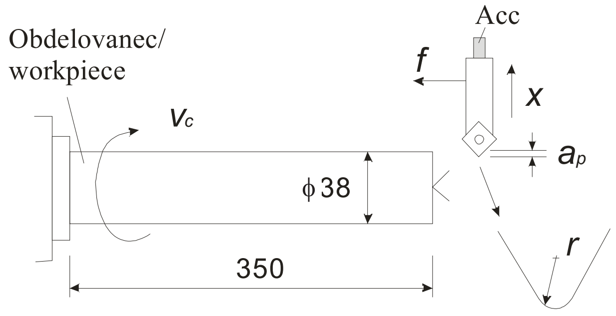
signals for acceleration in the x-axis were recorded, and after that transformed and averaged in the frequency domain. Thus, the presented results are the average spectra of 10 single spectra, obtained with a discrete FFT. The sampling frequency during the signal recording was 100 kHz and number of discrete points was 8192. According to the relations between the sampling frequency, the number of discrete points and the time of recording, the latter was 0.08192 s. This means that the frequency resolution of the average frequency spectra was approximately 12.207 Hz.

Fig. 11 shows the effect of the nose radius (r_ε) on the accelerometer's data signal. One can see that a smaller r_ε means higher amplitudes, in general. The analysis of the effect of the nose radius shows that the amplitude peak at 4 kHz is inversely proportional to the nose radius r_ε. Therefore, one can conclude that the amplitude peak at 4 kHz is a reliable criterion for the identification of the cutting-nose radius. From Fig. 11 one can see that there is an additional prominent peak at 10 kHz; however, its amplitude is higher for a larger nose radius, which is not in agreement with the conclusions from the first amplitude peak (see above). Therefore, it is reasonable to conclude that only the first resonant peak has a physically logical meaning: a smaller nose radius results in a reduced tool-holder stability (stronger vibrations) at this frequency in comparison to a larger nose radius.

3 CONCLUSION

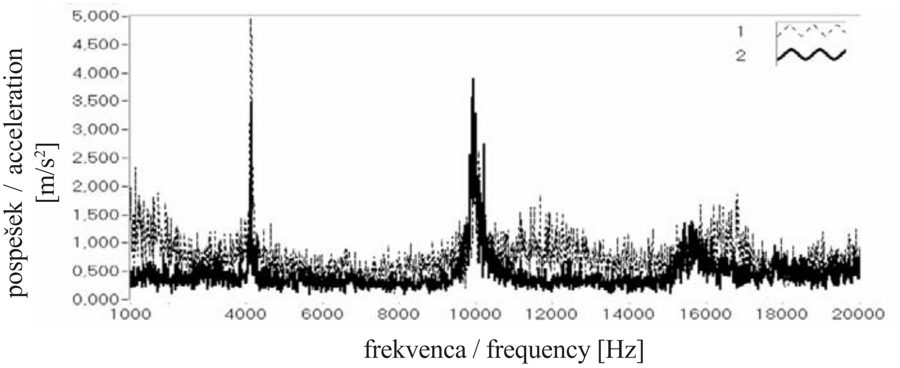
The general results provided during the hard-turning stability evaluation are:

- it was found that the DOC variation was 60%, with the tool/workpiece interface modeling, and



Sl. 10. *Testiranje vplivnosti polmera rezilnega orodja (f-podajanje, v_c-rezalna hitrost, r-polmer rezalnega orodja, Acc-merilnik pospeškov)*

Fig. 10. *Setup for testing the significance of the nose radius (f-feed rate, v_c-cutting speed, r-insert radius, Acc-accelerometer)*



Sl. 11. *Vpliv polmera rezalnega robu orodja na pospeške v smeri x, v_c = 450 m/min, a_p =0,2 mm, f =0,2 mm/vrt (1- r_ε =0,4 mm, 2 – r_ε =1,2 mm)*

Fig. 11. *The influence of tool-nose radius on the acceleration data, v_c = 450 m/min, a_p =0.2 mm, f =0.2 mm/rev (1- r_ε =0.4 mm, 2 – r_ε =1.2 mm)*

podlagi modeliranja stika orodje - obdelovanec. Analitično modeliranje je bilo potrjeno z meritvami odrivne komponente sile odrezovanja. Izmerjeni delež spreminjanja sile je bil rahlo večji 70%, zaradi tako imenovanega učinka odrivanja.

- Lastne frekvence posameznih delov stružnice so bile določene na različnih mestih obdelane površine kakor tudi različnih resonančnih področjih.
- Te resonančne frekvence in lege resonančnih območij so potrjene z analizo MKE (metodo končnih elementov), pri katerih je bil obdelovanec modeliran kot nosilnik, medtem ko je bilo orodje modelirano kot sklop elementov togosti in dušenja.
- Analitično določene lastne frekvence obdelovanca, določene z metodo končnih elementov se zelo dobro ujemajo. V primeru predpostavke elastičnega vpetja obdelovanca glavo z visoko togostjo in upoštevanjem stika med obdelovancem in orodjem, je odstopanje približno en odstotek.
- Izrazite amplitude odrivne komponente rezalne sile v frekvenčnem prostoru se pojavljajo le v področju pod 2 kHz (merjeno do 40 kHz). Največja moč spektra je bila določena pri frekvenci, ki se ujema s frekvenco prečkanja orodja doline ali vrha obdelane površine iz prejšnje obdelave.
- Vpliv polmera konice rezalnega robu orodja (r_ε) na pospeške orodja je lahko posplošen, npr.: manjši ko je polmer konice rezalnega robu, r_ε večje so amplitude pospeška.
- Pod obravnavanimi pogoji je amplituda pospeškov v frekvenčnem spektru pri frekvenci 4 kHz ugodna cenilka vplivanja rezalnega robu orodja. Velikost amplitude pri tej frekvenci je v obratnem razmerju s polmerom konice rezalnega robu r_ε.

confirmed with the passive force measurement, where variation is slightly higher (70%), probably because of the influence of the “push off” effect,

- the natural frequencies of the lathe components are determined at different locations in the work area and the resonant frequency as well,
- this resonance frequency and the location of the resonance was confirmed by a FEM analysis, where the workpiece was modeled as a beam element, and the cutting tool was represented by combined elements that include spring rigidity and damping,
- the natural frequencies of the workpiece obtained with the finite-element analysis match well (1% difference) with the experimental data if the chuck is considered as an elastic support with high rigidity and the tool is in contact,
- significant passive-force component (F_p) peaks in the frequency domain are only in the range below 2 kHz (the observed range was up to 40 kHz), and the high-power peak is estimated at the frequency which corresponds to the frequency when the tool is passing over the valley peaks of the previous pass,
- the effect of nose radius (r_ε) on the accelerometer data signal can be generalized by the conclusion in which the smaller r_ε means higher amplitudes,
- under the given circumstances the amplitude peak at 4 kHz is a reliable criterion for the identification of the cutting-nose radius influence, and the acceleration amplitude at this frequency was inversely proportional to the tool-nose radius r_ε,

- Skleniti je moč, da je možnost izboljšati storilnost z določitvijo primernih odrezovalnih pogojev in geometrijsko obliko orodja in/ali spreminjanjem hitrosti odrezovanja.

- the findings can be applied to increase productivity by guiding the correct choice of cutting conditions and tooling geometry, and/or by regulating the spindle speed.

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Authors' Addresses: Prof. Dr. Antun Stoić
Mirjana Lucić
Univerza v Osijeku
Fakulteta za strojništvo
Trg Ivane Brlić-Mažuranić 18
35000 Slavonski Brod, Hrvatska
astoic@sfsb.hr
mlucic@sfsb.hr

Prof. Dr. Janez Kopač
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
janez.kopac@fs.uni-lj.si

Authors' Addresses: Prof. Dr. Antun Stoić
Mirjana Lucić
University of Osijek
Faculty of Mechanical Eng.
Trg Ivane Brlić-Mažuranić 18
35000 Slavonski Brod, Croatia
astoic@sfsb.hr
mlucic@sfsb.hr

Prof. Dr. Janez Kopač
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia
janez.kopac@fs.uni-lj.si

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