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Analiza kakovosti izdelka pri postopku frezanja z uporabo kibernetskega modela
Analysis of Product Quality in Milling Procedure by Means of a Cybernetic Model

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Zasnova modernih računalniško krmiljenih (RK) obdelovalnih strojev in sistemov temelji na kibernetskem načelu optimalnega vodenja geometrijskih in tehnoloških veličin postopka obdelave. V pričujočem prispevku je predstavljen kibernetski dinamični opis RK frezalnega stroja in postopka frezanja, s katerim je bil izdelan računalniški simulirni model za analizo izdelka pri frezanju.

Primerjalni eksperimentalni rezultati so bili ugotovljeni na RK frezalnem stroju BEA 1 podjetja Heller v Tehnološkem laboratoriju Inštituta za proizvodno strojništvo Fakultete za strojništvo v Mariboru.

The concept of modern CNC machine tools is based on cybernetic principle of optimum control of geometrical and technological data of machining process. This paper describes a cybernetic and dynamic model of a CNC — milling machine and milling procedure on base of which a computer simulation model for the analysis of product quality in the milling procedure has been developed.

The comparable experimental results have been obtained on CNC milling machine BEA 1 of Heller firm in Technological Laboratory of the Faculty of Mechanical Engineering in Maribor.

0 UVOD

Doseganje optimalnih rezultatov v proizvodnji je v današnjem času vezano na uporabo sodobnih vrhunskih tehnologij. Pojem optimalni proizvodni rezultat vključuje nasledne lastnosti proizvodnega procesa:

— cenovno konkurenčen izdelek,
— kakovostno konkurenčen izdelek,
— proizvodni proces z največjo izrabo stroja.

Na področju proizvodnega strojništva so omenjene tehnologije številsko krmiljeni (ŠK) in računalniško krmiljeni (RK) obdelovalni stroji in sistemi.

Številsko krmiljeni stroj, center ali sistem je po svoji tehnični zasnovi enota z več neodvisnimi reguliranimi pogonskimi osmi, izvedenimi z električnimi ali hidravličnimi motorji. Veličine, ki so »izpostavljene« načelu regulacije, delimo v:

— skupino tehnoloških veličin (moč, sila, vrtilni moment reza orodja),

— skupino geometrijskih veličin (podajalni pomiki, hitrosti, pospeški v posameznih podajalnih oseh orodja nasproti obdelovancu).

V raziskovalnem delu, iz katerega izhaja pričujoči članek, so bile raziskane delovne razmere pri postopku čelnega frezanja in vpliv dinamičnega obnašanja posameznih komponent delovnega procesa na kakovost izdelka.

Pri postopku čelnega frezanja je aktiven pogon delovnega vretena (n_{sp}— tehnološka veličina) in pogon ene podajalne osi (Y— geometrijska veličina)

0 INTRODUCTION

Achieving the optimum production results involves the use of modern high-productive technologies. The term »optimum production result« includes the following characteristics of the production process:

— competitive product with regard to price,
— competitive product with regard to quality,
— production process with maximum machine efficiency.

In the field of production engineering, the quoted technologies are presented by NC and CNC machine tools in the widest sense of the word.

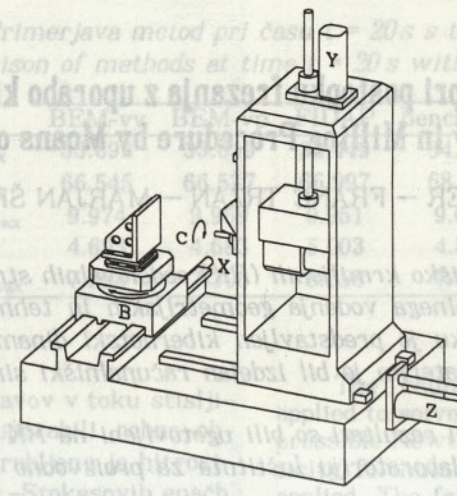
According to its technical concept, a CNC machine, centre or system is an unit with several independent control drive axes operated by electric or hydraulic motors. The values acting according to the principle of control include:

— a group of technological values (power, force, creating force torque),

— a group of geometrical values (feeds, speeds, accelerations in individual feed axes of tools with regard to workpiece).

The research work which is the basis of this paper, dealt with the working conditions in a face milling procedure and the influence of the dynamic-behaviour of individual components of product quality.

In a face milling procedure, the drive of the work spindle (n_{sp} — technological value) and the drive of the one feed axis (Y— geometrical value)



Sl. 1. *Tehnološka shema RK frezalnega stroja*
Fig. 1. *Technological drawing of CNC milling machine*

in sta tako v kibernetskem dinamičnem modelu upoštevana ta dva pogona. Poenostavljeno tehnološko shemo obravnavanega RK frezalnega stroja prikazuje slika 1. Stroj vsebuje štiri identične ŠK servopogone podajalnih osi *X*, *Y*, *Z*, *B* in pogon delovnega vretena *C*.

1 OPIS DINAMIČNEGA OBNAŠANJA KOMPONENT FREZALNEGA PROCESA

Zasnova pogonov RK frezalnega stroja temelji na ločenih reguliranih pogonih podajalnih osi in glavnega delovnega vretena. Temeljna blokovna shema frezalnega procesa vključuje tako sklenjene sisteme vodenja tehnoloških in geometrijskih veličin in je sestavljena iz treh med seboj povezanih funkcijskih enot:

— frezalnega procesa,
— reguliranih pogonov geometrijskih in tehnoloških veličin,
— računalniške naprave za krmiljenje procesa.

Pri obravnavanem čelnem frezanju sodelujejo naslednje komponente, katerih dinamični opis bo podan: pogon delovnega vretena, podajalni pogon v smeri osi *Y* in povezava orodje — obdelovanec — vpenjalna naprava. Blokovno shemo, po kateri je izdelan računalniški simulirni dinamični model, prikazuje slika 2.

are active, so these two drives have been considered in the cybernetic dynamic model. A simplified technological diagram of the described CNC milling machine is shown in Fig. 1. The machine includes four identical NC servodrives of feed axes *X*, *Y*, *Z*, *B* and the drive of work spindle *C*.

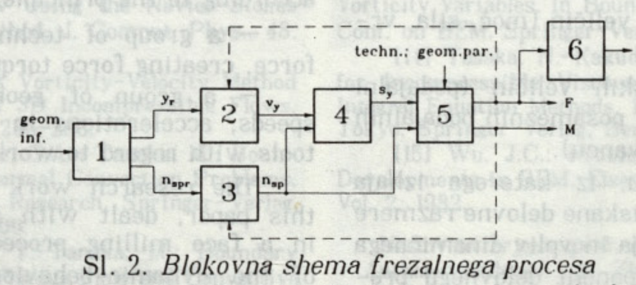
1 DESCRIPTION OF THE DYNAMIC BEHAVIOUR OF MILLING PROCESS COMPONENTS

The concept of drives of a CNC milling machine is a concept of individual control drives (servo drives) of the feed axes and of the main work spindle. A basic cybernetic block diagram of the milling process includes closed loops of the technological and geometrical values. The cybernetic block diagram consists of three interconnected functional units:

— cutting process,
— control drives for geometry and process data,
— CNC device for process control.

The surface milling dealth with involves the following components, whose dynamic description will be given: drive of the work spindle, feed drive in the direction of the *Y* axis and the combination tool — workpiece-clamping device.

The block diagram, on the basis of which the computer simulation model has been developed, concerning the dynamic behaviour of the individual components, is shown in fig. 2.



Sl. 2. *Blokovna shema frezalnega procesa*
1 — računalniška naprava za krmiljenje procesa, 2 — podajalni pogon, 3 — pogon delovnega vretena, 4 in 5 — odrezovalni proces, 6 — vpenjalna naprava

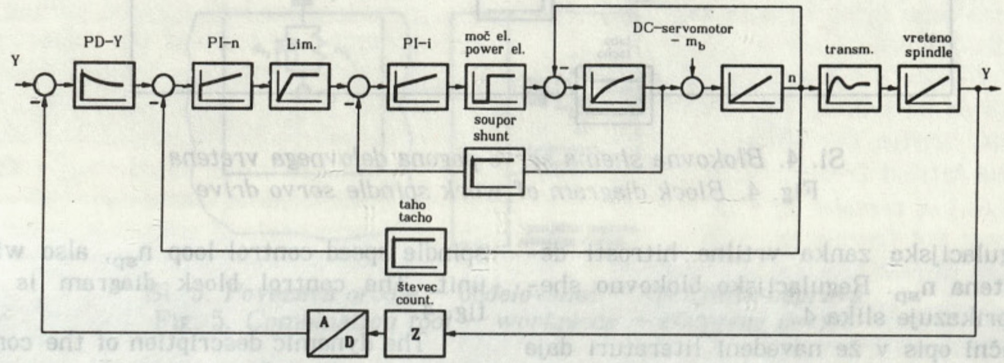
Fig. 2. *Block diagram of a milling process*
1 — computing unit for process control, 2 — feed drive, 3 — work spindle drive, 4 and 5 — cutting process, 6 — clamping device

1.1 **Podajalni servopogon v osi *Y***

Pogon je izveden z istosmernim servomotorjem, napajanim z blokom močnostne elektronike. Zasnova vodenja v smeri *Y* je izvedena kot večkratna regulacijska zanka. Regulacijsko blokovno shemo prikazuje slika 3.

1.1 **Feed servo drive in the *Y*— axis**

The drive has been designed with a DC servo motor fed with a block of power electronics. The concept of guiding in direction *Y* has been designed as a multi-loop control. The control block diagram is shown in fig. 3.



Sl. 3. *Blokovna shema podajalnega servopogona*
Fig. 3. *Block diagram of feed servo drive*

Notranja tokovna regulacijska zanka je izvedena z regulatorjem PI. Regulacijska zanka vrtilne hitrosti je prav tako izvedena z regulatorjem PI. Zaradi zahteve po veliki natančnosti pozicioniranja in ustreznem dinamičnem odzivu je merjenje v zunanji regulacijski zanki izvedeno z digitalnim merilnim sistemom in regulatorjem P ali PD. Dinamični opis posameznih regulacijskih komponent temelji na znanih fizikalnih načelih, ob upoštevanju podatkov iz literature [1], [2], [4] sledijo naslednje oblike prenosnih funkcij:

The inner current control loop has been designed with a PI unit. The control loop of speed has also been designed with a PI-unit. To meet the requirements for correct positioning and adequate dynamic response the measurement of the outer control loop has been designed with a digital measuring system and P or PD - unit. The dynamic description of the individual control components is based on known physical principles, and by considering the data in the references [1], [2], [4], results in the following forms of transfer functions:

$$H_{fsd}(s) = \frac{y(s)}{y_r(s)} = \frac{F_R(s)\,F_s(s)}{1+F_R(s)\,F_s(s)} \quad (1)$$

$$F_R(s) = K_{Ry}\,\frac{1+sT_d}{1+sT_d} \quad (2),$$

$$F_s(s) = K\,\frac{s^2 b + \dots + 1}{s(s^7 a + \dots + 1)} \quad (3).$$

K, a in b so konstante prenosnih funkcij, odvisne od konstrukcijskih komponent podajalnega servopogona [3].

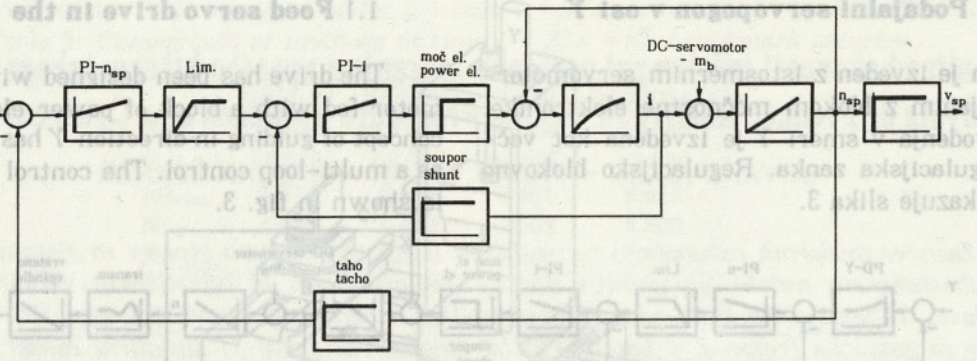
K, a and b are constants of transfer functions depending on the structural components of the feed servo drive. [3]

1.2 **Servopogon delovnega vretena**

Pogon delovnega vretena je podobno kakor podajalni pogon izveden kot večzančni regulacijski sistem. Notranja tokovna regulacijska zanka je izvedena z regulatorjem PI, prav tako pa tudi

1.2 **Work spindle servo drive**

The work spindle drive, like the drives of the feed axes, is designed with an inner current control loop with PI - unit and with outer work



Sl. 4. *Blokovna shema servo pogona delovnega vretena*
Fig. 4. *Block diagram of work spindle servo drive*

zunanja regulacijska zanka vrtilne hitrosti delovnega vretena n_{sp}. Regulacijsko blokovno shemo pogona prikazuje slika 4.

Dinamični opis v že navedeni literaturi daje naslednje oblike prenosnih funkcij:

spindle speed control loop n_{sp}, also with a PI - unit. The control block diagram is shown in fig. 4.

The dynamic description of the control components in the references is:

$$H_{wsd}(s) = \frac{n_{sp}(s)}{n_{spr}(s)} = \frac{F_R(s)F_s(s)}{1 + F_R(s)F_s(s)} \tag{4}$$

$$F_R(s) = K_{Rn}\frac{1 + sT_{In}}{sT_{In}} \tag{5}$$

$$F_s(s) = K\frac{sc + 1}{s(s^3 d + \ldots + 1)} \tag{6}$$

K, c in d so pripadajoče konstante v prenosnih funkcijah, odvisne od konstrukcijskih komponent pogona delovnega vretena [3].

K, c and d are corresponding constants depending on the structural components of the work spindle servo drive [3].

1.3 Povezava orodje — obdelovanec — vpenjalna naprava

Povezavo orodje — obdelovanec — vpenjalna naprava s simbolično nakazanimi konstrukcijskimi dinamičnimi konstantami prikazuje slika 5. Dinamični opis je zasnovan na analitičnih in eksperimentalnih ugotovitvah iz literature [6], prirejenih tehnološkim delovnim razmeram v našem tehnološkem laboratoriju.

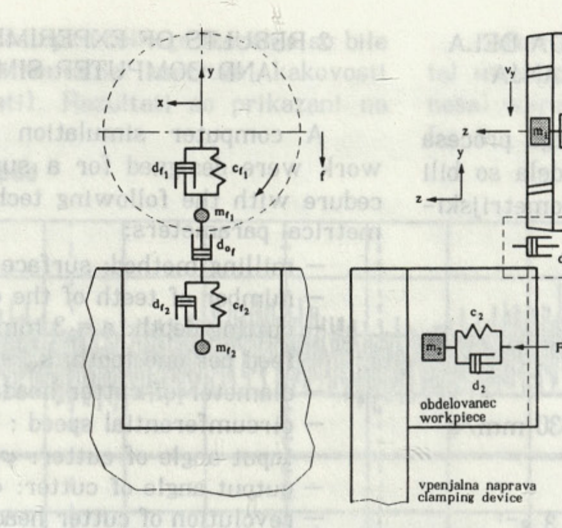
Prenosne funkcije, ki izhajajo iz teh ugotovitev, se v poenostavljeni obliki glasijo (poenostavitev je dopustna glede na ugotovitve preizkusov):

1.3 Combination: tool — workpiece — clamping device

The combination: tool — workpiece — clamping device with indicated structural dynamic constants is shown in fig. 5. The dynamic description is based on analytical and experimental findings from the references [6] adapted to the technological working conditions in our laboratory.

The transfer functions resulting from these findings read in a simplified form as follows (the simplification is admissible with regard to experimental findings):

$$F_m(s) = \frac{m(s)}{n_{sp}(s)} = \frac{K_m}{1 + sT_m} \tag{7}$$



Sl. 5. *Povezava orodje — obdelovanec — vpenjalna naprava*
Fig. 5. *Combination tool — workpiece — clamping device*

$$F_f(s) = \frac{f(s)}{v_y(s)} = \frac{K}{1 + sT_f} \quad (8),$$

$$F_{cd}(s) = \frac{z(s)}{f_z(s)} = \frac{K_{cd}}{1 + s2\beta + s^2 T_z^2} \quad (9).$$

K_m in K_f v enačbah (7) in (8) sta nelinearni spremenljivki, odvisni od tehnoloških razmer pri delu in sta v tesni povezavi z enačbo za izračun rezalne sile oz. momenta:

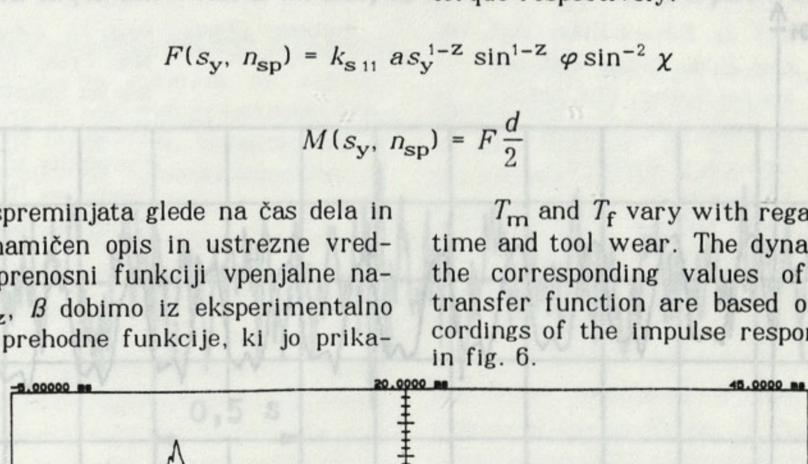
K_m and K_f in equations (7) and (8) are non-linear variables depending on technological working conditions and are in close connection with the equation for calculating the cutting force and torque respectively.

$$F(s_y, n_{sp}) = k_{s11}\, a s_y^{1-z} \sin^{1-z} \varphi \sin^{-2} \chi \quad (10),$$

$$M(s_y, n_{sp}) = F \frac{d}{2} \quad (11).$$

T_m in T_f se spreminjata glede na čas dela in obrabo orodja. Dinamičen opis in ustrezne vrednosti konstant v prenosni funkciji vpenjalne naprave (9) K_{cd}, T_z, β dobimo iz eksperimentalno posnete impulzne prehodne funkcije, ki jo prikazuje slika 6.

T_m and T_f vary with regard to the machining time and tool wear. The dynamic description and the corresponding values of constants in the transfer function are based on experimental recordings of the impulse response function shown in fig. 6.



Sl. 6. *Impulzna prehodna funkcija vpenjalne naprave*
Fig. 6. *Impulse response function of the clamping device*

2 REZULTATI EKSPERIMENTALNEGA DELA IN RAČUNALNIŠKEGA SIMULIRANJA

Računalniško simuliranje frezalnega procesa in ustrezni eksperimentalni rezultati dela so bili izvedeni s podanimi tehnološkimi in geometrijskimi parametri:

- metoda dela: čelno frezanje
- število zob orodja: $z = 5$
- globina reza: $a = 3$ mm
- podajanje na zob: $s_v = 0{,}15$ mm
- premer orodja: $D = 80$ mm
- obodna hitrost frezala: $v_{sp} = 1330$ mm/s
- vstopni kot frezala: $\varphi_1 = 29^0$
- izstopni kot frezala: $\varphi_2 = 29^0$
- vrtilna hitrost frezala: $n_{sp} = 5{,}3\ s^{-1}$

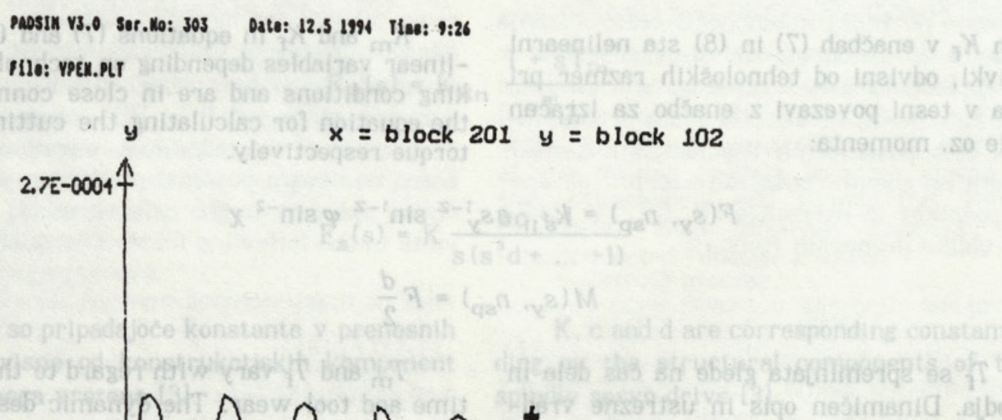
Računalniško simuliranje dinamičnega obnašanja aktivnih pogonskih osi in elementov sistema vpenjalna glava – obdelovanec – orodje je bila izvedena z uporabo simulirnega programa PADSIM, ki ga imamo v laboratorijih na Fakulteti za strojništvo v Mariboru in je inštaliran na osebnih računalnikih. Rezultat simuliranja prikazuje slika 7.

2 RESULTS OF EXPERIMENTAL WORK AND COMPUTER SIMULATION

A computer simulation and experimental work were designed for a surface milling procedure with the following technological and geometrical parameters:

- milling method: surface milling
- number of teeth of the cutter: z = 5
- cutting depth: a = 3 mm
- feed per one tooth: $s_v = 0.15$ mm
- diameter of cutter head: D = 80 mm
- circumferential speed : $v_{sp} = 1330$ mm/s
- input angle of cutter: $\varphi_1 = 29^0$
- output angle of cutter: $\varphi_2 = 29^0$
- revolution of cutter head: $n_{sp} = 5.3$ rps

The computer simulation of the dynamic behaviour of individual control drives and the elements of the system »clamping device–workpiece–tool« was carried out with the simulation programme PADSIM developed in the laboratories of the Faculty of Mechanical Engineering in Maribor and installed on a PC. The results of simulation are shown in figure 7.



Sl. 7. *Računalniško simuliranje podajanja vpenjalne naprave v smeri osi Z*

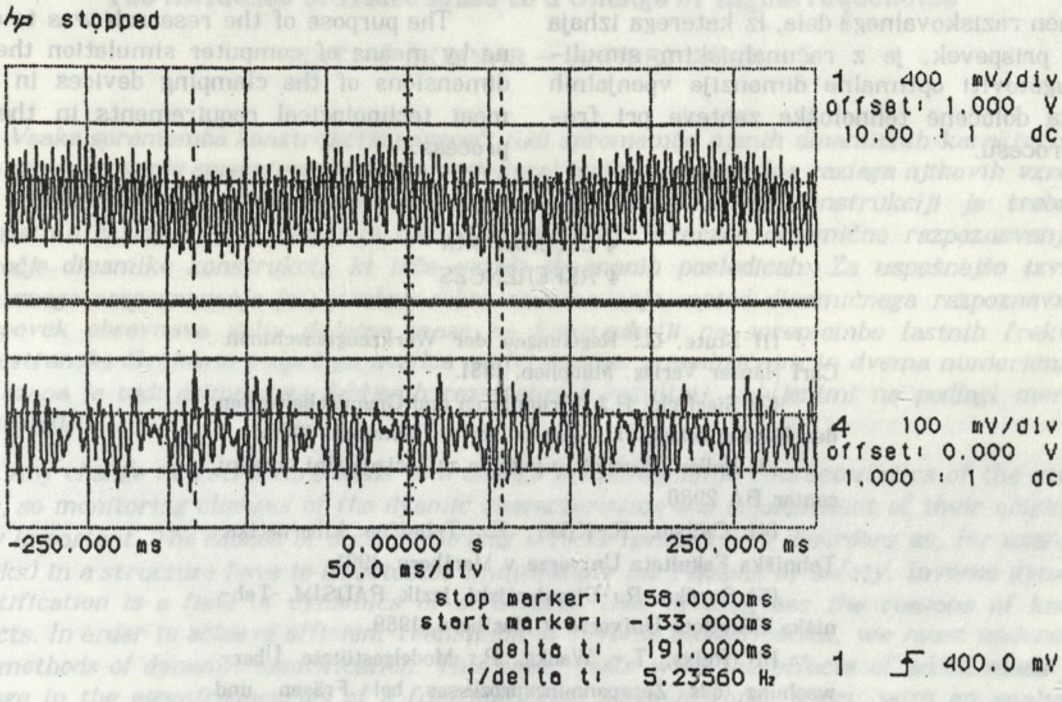
Fig. 7. *Computer simulation of the clamping device feed in axe Z*

Primerjalni eksperimentalni rezultati (sl. 8) so bili dobljeni na RK frezalnem stroju, tip BEA 1 podjetja Heller v Tehnološkem laboratoriju na Fakulteti za strojništvo v Mariboru.

Comparable experimental results were obtained on a CNC milling machine, type BEA 1, from the Heller company, in the Technological Laboratory of the Faculty of Mechanical Engineering in Maribor.

Po delovnem postopku čelnega frezanja so bile opravljene eksperimentalne meritve kakovosti obdelave (hrapavosti). Rezultati so prikazani na sliki 9.

After the face milling procedure, experimental measurements of machining quality (roughness) were carried out. The results are shown in fig. 9.

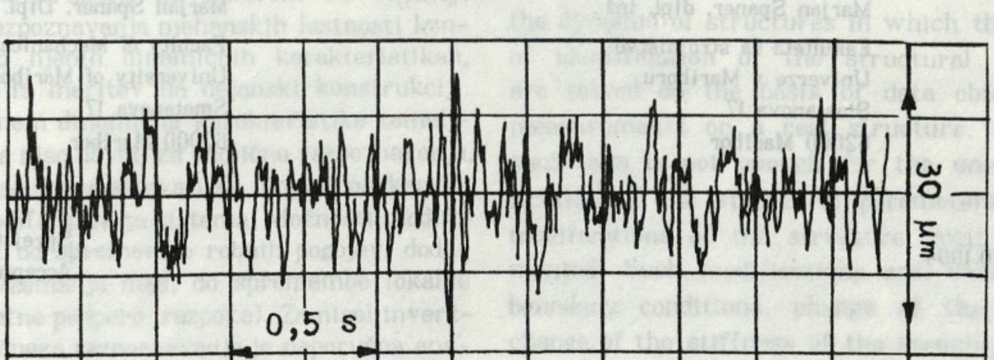


Sl. 8. *Eksperimentalni rezultati*

zgoraj: moment; spodaj: podajanje vpenjalne naprave v osi Z (100 mV/delec ≡ 90 μm)

Fig. 8. *Eksperimental results*

above: torque; below: feed of the clamping device in axe Z (100 mV/part ≡ 90 μm)



Sl. 9. *Rezultati merjenja hrapavosti obdelovanca*

Fig. 9. *Results of the workpiece roughness measurements*

3 SKLEP

Iz primerjave rezultatov računalniškega simuliranja dinamičnega obnašanja med procesom frezanja, eksperimentalnih rezultatov tega postopka ter eksperimentalnih meritev kakovosti

3 CONCLUSION

A comparison of the results of computer simulation of the dynamic behaviour during the milling process, experimental results of the same procedure and experimental measurement of the obdelave (hrapavosti) obdelovanca izhaja podobnost ugotovitev in medsebojna soodvisnost. Togost vpenjalne naprave močno vpliva na kakovost obdelave.

Namen raziskovalnega dela, iz katerega izhaja pričujoči prispevek, je z računalniškim simuliranjem ugotoviti optimalne dimenzije vpenjalnih naprav za določene tehnološke zahteve pri frezalnem procesu.

machining quality (roughness) of the work piece show a similarity of findings and interdependence. The rigidity of the clamping device has a strong influence on the machining quality.

The purpose of the research was to determine by means of computer simulation the optimal dimensions of the clamping devices in order to meet technological requirements in the milling process.

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