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Modelno podprt sistem za dinamično nastavljanje rezalnih parametrov pri postopku frezanja

A Model-Based System for the Dynamic Adjustment of Cutting Parameters during a Milling Process

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V prispevku je predstavljen modelno podprt mehanizem vodenja, ki z obvladovanjem rezalnih sil zagotavlja stalno kakovost obdelane površine pri postopku oblikovnega frezanja. Sistem z dinamično prilagajanje podajanja in vrtljajev obvladuje hrapavost površine ter rezalne sile na frezalu. Namen izdelave predlaganega mehanizma je poiskati omejitve takšnega načina vođenja, ki s prilagajanjem rezalnih parametrov ohranja stalno rezalno silo. Modelno podprt sistem vodenja je izdelan z razvojno metodo genetskega programiranja (GP). Za določitev empirične povezave med kakovostjo površine in rezalno silo je izdelan načrt preizkusov. Pri vnaprej definirani globini rezanja je preizkusno raziskan vpliv obdelovalnega materiala in rezalnih parametrov (podajanje, globina rezanja) na omenjeno povezavo.

Razvojna metoda GP je uporabljena za izpeljavo izkustvenih povezav med kakovostjo površine in rezalno silo pri obdelavi jekla. Te povezave se nato uporabijo pri izdelavi modelno podprtega sistema za dinamično nastavljanje rezalnih parametrov (SDNRP), v katerem se s krmiljenjem rezalnih sil dviga zahtevana kakovost površine. Rezultati zagotovijo načine za povečanje učinkovitosti postopka z izboljšanjem kakovosti površine, zmanjšanjem posledic spremenljivosti postopka in zmanjšanjem stroškov napak pri opravilih končne obdelave.

(Ključne besede: končno frezanje, rezilni parametri, genetsko programiranje, sistemi vodenja, modelno podprti sistemi)

This paper presents a model-based mechanism of control ensuring the constant quality of the surface finish by controlling the cutting forces during the end-milling process. Using the dynamic adaptation of feeding and speed the system controls the surface roughness and the cutting forces on the milling cutter. The purpose of developing such a mechanism is to find the limitations of this type of control, which maintains a constant cutting force by adapting the cutting parameters. This model-based system of control was developed by the evolutionary method of genetic programming (GP). A drawing of experiments was made in order to determine the empirical correlations between the quality of the surface finish and the cutting force. With the depth of cutting defined in advance the influence of the workpiece material and cutting parameters (feeding, cutting depth) on the abovementioned correlation has been experimentally researched.

The evolution genetic programming method (GP) was applied to derive an empirical relationship for the surface finish and the cutting force values for steel materials. These relationships were applied to develop the proposed evolution simulation model in which the cutting force is adjusted to improve the required surface quality for the end-milling process. The results provide a means for greater efficiency by improving the surface quality, minimizing the effect of the process variability and reducing the error cost during finishing operations.

(Keywords: end-milling, cutting parameters, genetic programming, model-based control)

0 UVOD

Vodenje postopkov frezanja je trenutno v središču pozornosti zaradi potencialnih ekonomskih

0 INTRODUCTION

The control of milling processes is currently receiving a lot of attention due to the potential koristi, povezanih z avtomatizacijo odrezovanja [1]. Deset odstotna dodatna investicija v izboljšanje zmogljivosti sistema vodenja povzroči 10-odstotno povečanje storilnosti frezanja. To pomeni 1000-kratno povrnitev investicije med dobro trajanja stroja [1]. Postopki frezanja so zanimivi z vidika vodenja zaradi težav, kakršne so nelinearnosti, časovno spremenljivi parametri in obraba orodja ([2] in [3]). Nedavno so mnogi raziskovalci preučevali ta problem [4]. Tehnike vodenja, ki so izdelane za postopke obdelave, tradicionalno zahtevajo neki način prilagajanja parametrov ([1] in [5]). Rešitev tega problema je prilagajajoče se vodenje. Prilagajajoče se sisteme vodenja vpeljeta v postopek odrezovanja Stute in Goetz [6]. Najpogosteje uporabljena sistema sta MRAC (modelno referenčno prilagajajoče se vodenje) [7] in STR (samonastavljivo krmiljenje) [8]. MRAC izhaja iz teorije prilagajajočega se vodenja in je pogosto uporabljen zaradi svoje grobosti in zmožnosti odpravljanja motenj. Izdelane so številne oblike sistema MRAC ([9] in [10]). Druga rešitev tega problema so inteligentne nadzorne strategije ([11] in [12]). Pomanjkljivost inteligentnih strategij je v tem, da računanje nevronske mreže in genetskega algoritma terja nekaj časa, kar omejuje odzivnost inteligentnega sistema vodenja.

Kljub začetnim razvojnim težavam je opaziti usmeritev nadgrajevanja računalniško krmiljenih (RK) frezalnih strojev s sodobnimi prilagojenimi sistemi. Zaradi potrebe po povečevanju storilnosti, zmanjševanju stroškov dela, preprečevanju delovnih nezgod, izboljšanju kakovosti obdelave in zmanjšanju človeškega vpliva na postopek se usmeritev avtomatizacije postopka frezanja še stopnjuje.

Za uspešno avtomatizacijo, pri kateri se postopek odvija brez človekovega posredovanja, je treba neprekinjeno spremljati postopek obdelave. To se najpogosteje izvede z merjenjem rezalnih sil, ker te vsebujejo največ informacij o postopku in stanju orodja. Z analizo značilke rezalne sile je mogoče oceniti spremembe v kakovosti obdelane površine [13].

Našteta dejstva so izhodišča za izdelavo modelno podprtega sistema za dinamično nastavljanje in optimiranje rezalnih parametrov (SDNRP). To je prilagajajoči se sistem vodenja, ki z neprekinjenim dinamičnim nastavljanjem rezalnih parametrov nadzoruje rezalno silo in ohranja stalno hrapavost obdelane površine med obdelavo. V okviru raziskave je izdelan simulacijski model, ki

economic benefits associated with automated machining [1]. An additional investment of 10% to increase the capabilities of the control system gives a 10% increase in productivity for the milling operations. Over the lifetime of a machine, this results in a return on investment of 1000 times [1]. Milling processes are interesting from a control perspective due to difficulties such as system nonlinearities, time-varying parameters and tool wear ([2] and [3]). Various investigations have looked at this problem in the recent past [4]. Control techniques that have been developed for machining traditionally require some form of parameter adaptation ([1] and [5]). One solution to this problem is adaptive control. An adaptive control system is introduced in the cutting process by Stute and Goetz [6]. The most frequently used systems are MRAC (Model Reference Adaptive Control) [7] and STR (Self Tuning Regulations) [8]. MRAC, developed from adaptive control theory, is widely used because of its robustness and disturbance-rejection capability. Numerous forms of the MRAC system have been developed ([9] and [10]). Another solution to this problem is a number of intelligent control strategies ([11] and [12]). The drawback of intelligent strategies is that neural-network- and genetic-algorithm-based calculations take time, which limits the response of the intelligent control system.

In spite of the initial difficulties in the development, a trend towards equipping CNC milling machines with modern adaptive systems is clear. Because of the requirements for increased productivity, reduced working costs, the prevention of accidents, improved quality of the milling and a reduced human influence on the process the trend towards automation of the milling process increases.

For effective automation, where the process takes place without human interference, continuous monitoring of the milling process is necessary. Most frequently, this is realised by measuring the cutting forces, because they contain the most information about the process and the tool's condition. By analyzing the cutting force's characteristics it is possible to assess the changes of the quality of the surface finish [13].

The above-mentioned facts are the basis for the development of a model-based system for the dynamic adjustment and optimization of the cutting parameters (SDNRP). This is an adaptive system of control, which controls the cutting force and maintains the constant roughness of the machined surface during milling by a continuous and dynamic adjustment of the cutting parameters. Within the frame of the se uporablja za testiranje stabilnosti in usklajevanje parametrov prilagajajočega se sistema SDNRP - Poglavje 5. SDNRP spreminja svoje odzive kot odgovor na motnje in spremembe v dinamiki postopka odrezovanja.

Po izvedenih simulacijah je sistem SDNRP popolnoma pripravljen in usklajen za uporabo v dejanskem postopku frezanja. Simulacijska shema predlaganega sistema je predstavljena na sliki 3.

1 MODELNO PODPRTO VODENJE POSTOPKA FREZANJA

Na modelu temelječ sistem vodenja vsebuje krmilnik, ki lahko prilagaja svoje delovanje kot odgovor na spremembe dinamike postopka in motnje. Če ostaja rezalna sila nespremenjena med postopkom obdelave, potem tudi kakovost površine ostane nespremenljiva. V prejšnjih raziskavah [14] se pridobi izhajajoča rezalna sila s pomočjo Kistlerjevega merilnika, ki določi tri pravokotne komponente dinamičnih sil: F_x, F_y, F_z. Te sile so izmerjene sproti z uporabo programske opreme LabView. Izmerjeni signali rezalnih sil se uporabijo v modelnem krmilniku pri uravnavanju rezalne sile. Glavni cilj te raziskave je izdelati na genetskem modelu temelječ sistem vodenja, ki lahko reši takšne zahtevne probleme vođenja odrezovanja. Cilj predlaganega sistema vodenja je krmiliti parametre postopka frezanja, to so podajanje in vrtilna frekvenca vretena ter ohranjati rezalno hitrost nespremenjeno, da se sproti doseže zahtevana vrednost kakovosti površine. Uporabimo frezalni stroj Heller BEA01 v povezavi s krmilnikom podajalnega pogona.

2 RK PODAJALNI SERVO-SISTEM STROJA

Preizkusi so izvedeni na RK frezalnem stroju Heller. To je štiriosni obdelovalni stroj, ki dopušča tri premike vzdolž osi X, Y in Z ter vrtenje palete v vodoravni ravnini. Vgrajeno je računalniško krmilje FAGOR 8040-M. Pogon podajalnih osi je prek krogličnih vodil izveden z izmeničnimi električnimi servomotorji, ki so sinhronizirani s trajnimi magneti. Oznaka servopogona je: Heller S 044/82 8-A20-2220-001/02C. Blokovno shemo (simulacijski model) podajalnega servosistema prikazuje slika 2. Številčne vrednosti stalnic blokovne sheme so prikazane v preglednici 1. Na vhodnem kanalu sistema pride do časovne

research a simulation model for testing stability and harmonizing parameters of the adaptive system (SDNRP), Section 5, has been developed. The SDNRP changes its reactions in response to disturbances and changes in the dynamics of the cutting process.

After the execution of the simulations the system (SDNRP) is fully ready and harmonized for use in a real milling process. The simulation diagram of the proposed system is presented in Figure 3.

1 MODEL-BASED MILLING-PROCESS CONTROL

A model-based control system is a controller that can modify its behaviour in response to a change in the dynamics of the process and the disturbances. If the cutting force is maintained constant during the process of machining, then the surface finish also remains stable. In previous research work [14] the resultant cutting force is obtained using a Kistler force transducer, which provides three orthogonal components of the dynamics forces, F_x, F_y, F_z, and these forces were measured online using LabView software. These measured cutting force signals are used in a model controller to regulate the cutting force. The main objective of this research is to develop a genetic model-based control system that can solve such difficult machining control problems. The objective of the proposed control system is to regulate the milling process' operation parameters, such as the feed rate and the spindle speed, and maintain the constant cutting force to achieve online the required value of the surface finish. A Heller BEA01 milling machine was used in connection with a feed drive controller.

2 CNC MACHINE FEED DRIVE SYSTEM

The tests were carried out on the Heller CNC milling machine. This is a four-axes machine tool allowing three translations along the *X*, *Y* and *Z* axes and rotation of the machine table in the horizontal plane. It is fitted with FAGOR 8040-M CNC controls. The feeding axles are driven through ball screw drives by AC servomotors synchronized with permanent magnets. The servo-drive type is Heller S 044/82 8-A20-2220-001/02C. The block diagram (simulation model) of the feeding servo-system is shown in Figure 2. The numerical values of the constants of the block diagram are presented in Table 1. On the input channel of the system a time delay in the transmission of the zakasnitve pri prenosu ukaza podajanja: to je posledica obdelave ukaznega signala v postopkovnem računalniku (PLK - programljivem krmilju RK sistema). Naloga PLK-ja je, da spremlja stanje zaznaval na stroju in ustrezno logično ustvarja ukaze za uporabnika in del računalniškega krmilja. Prenosna funkcija, ki podaja razmerje med spremembo ukaznega signala podajanja f_c in spremembo dejanske vrednosti podajanja delovne mize f_a ima naslednjo obliko:

command occurs: this is the result of processing the command signal in the processing computer (PLC-programmable controls of the CNC system). The duty of the PLC is to follow up the state of the sensors on the machine and to generate properly and logically the commands for the user and CNC part of the controls. The transfer function stating the relation between the change of the command signal of feeding f_c and the change of the actual value of feeding of the work table f_a has the following form:

$$\frac{f_a(s)}{f_c(s)}=\frac{K_i\cdot K_{ip}\cdot K_t\cdot e^{-s\cdot t}}{J_e\cdot L_a\cdot s^3+J_e(R_{ra}+K_H\cdot K_{ip})\cdot s^2+K_t(K_p\cdot K_{ip}+K_b)\cdot s+K_i\cdot K_t\cdot K_{ip}} \quad (1).$$

Z vstavljanjem tehničnih stalnic sistema iz preglednice 1 se zgornja prenosna funkcija preoblikuje v:

By entering the technical constants of the system from Table 1 the above transfer function is transformed as follows:

$$\frac{f_a(s)}{f_c(s)}=\frac{497000\cdot e^{-0.08s}}{(s+14,0)+(s^2+155s+35500)} \quad (2).$$

Zaradi majhne poenostavite uporabimo za simulacijski model podajalnega servo-sistema naslednjo prenosno funkcijo (sl. 1):

Because of a small simplification the following transfer function is used for the simulation model of the feeding servo-system (Fig. 1):

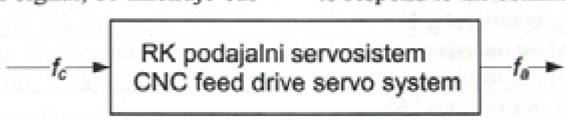
$$\frac{f_a}{f_c}=\frac{14,0\cdot e^{-0,08s}}{(s+14,0)} \quad (3),$$

kjer so:
- t = 8 s: čas zakasnitve,
- f_c: ukaz podajanja [mm/min],
- f_a: dejansko podajanje [mm/min].

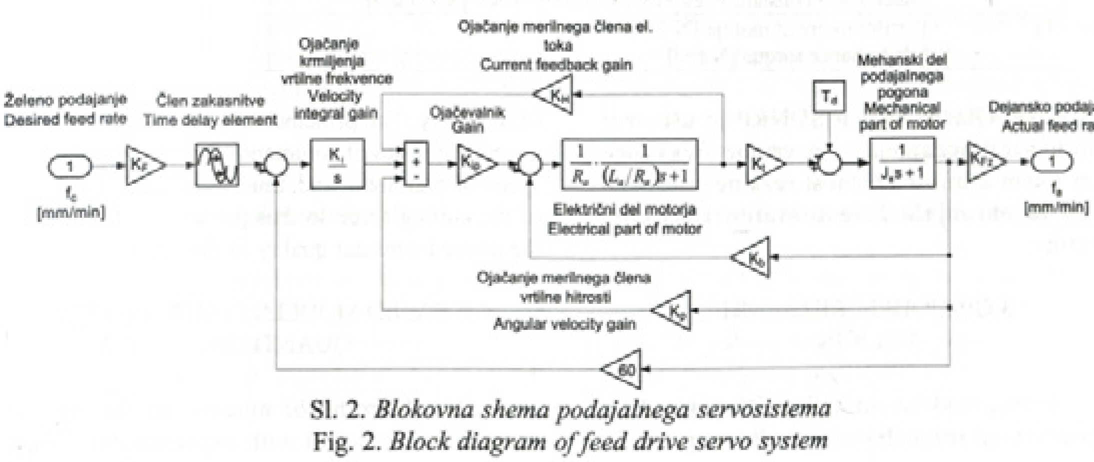
where:
- t = 8 s: time delay,
- f_c: feed rate command [mm/min],
- f_a: actual feed rate [mm/min].

Čas, ki je potreben, da se programljivo krmilje odzove na ukazni signal, se imenuje čas

The time required for programmable controls to respond to the command signal is called the time



Sl. 1. *Model RK podajalnega servosistema*
Fig. 1. *Model of the CNC feed drive system*



Sl. 2. *Blokovna shema podajalnega servosistema*
Fig. 2. *Block diagram of feed drive servo system*

Preglednica 1. *Heller Ltd. Tehnični podatki podajalnega servosistema*
Table 1. *Heller Ltd. Technical data for the feed drive system*

Parameter	Opis /Description	Vrednost/Value
f_c	želeno podajanje (ukaz podajanja) [mm/min] desired feed rate (Feed rate command) [mm/min]	-
f_a	dejansko podajanje [mm/min] actual feed rate [mm/min]	-
ω_c	ukaz kotne hitrosti [rad/min] angular velocity command [rad/min]	-
K_i	ojačanje I-krmilnika vrtilne hitrosti [V/(rad s)] velocity integral gain [V/(rad s)]	8,2
K_p	faktor ojačanja merilnega člena vrtilne frekvence [V/(rad s)] velocity proportional gain [V/(rad s)]	0,4944
V_{ic}	ukaz toka [f] current command [f]	-
K_H	faktor ojačanja - merilnik električnega toka [f/A] current feedback gain [f/A]	0,007
R_{ra}	upor rotorskega navitja [Ω] armature coil resistance [Ω]	0,15
K_t	stalnica vrtilnega momenta [N f m/A] torque constant [N f m/A]	0,165
T_m	stalnica vrtilnega momenta elektromotorja [N f m] electro motor torque gain [N f m]	-
J_e	ustrezna vztrajnost podajalnega pogona [N f m s] equivalent feed drive inertia [N f m s]	0,0146
ω_a	dejanska vrtilna frekvenca gredi motorja [rad/min] actual velocity [rad/min]	-
K_F	količnik ojačanja - vrtilna frekvenca [(rad/s)/(mm/min)] angular velocity gain [(rad/s)/(mm/min)]	0,105
K_{Fz}	ojačanje - podajanje [(mm/min)/(rad/s)] feed rate gain [(mm/min)/(rad/s)]	1,04
V_{if}	dejanski tok - povratna zveza [f] feedback current [f]	-
K_{ip}	proporcionalno ojačanje krmilnika toka current proportional gain	7,5429
L_a	induktivnost rotorskega navitja [mH] armature coil inductance [mH]	1,20
I_q	dejanski električni tok [A] actual current [A]	-
K_b	stalnica EMF – merilni člen hitrosti [V/(rad/s)] back EMF constant - velocity measuring block [V/(rad/s)]	0,38
T_d	vrtilni moment motnje [N f m] disturbance torque [N f m]	-

zakasnitve. Glavni namen SDNRP je ustvariti vrsto ukazov podajanja f_c in vrtilne frekvence n_c ter s tem krmiliti vrednost rezalne sile, tako da bo ta ohranjala želeno stalno kakovost površine.

of the delay. The principal aim of the SDNRP is to generate a series of commands for feeding f_c and the speed of rotating n_c and, thus, to regulate the values of the cutting force so that the latter will maintain the desired constant quality of the surface.

3 GP-MODELI REZALNIH VELIČIN

3 GP-BASED MODELS OF THE CUTTING QUANTITIES

Učenje modelov rezalnih veličin je izvedeno z izkustvenimi rezultati, ki so podani v prejšnjih

The learning of models for the cutting quantities is effected with experimental results raziskavah ([15] in [16]). Namen modelov je podati funkcionalne odvisnosti med vplivnimi odrezovalnimi parametri: vrtilno frekvenco, hrapavostjo površine in rezalno silo. Za določitev medsebojnih razmerij med vrtilno frekvenco in podajanjem ter rezalno silo in hrapavostjo je uporabljena metoda genetskega programiranja (GP). Pri GP je rezultat matematična formula, sestavljena iz nabora predpisanih opravil. Omenjena metoda bo predstavljena v nadaljevanju.

3.1 Modeliranje GP

V simulacijah se uporabijo GP modeli, ker jih je v simulacijskem paketu Simulink laže preoblikovati v blokovni zapis. Za izdelavo vsakega genetskega modela se uporabi 185 preizkusnih podatkov. Merilni podatek vsebuje vrednost napovedane (modelirane) veličine in pripadajoče vplivne parametre (rezalne parametre). Na podlagi vhodnih in merilnih podatkov ter ob izbranem naboru računskih opravil se ustvarijo modeli: K1, K2, K3, K4, K5=K6. Blokovne sheme najbolj prilagojenih modelov so podane v poglavju 3.2. Izbran je nabor naslednjih osnovnih računskih opravil $\mathcal{F} = \{+, -, *, u^v, \ln\}$ in razlogov $\mathcal{P} = \{2, 2, 3, 2\}$. Množica omejil ($\mathcal{T}$) je podana ob blokovni shemi posameznega modela. Množico omejil običajno sestavljajo vhodni podatki in spremenljivke sistema.

Za določitev modela odrezovanja (K4) je izbrana velikost populacije organizmov $M = 1500$ in število generacij $G = 100$. V drugih modelih je $M = 850$ in $G = 100$. Uporabljene so standardna genetska opravila reprodukcije, križanja in mutacije. Verjetnost reprodukcije je $p_r = 0{,}15$, križanja $p_c = 0{,}5$ in mutacije $p_m = 0{,}1$. Razvoj modela se ustavi, ko je doseženo predpisano število generacij ali ko je prilagojenost organizma večja od 97 odstotkov.

3.2 Izpeljani GP modeli rezalnih veličin

Pred vsako obdelavo je znana zahtevana kakovost obdelane površine R_a. Spodnja enačba podaja rezalno silo F_d, s katero se doseže in ohranja zahtevana hrapavost površine. Za modelni parameter F_d je po metodi GP izoblikovan naslednji obrazec:

stated in previous researches ([15] and [16]). The purpose of models is to define functional dependences between the influencing cutting parameters: spindle speed, surface roughness and cutting force. The genetic programming (GP) method is used for the determination of mutual relations between the rotating speed and feeding and between cutting force and roughness. In case of GP the result is the mathematical formula consisting of a series of prescribed operations. That method will be presented hereinafter.

3.1 GP Modelling

GP models are used in simulations because, in the simulation package Simulink, they can be more easily transformed into the block recording. A total of 185 pieces of experimental data are used to develop each genetic model. The experimental datum contains the value of the predicted (modelled) quantity and the appurtenant influencing parameters (cutting parameters). On the basis of the input and the experimental data and with a selected series of calculation operations the models, K1, K2, K3, K4, K5 = K6, are generated. The block diagrams of the most adapted models are given in Section 4.2. The series of the following basic calculation operations $\mathcal{F} = \{+, -, *, u^v, \ln\}$ and arguments $\mathcal{P} = \{2, 2, 3, 2\}$ is selected. The set of terminals ($\mathcal{T}$) is given in addition to the block diagram of the individual model. Usually, the set of terminals consists of input data and the variables of the system.

The size of the population of organisms, $M = 1500$, and the number of generations, $G = 100$, were selected for the determination of the model of cutting (K4). On other models $M = 850$ and $G = 100$. The standard genetic operations of reproductions, crossover and mutation were used. The reproduction probability, p_r, was 0.15, the crossover probability, p_c, was 0.5 and the mutation probability, p_m, was 0.1. The development of the model is stopped when the prescribed number of generations is reached or when the fitness of the organism is greater than 97 %.

3.2 Derived GP Models of Cutting Quantities

Prior to any machining the required quality of the surface finish R_a is set. The equation below gives the cutting force F_d with which the required surface roughness is reached and maintained. For the model parameter F_d the following formula was formed according to the GP method:

$$F_d = 293 - \frac{593}{\sqrt{39{,}37 \cdot R_a}} \quad (4).$$

Za določitev optimalnih rezalnih parametrov sta v uporabi naslednja GP modela:

The following two GP models are in use for the determination of the optimum cutting parameters:

$$f = 25{,}4 \cdot \left(189 - \frac{5926160}{F^2}\right) \quad (5)$$

$$n = \sqrt{(30064193 - 2{,}28 \cdot F^3)} \quad (6).$$

Pri tem sta: f - podajanje [mm/min], n - vrtljaji vretena [min^{-1}].

Where f is the feed rate [mm/min] and n is the spindle speed [min^{-1}].

Po zgornjih enačbah se določijo parametri, s katerimi se zagotavlja zahtevana hrapavost površine R_a. Cilj SDNRP je zagotavljati nespremenljivo rezalno silo F. Za simulacijo postopka odrezovanja se uporabi naslednji obrazec (modelni parameter K4).

The parameters with which the required surface roughness R_a is ensured are determined according to the above equations. The objective of the SDNRP is to ensure a constant cutting force F. The following formula (model parameter K4) is used to simulate the cutting process.

$$F = 286{,}44 - \left(\frac{5{,}82}{10^{10}}\right) \cdot n^3 - 8973 \cdot \frac{\ln(0{,}039 \cdot f)}{f} \quad (7).$$

Hrapavost površine se testira po naslednji enačbi:

The surface roughness is tested according to the following equation:

$$R_a = 0{,}0254 \cdot \left(\frac{593}{293 - F}\right)^2 \quad (8),$$

kjer sta: R_a: hrapavost površine [μm], F: rezalna sila [N].

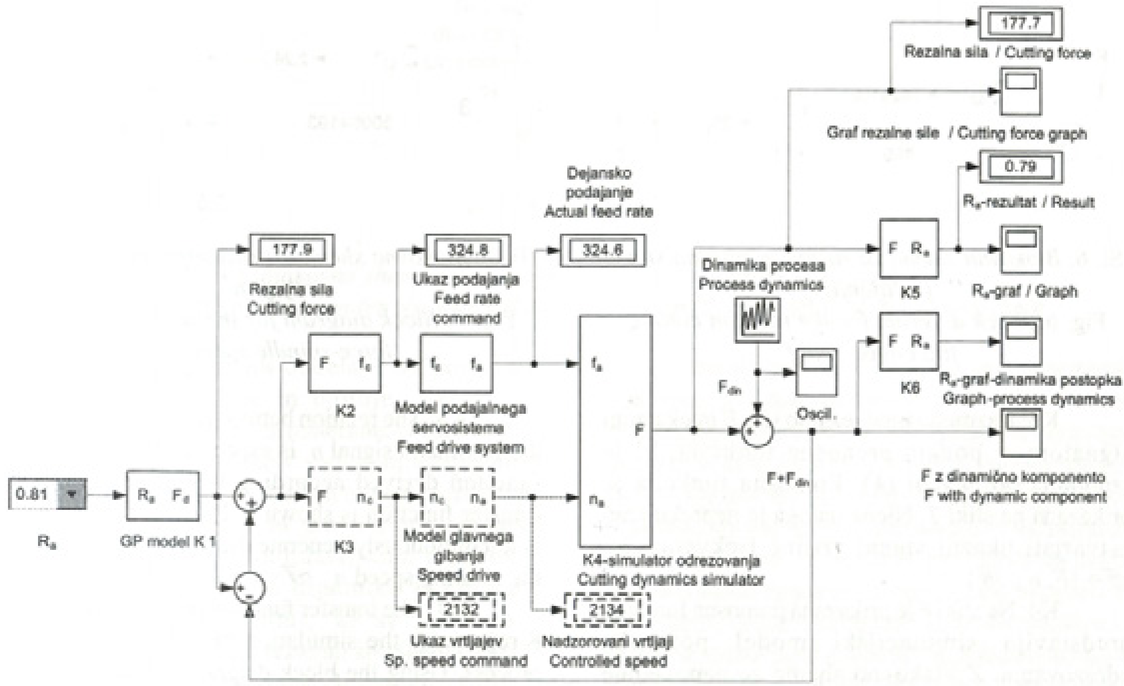
where R_a is the surface roughness [μm] and F is the cutting force [N].

4 SIMULATOR SDNRP

4 SIMULATOR OF SDNRP

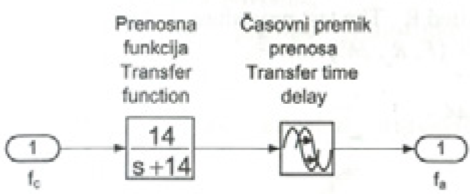
Blokovna shema simulatorja SDNRP je prikazana na sliki 3. Če v blokovni shemi nadomestimo model K4, simulacijski model podajalnega servosistema in model glavnega gibanja obdelovalnega stroja, dobimo usklajen sistem za dinamično nastavljanje rezalnih razmer, ki je pripravljen za takojšnjo uporabo. Sistem s krmiljenjem rezalne sile zagotavlja zahtevano hrapavost površine. Dinamika podajalnega servosistema je podana z enačbo (3). Enačba je izpeljana na temelju določil izdelovalca Heller Ltd. Blokovno shemo prenosne funkcije podajalnega servosistema prikazuje slika 4. Simulacijsko shemo sestavljajo: simulator računalniškega krmilja, simulator podajalnega in glavnega servopogona, simulator odrezovanja, primerjalni blok in modeli, ki določajo medsebojna razmerja med vplivnimi rezalnimi veličinami. Simulacijski modeli dinamike stroja so izdelani na temelju tehničnih določil izdelovalca Heller.

The block diagram of the simulator of the SDNRP is shown in Figure 3. If in the block diagram the model K4, the simulation model of the feed servo-drive and the model of main spindle rotation are replaced by the real machine tool, a harmonized system for the dynamic adjustment of cutting conditions, ready for immediate use, is obtained. The system with regulation of the cutting force ensures the required surface roughness. The dynamics of the feed servo-drive is defined with Equation 3. The equation is derived on the basis of the specifications of the maker, Heller Ltd. The block diagram of the transfer function of the feed servo-drive is shown in Figure 4. The simulation diagram comprises the simulator of CNC controls, the simulator of the feed and main servo-drive, the simulator of the cutting, the reference block and the models determining the mutual relations between the influencing cutting values. The simulation models of the machine dynamics are made on the basis of the technical specifications of the maker, Heller.



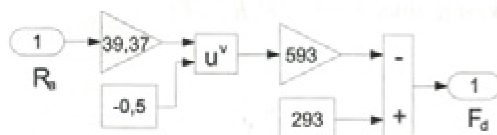
Sl. 3. *Blokovna shema sistema za dinamično nastavljanje rezalnih parametrov*

Fig. 3. *Block diagram of the system for dynamic adjusting of the cutting parameters*



Sl. 4. *Prenosna funkcija podajalnega servosistema*

Fig. 4. *Feed-drive servo-system transfer function*



Sl. 5. *Blokovna shema za razmerje hrapavost površine - rezalna sila*

Fig. 5. *Block diagram for the relation surface roughness-cutting force*

V nadaljevanju so podrobno predstavljene prenosne funkcije posameznih elementov SDNRP in pretok signalov med njimi.

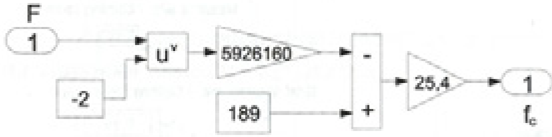
K1: Slika 5 prikazuje prenosno funkcijo, ki podaja odvisnost med želeno hrapavostjo površine in pripadajočo rezalno silo F_d. Prenosna funkcija je podana v obliki blokovne sheme. Modeliranje je izvedeno s standardno zbirko blokov v programskem paketu Matlab 6.5. Uporabljena je množica omejil: $\mathscr{T} = \{R_a, F_d, \mathscr{R}\}$. $\mathscr{R}$- realna števila na območju od -10 do 10.

K2: Prenosna funkcija za napovedovanje optimalnega podajanja f_c je izpeljana po enačbi (5). Slika 6 prikazuje njeno blokovno shemo. $\mathscr{T} = \{F, f_c, \mathscr{R}\}$.

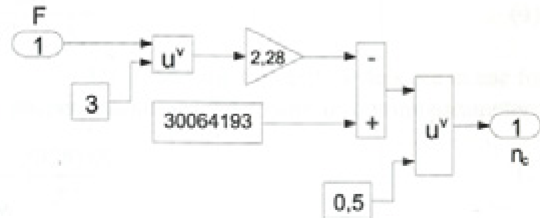
In the following the transfer functions of the individual elements of the SDNRP and the flow of signals between them are presented in detail.

K1: Figure 5 shows the transfer function defining the dependence between the desired surface roughness and the appurtenant cutting force F_d. The transfer function is given in the form of block diagrams. Modelling is effected with the standard set of blocks in the programme package Matlab 6.5. The set of terminals $\mathscr{T} = \{R_a, F_d, \mathscr{R}\}$ is used, where $\mathscr{R}$ is a real number in the interval from -10 to 10.

K2: Transfer function for the prediction of the optimum feeding f_c is derived according to Equation 5. Figure 6 shows its block diagram. $\mathscr{T} = \{F, f_c, \mathscr{R}\}$.



Sl. 6. *Blokovna shema za razmerje rezalna sila - podajanje f_c*
Fig. 6. *Block diagram for the relation cutting force-feed rate f_c*



Sl. 7. *Blokovna shema za razmerje rezalna sila - vrtljaji n_c*
Fig. 7. *Block diagram for the relation cutting force-spindle speed n_c*

K3: Razmerje med rezalno silo F in ukaznim signalom n_c podaja prenosna funkcija, ki je izpeljana po enačbi (4). Prenosna funkcija je prikazana na sliki 7. Njena naloga je neprekinjeno ustvarjati ukazni signal vrtilne frekvence n_c. $\mathcal{T}=\{F, n_c, \mathcal{R}\}$.

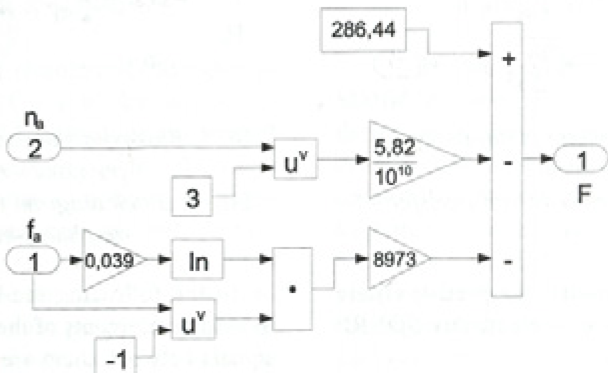
K4: Na sliki 8 je prikazana prenosna funkcija predstavlja simulacijski model postopka odrezovanja. Z blokovno shemo se napoveduje vrednost dejanske rezalne sile na rezilu orodja, in sicer pri danih rezalnih razmerah. $\mathcal{T}=\{n_a, f_a, F, R\}$.

K5, K6: Z blokovno shemo testiramo, ali se simulirana R_a ujema z želeno R_a. Testni postopek prikazuje slika 9. $\mathcal{T}=\{F, R_a, \mathcal{R}\}$.

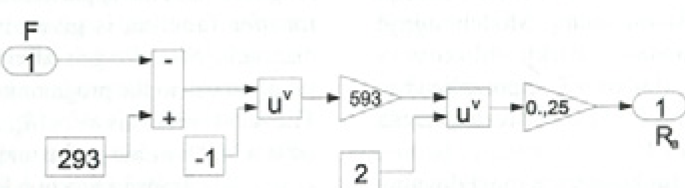
K3: The relation between cutting force F and the command signal n_c is expressed by the transfer function derived according to Equation 4. The transfer function is shown in Figure 7; its purpose is to continuously generate the command signal of the rotating speed n_c. $\mathcal{T}=\{F, n_c, \mathcal{R}\}$.

K4: The transfer function presented in Figure 8 represents the simulation model of the cutting process. Using the block diagram the value of the actual cutting force on the tool cutter with given cutting conditions is predicted. $\mathcal{T}=\{n_a, f_a, F, R\}$.

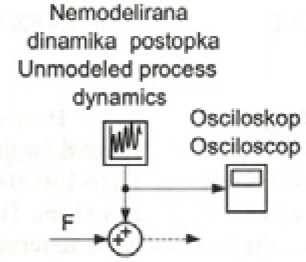
K5, K6: Using the block diagram we can test whether the simulated R_a corresponds to the desired R_a. The test procedure is shown in Figure 9. $\mathcal{T}=\{F, R_a, \mathcal{R}\}$.



Sl. 8. *Simulator postopka odrezavanja*
Fig. 8. *Cutting-process simulator*



Sl. 9. *Blokovna shema za preizkušanje kakovosti površine*
Fig. 9. *Block diagram of surface-finish inspections*



Sl. 10. *Blokovna shema za ustvarjanje dinamične komponente rezalne sile*
Fig. 10. *Block diagram for the generation of the dynamic component of the cutting force*

Med postopkom obdelave se pojavljajo nezaželene vibracije in motnje. Vzroki so: nehomogenost osnovnega materiala, obraba orodja, poškodbe orodja, napake v vodilih in ležajih stroja itn. Z vključevanjem naključnih motenj v simulacijo se testirata stabilnost in grobost predlaganega sistema vodenja. V simulacijskem modelu se ustvarja nemodelirano dinamiko postopka z naključnimi vrednostmi, ki se ujemajo z oscilacijami izmerjenih rezalnih sil. Shema na sliki 10 simulira nemodelirano dinamiko stroja in postopka.

Med simulacijo se na diagramih nadzorne konzole izrisujejo naslednje veličine:

- dejanska hrapavost površine,
- hrapavost površine pri upoštevani dinamiki stroja,
- največja rezalna sila,
- največja rezalna sila z dinamično komponento,
- dejansko podajanje,
- dejanski vrtljaji vretena.

5 POTEK IZVEDBE SIMULACIJE SDNRP

Zmogljivost SDNRP je testirana s simulacijami. Uporabljen je Matlabov simulacijski paket Simulink. Simulacijo sprožimo z nastavitvijo referenčne vrednosti R_a, nato se po modelu K1 napove želena rezalna sila F_d. Ko je znana sila F_d, se po modelu K2 in K3 v trenutku izračunajo vrednosti f_c in n_c. Dinamični odziv servosistema na signal f_c je simuliran z blokovno shemo, ki je podana na sliki 2. Prenosni funkciji servosistemov ustvarjata dejansko podajanje f_a in vrtljaje n_a, tako da je po modelu K4 napovedana rezalna sila nespremenljiva. Simulirana R_a se določi s prenosno funkcijo modela K5.

During the machining process undesirable vibrations and disturbances occur. They are caused by inhomogeneity of the base material, tool wear, tool damage, defects in guides and bearings of the machine, etc. By introducing the random disturbances into the simulation the stability and robustness of the proposed control system can be tested. In the simulation model the unmodeled dynamics of the process is generated by random values corresponding to the oscillations of the measured cutting forces. The diagram in Figure 10 simulates the unmodeled dynamics of the machine and the process.

During the simulation the following values are drawn in the diagrams of the control console:

- Actual surface roughness,
- Surface roughness considering the machine-tool dynamics,
- Maximum cutting force,
- Maximum cutting force with the dynamic component,
- Actual feeding,
- Actual spindle speed.

5 THE REALIZATION COURSE OF THE SDNRP SIMULATION

The SDNRP capacity was tested by simulations. For this we used the Matlab simulation package Simulink. The simulation is initiated by the adjustment of the reference value R_a; afterwards the desired cutting force F_d is predicted according to the model K1. When the force F_d is known, the values F_c and n_c are calculated within a moment according to the model K2 and K3. The dynamic response of the servo-system to the signal f_c is simulated by the block diagram given in Figure 2. The two transfer functions of the servo-systems generate the actual feeding f_a and speed n_a, so that the cutting force, predicted according to the model K4, is constant. The simulated R_a is determined by the transfer function of the model K5.

6 PRIMER IZVEDENE SIMULACIJE SDNRP

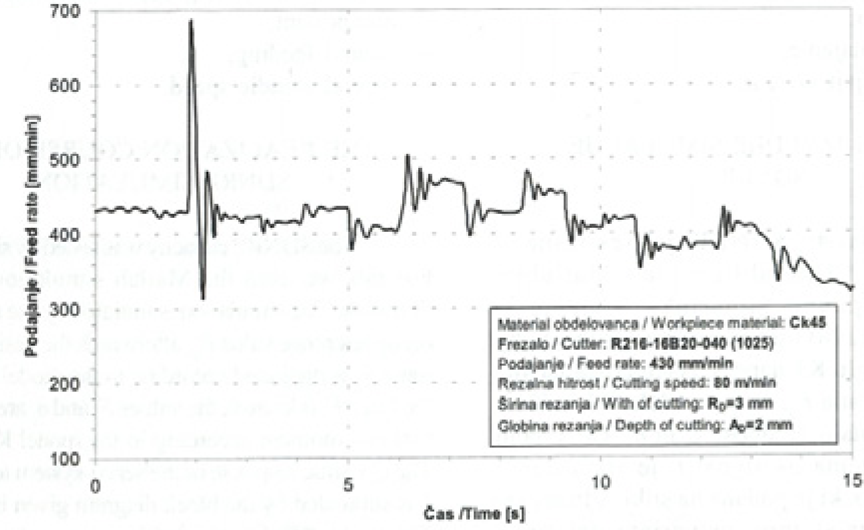
V nadaljevanju je prikazana simulacija št. 5 (pregl. 3), ki je izvedena za material Ck45 in frezalo R216-16B20-040. Izbrana primerjalna hrapavost je 0.81 mm. Začetni optimalni rezalni parametri so določeni z algoritmom PSO (optimizacija, ki oponaša gibanje delcev v velikih jatah) [17]. Podani so v preglednici 2. Rezultat simulacije je prikazan na blokovni shemi slike 4. Začetna vrednost podajanja je 430,4 mm/min. Sistem to vrednost spreminja, dokler ne doseže optimalnega podajanja 324,6 mm/min. Optimalna končna vrtilna frekvenca je 2134 min^{-1}. Dinamično nastavljanje podajanja in vrtilne frekvence je nujno za ohranjanje stalne največje rezalne sile 177,7 N. Rezultat simulacije je hrapavost 0,79 μm, ki je v primerjavi z želeno vrednostjo 0,81 μm sprejemljiva (sl. 16). Potek simulacije je prikazan na slikah 11 in 12. Razvidno je, da se z neprestanim nastavljanjem rezalnih parametrov zagotavlja zahtevana hrapavost pri največji dovoljeni obremenitvi orodja.

6 AN EXAMPLE OF A REALIZED SDNRP SIMULATION

Here we present simulation No. 5 (Table 3), effected for the material Ck45 and the milling cutter R216-16B20-040. The selected reference roughness is 0.81μm. The starting optimum cutting parameters were determined by the PSO (Particle Swarm optimization) algorithm [17]; they are given in Table 2. The simulation result is shown in the block diagram of Figure 4. The initial value of feeding is 430.4 mm/min. The system changes that value until the optimum feeding of 324.6 mm/min is reached. The optimum final spindle speed is 2134 min^{-1}. Dynamic adjustment of the feeding and spindle speed is a prerequisite for maintaining a constant maximum cutting force of 177.7 N. The simulation result is a roughness of 0.79 μm, which is acceptable when compared with the desired value 0.81 μm (Fig. 16). The process of the simulation is shown in Figure 11 and Figure 12. It is clear that with continuous adjusting of the cutting parameters the required roughness is ensured with the maximum allowable tool loading.

Preglednica 2. *Začetne rezalne razmere*
Table 2. *Initial cutting conditions*

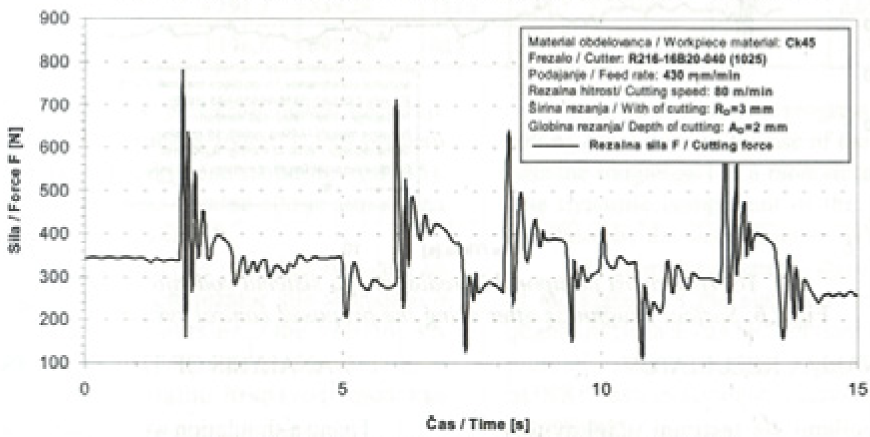
v_c = 80 m/min	R_D = 3 mm
f = 430,4 mm/min	A_D = 2 mm



Sl. 11. *Dinamično nastavljanje podajanja med simulacijo*
Fig. 11. *Dynamic adjusting of the feed rate during simulation*

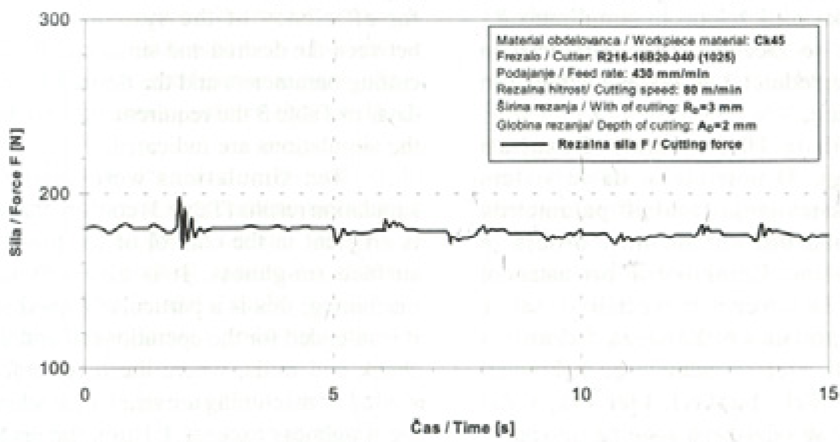
Sl. 12. *Dinamično nastavljanje vrtilne frekvence med simulacijo*

Fig. 12. *Dynamic adjusting of the spindle speed during simulation*



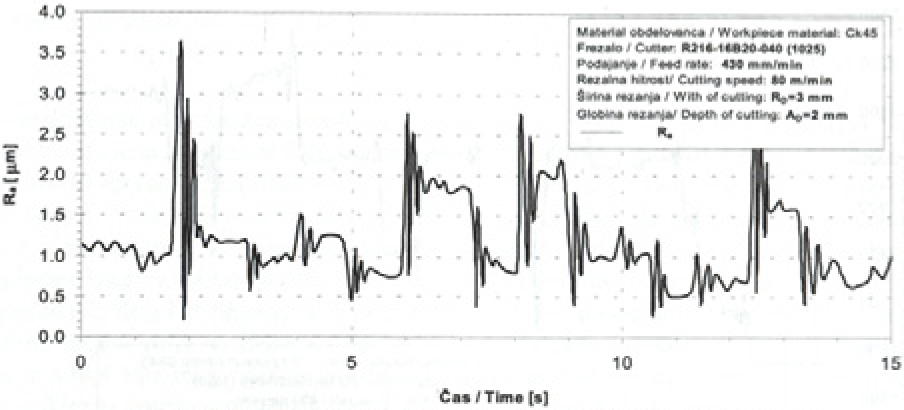
Sl. 13. *Potek rezalne sile brez uporabe SDNRP*

Fig. 13. *The course of the cutting force without the application of SDNRP*

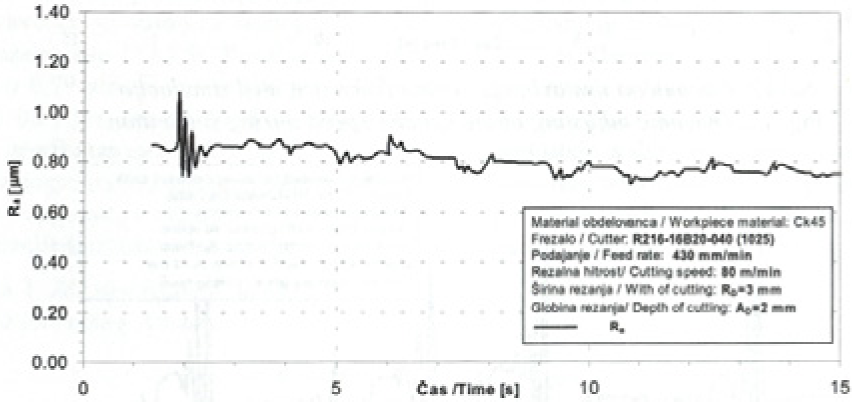


Sl. 14. *Potek rezalne sile pri dinamičnem nastavljanju rezalnih parametrov*

Fig. 14. *The course of the cutting force with dynamic adjusting of the cutting parameters*



Sl. 15. *Hrapavost pred uporabo predlaganega sistema vodenja*
Fig. 15. *Surface roughness before using the proposed control system*



Sl. 16. *Hrapavost po uporabi predlaganega sistema vodenja*
Fig. 16. *Surface roughness after using the proposed control system*

7 ANALIZA REZULTATOV

S simulacijami sta testirani učinkovitost in stabilnost SDNRP pri različnih zahtevah kakovosti površine. Merilo za učinkovitost sistema je razlika med želeno in simulirano R_a. Vhodni podatki so začetni rezalni parametri in želena R_a. V preglednici 3 so podane zahteve in rezultati simulacij.

Izvedenih je 10 simulacij. Rezultati simulacij (pregl. 3) potrjujejo, da je sistem dinamičnega nastavljanja rezalnih parametrov učinkovit pri nadzoru obremenitev orodja in hrapavosti površine. Učinkovit je pri natančni obdelavi; to je še posebej razveseljivo, saj je namenjen za opravila oblikovnega frezanja s paličnimi frezali, kjer so zahteve po kakovosti obdelave ostre. Pri obdelavi, kjer hrapavost preseže 1,1 µm, se odzivnost sistema upočasni. Zmanjša se njegova občutljivost za doseganje želene hrapavosti.

7 ANALYSIS OF THE RESULTS

Using a simulation we can test the efficiency and stability of the SDNRP with different requirements for the surface quality. The criterion for efficiency of the system is the difference between the desired and simulated R_a. The starting cutting parameters and the desired R_a are the input data. In Table 3 the requirements and the results of the simulations are indicated.

Ten simulations were carried out. The simulation results (Table 3) confirm that the SDNRP is efficient in the control of the tool loading and surface roughness. It is also efficient in fine machining; this is a particularly good result, since it is intended for the operations of end milling with shank end mills, where the requirements for the quality of machining are strict. In machining, where the roughness exceeds 1.1 µm, the responsiveness of the system is slowed down and its sensitivity for reaching the desired roughness is reduced.

Preglednica 3. *Preizkusni rezultati simulacij*
Table 3. *Simulation experimental results*

Sim. št.: Sim no.:	Želena hrapavost površine Desired surface roughness R_a [μm]	Začetni rezalni parametri pred simulacijo Initial cutting conditions before simulation			Servo pogonski sistem po 15s Servo drive system after 15s			Dejanska hrapavost površine Produced surface finish R_a [μm]
		F_d [N]	f_c [mm/min]	n_c [min^{-1}]	F [N]	f_a [mm/min]	n_a [min^{-1}]	
1	0,38	161,4	357,12	1974	166,5	264,92	2443	0,50
2	0,51	166,67	379,98	1895	169,9	282,19	2356	0,58
3	0,64	172,1	414,53	1704	173,0	297,94	2272	0,66
4	0,76	176,8	435,26	1563	175,9	313,94	2189	0,74
5	0,81	178,5	430,41	1571	177,7	324,61	2134	0,79
6	0,89	180,9	462,19	1437	178,6	329,95	2108	0,81
7	1,02	184,7	485,14	1377	181,6	350,52	2007	0,91
8	1,14	188,1	507,75	1270	183,9	355,60	1925	0,99
9	1,27	191,2	539,24	1116	185,7	381,25	1880	1,05
10	1,52	196,8	592,58	825	195,2	411,99	1716	1,18

Na sliki 13 je prikazan potek največje rezalne sile brez uporabe SDNRP. V tem primeru ima tudi hrapavost naključna usmeritev (sl. 15). Dinamična komponenta rezalne sile je simulirana z blokovno shemo na sliki 10.

Iz grafov simulacij je razvidno, da lahko na podlagi signalov največje rezalne sile sklepamo o kakovosti obdelane površine. Obe veličini sta medsebojno povezani in imata enake usmeritve. SDNRP zagotavlja stalno hrapavost med vso obdelavo.

Simulacije potrdijo, da je predlagani sistem učinkovit pri zagotavljanju zahtevane hrapavosti in ohranjanju nespremenljive obremenitve stroja. Sistem vodenja se na skok rezalne sile odzove s takojšnjim zmanjšanjem podajanja; iz tega izhaja padec rezalne sile na raven primerjalne vrednosti (sl. 14).

Stalne rezalne obremenitve privedejo do boljše kakovosti površine in preprečijo nezaželene vibracije in povese rezalnega orodja. Izboljšanje kakovosti površine je najbolj opazno pri obdelavi kotov, žepov, utorov in ukrivljenih površin, pri katerih sistem z zmanjšanjem podajanja prepreči nezaželene povese frezala.

Sistem nekoliko slabše sledi hitrim spremembam rezalnih razmer; to je posledica njegove zapletene zgradbe in napak pri modeliranju. Vzrok za počasno odzivnost in

Figure 13 shows the progress of the maximum cutting force without the use of the SDNRP. In this case the roughness has a random trend (Figure 15). The dynamic component of the cutting force is simulated by the block diagram in Figure 10.

The simulation graphs show that on the basis of the signals of the maximum cutting force the quality of surface can be supposed. Both values are mutually related and have identical trends. The SDNRP ensures constant roughness throughout the machining.

The simulations confirm that the proposed system is efficient for ensuring the required roughness and maintaining the constant machine loading. The control system responds to the rise of the cutting force by an immediate reduction of the feeding; as a result, the cutting force drops to the reference value (Figure 14).

Constant cutting loadings lead to a better quality of surface and prevent undesirable vibrations and deflections of the cutting tool. The improvement of the surface quality is most obvious when machining corners, pockets, slots and curved surfaces, where the system prevents undesirable milling cutter deflections by a reduction of the feeding.

The system deals with rapid changes to the cutting circumstances not so well, due to its complex structure and the errors in modelling. The reason for the slow responsiveness and inaccuracy can also be nenatančnost je treba iskati tudi v načinu izgradnje simulacijskega modela podajalnega servosistema. V simulator SDNRP je vključen model podajalnega servo-sistema, ki deluje po poenostavljeni prenosni funkciji (en. (3)). Ta je matematično izpeljana na podlagi določil proizvajalca. S preizkusnim posnetjem dinamike podajalnega servosistema, je mogoče odzivnost sistema močno izboljšati.

Rezultati simulacij nakazujejo naslednje ugotovitve:

- Modelno podprt sistem za dinamično nastavljanje rezalnih parametrov je zmožen nadzorovati rezalno silo v širokem območju rezalnih parametrov.
- Zahtevana hrapavost se doseže s simultanim nastavljanjem podajanja in rezalne hitrosti.
- Sistem je stabilen.
- Signali največjih rezalnih sil so v odvisnosti od hrapavosti površine.
- Največje odstopanje dejanske hrapavosti od izmerjene je 4,1 %.
- Največje odstopanje vodene rezalne sile proti primerjalni je 5,2 %.
- Sistem je najbolj učinkovit pri opravilih natančne obdelave, pri kateri hrapavost površine ne preseže 1,1 μm.

8 POVZETEK

V prispevku je predstavljen modelno podprt sistem dinamičnega nastavljanja rezalnih parametrov. Sistem z dinamičnim prilagajanjem podajanja in vrtljajev obvladuje hrapavost površine ter rezalne sile na frezalu. Med obdelavo spremlja vrednosti največjih rezalnih sil. Soodvisnost med hrapavostjo površine in rezalnimi silami določimo z metodo GP. Za primerjavo so izpeljane z metodo genetskega programiranja še matematična razmerja med vplivnimi rezalnimi veličinami, ki so osnova za izdelavo računalniških simulacij v paketu Simulink.

S simulacijami je potrjena ustreznost in stabilnost sistema vodenja. Dokazano je, da lahko z obvladovanjem rezalnih sil uspešno nadzorujemo hrapavost površine, ki je bistven kazalnik kakovosti postopka. Z ohranjanjem nespremenljive rezalne sile zagotavljamo stalno kakovost obdelane površine.

Na podlagi rezultatov številnih simulacij se odločimo, da preizkusno izvedemo opisan sistem

traced to the manner of the development of the simulation model of the feeding servo-system. The SDNRP simulator incorporates the model of the feeding servo-system, which functions according to the simplified transfer function (Equation 3). The latter is mathematically derived on the basis of the maker's specifications. By experimentally capturing the dynamics of the feeding servo-system it is possible to considerably improve the responsiveness of the system.

The simulation results indicate the following findings:

- A model-based system for dynamically adjusting the cutting parameters is capable of controlling the cutting force over a wide range of cutting parameters.
- The required roughness is reached by simultaneous adjustment of the feeding and cutting speeds.
- The system is stable.
- The signals of the maximum cutting forces correlate with the surface roughness.
- The maximum deviation of the actual from the measured roughness is 4.1%.
- The maximum deviation of the controlled from the reference cutting force is 5.2%.
- The system is most efficient during fine-machining operations, where the surface roughness does not exceed 1.1 μm.

8 CONCLUSION

This paper presents a model-based system for dynamically adjusting cutting parameters. By a dynamic adaptation of the feeding and spindle speed the system controls the surface roughness and the cutting forces on the milling cutter. During machining it follows the values of the maximum cutting forces. The correlation between the surface roughness and the cutting forces is determined by the GP method. Furthermore, mathematical relations between the influencing cutting values, on which the development of the computer simulations in the package Simulink is based, are derived for comparison.

Using simulations the adequacy and stability of the control system are confirmed. It was proved that the surface roughness, which is an important indicator of the process quality, can be successfully controlled by controlling the cutting forces, and by maintaining a constant cutting force a constant quality of surface finish is ensured.

On the basis of the results of numerous simulations we decided to realize experimentally vodenja. Sistem je zasnovan za opravilo oblikovnega frezanja, čeprav ga je mogoče prilagoditi za vse postopke obdelave z odrezovanjem. Primeren je za vključitev v obdelovalne sisteme, ki se uporabljajo v avtomobilski in orodjarski industriji. Odpravlja probleme, ki so povezani z zagotavljanjem kakovosti obdelave, učinkovitosti obdelave in preprečevanjem poškodb orodja.

the described system of control. The system was conceived for the end milling operation, although it can be modified for all processes of machining by cutting. It is suitable for the incorporation into manufacturing systems used in the automobile and tool-making industries. It also eliminates the problems related to the ensurance of the quality of machining, the efficiency of machining and the prevention of tool damage.

7 LITERATURA
7 REFERENCES

[1] Ulsoy, A.G., Y. Koren (1993) Control of machining processes, *J. of Dynamic Systems Measurement and Control* 115(1993), pp. 291-300.

[2] Balič, J. (2000) A new NC machine tool controller for step-by-step milling, *Int. j. adv. manuf. technol.* 8(2000) pp. 399-403.

[3] Cus, F., U. Zuperl, E. Kiker, M. Milfelner (2006), Adaptive controller design for feedrate maximization of machining process, *Journal of Achievements in Materials and Manufacturing Engineering* 17(2006),pp. 237-240.

[4] Tlusty, J., M.A. Elbestawi (1977) Analysis of transients in an adaptive control servomechanism for milling with constant force, *Transactions of the ASME, Journal of Engineering for Industry* 99(1977), pp. 766-772.

[5] Koren, Y. (1983) Computer control of manufacturing systems, New York, McGraw±Hill, 1983

[6] Stute, G., F.R. Goetz (1975) Adaptive control system for variable gain in ACC systems, *Proceedings of the Sixteenth International Machine Tool Design and Research Conference*, Manchester England, pp. 117-121.

[7] Tomizuka, M., J.H. Oh, D.A. Dornfeld (1983) Model reference adaptive control of the milling process, *Proceedings of the Symposium on Manufacturing on Manufacturing Process and Robotic Systems*, New York, (1983), pp.55-63.

[8] Huang, S.J., C.C. Lin (2002), A self-organising fuzzy logic controller for a coordinate machine, *Int. J. Adv. Manuf. Technol.* 19(2002), pp.736-742.

[9] Ahmed, M.S. (1995) BPD computation and model reference adaptive control of Hammerstein plants, *IEE Proceedings Part-D (Control Theory and Application)*, 142 (1995), pp. 475-485.

[10] Daeshmend, L.K., H.A. Pak (1986) Model reference adaptive control of feed force in turning, *ASME J. of Dynamic Systems, Measurement and Control* 108(1986), pp. 215-222.

[11] Liu, Y., L. Zuo, C. Wang (1999) Intelligent adaptive control in milling process, *International Journal of Computer Integrated Manufacturing,* 12(1999), pp. 453-460.

[12] Liu, Y., C. Wang, (1999) Neural networks based adaptive control and optimisation in milling process, *International Journal of Advanced Manufacturing Technology* 15(1999), pp. 791-795.

[13] Kopač, J. (2002) Rezalne sile in njihov vpliv na gospodarnost obdelave = Cutting forces and their influence on the economics of machining. *Stroj. vestn*. 3(2002), pp. 121-132.

[14] Milfelner, M., U. Župerl, F. Čuš (2005) Ustvarjanje modela rezalnih sil z uporabo umetne inteligence = Generation of a model for cutting forces using artificial intelligence. *Stroj. vestn.,* 1 (2005), pp. 41-54.

[15] Ficko, M., M. Brezočnik, J. Balič (2005) Oblikovanje prilagodljivega obdelovalnega sistema z genetskimi algoritmi = A model for forming a flexible manufacturing system using genetic algorithms. *Stroj. vestn.*, 1 (2005), pp. 28-40.

[16] Župerl, U., F. Čuš, E. Kiker, M. Milfelner (2005) Kombiniran sistem ločenega optimiranja in prilagodnega nastavljanja rezalnih parametrov med procesom oblikovnega frezanja = A combined system for off-line optimization and adaptive adjustment of the cutting parameters during a ball-end milling process. Stroj. *vestn.,* 9(2005), pp. 542-559

[17] Župerl, U., F. Čuš (2004) Določevanje značilnih tehnoloških in gospodarskih parametrov med postopkom odrezovanja = A determination of the characteristic technological and economic parameters during metal cutting. *Stroj. vestn.*, 5(2004), pp. 252-266.

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