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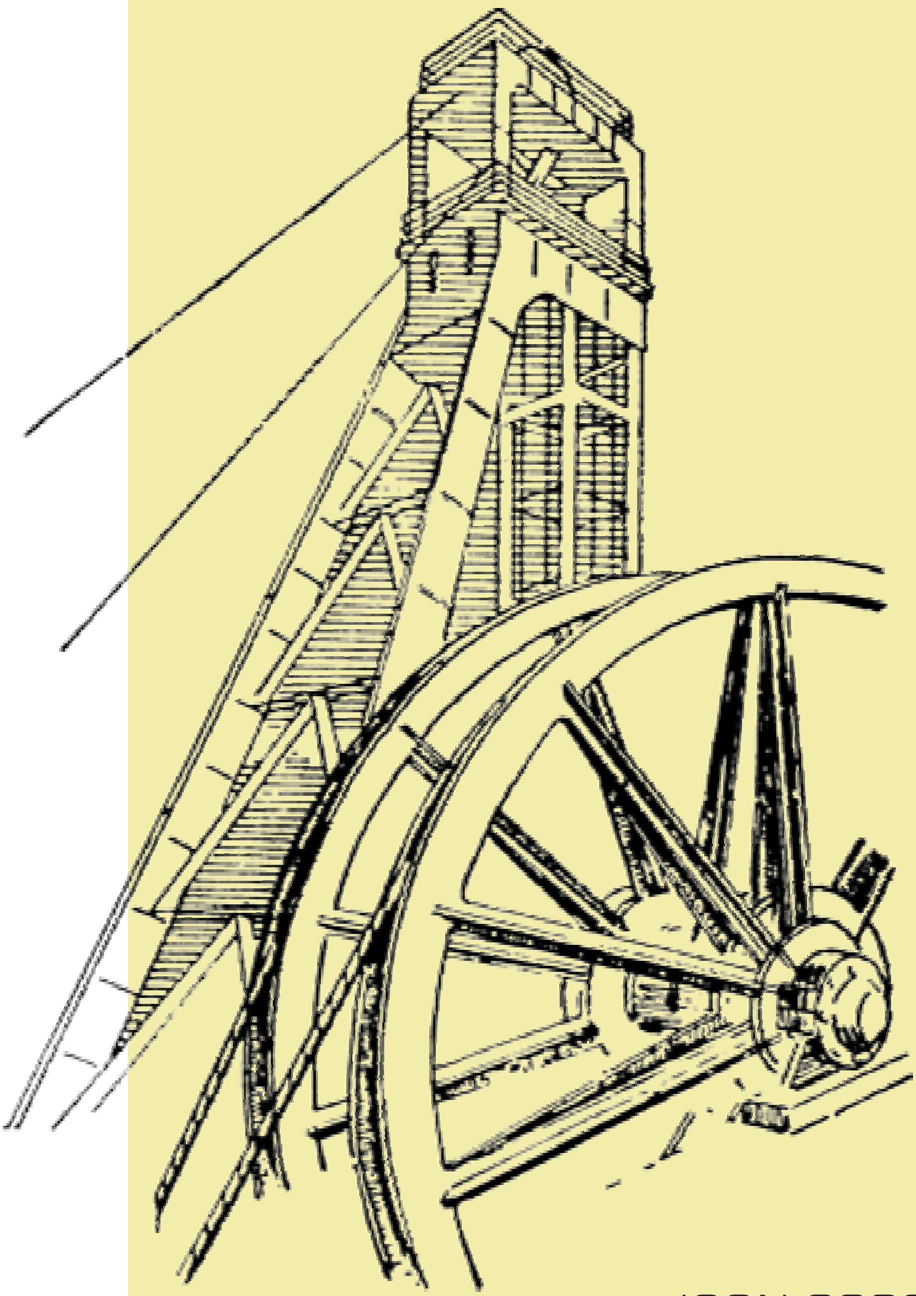

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Kombiniran sistem ločenega optimiranja in prilagodnega nastavljanja rezalnih parametrov med procesom oblikovnega frezanja

A Combined System for Off-Line Optimization and Adaptive Adjustment of the Cutting Parameters During a Ball-End Milling Process

Uroš Župerl - Franci Čuš - Edi Kiker - Matjaž Milfelner

V prispevku je prikazana uporaba združevanja metod nevronskih mrež in mehke logike pri modeliranju in prilagodnem krmiljenju postopka oblikovnega frezanja. Izdelan je celovit postopek hibridnega modeliranja postopka odrezovanja (sistem ANfis), ki ga uporabimo pri izdelavi simulatorja frezanja RNK. S hibridnim modeliranjem postopka, ločeno optimizacijo ter usmerjeno nevronsko krmilno shemo (UNKS) je zgrajen kombiniran sistem za posredno optimiranje in prilagodno nastavljanje rezalnih parametrov. To je prilagodni sistem krmiljenja, ki z digitalno prilagodljivostjo rezalnih parametrov nadzoruje rezalno silo in ohranja stalno hrapavost obdelane površine med frezanjem. Tako uravnoteži vse motnje postopka odrezovanja: obrabo orodja, nehomogenost obdelovanega materiala, vibracije, drdranje itn. Poglavitno načelo vodenja je izvedeno s krmilno shemo (UNKS), ki jo sestavljata dve nevronski razpoznavali dinamike postopka in primarni krmilnik. Simulator frezanja RNK testira stabilnost sistema in uglasi parametre krmilne sheme. Postopek je bil uspešno uporabljen na RNK frezalnem stroju Heller. S preizkusi je potrjena učinkovitost prilagodnega sistema krmiljenja, ki se kaže v izboljšani kakovosti površine in manjši obrabi orodja.

(Ključne besede: odrezovanje, krmiljenje sil, sistemi prilagoditveni, optimiranj, frezanje oblikovno)

This paper discusses the use of combining the methods of neural networks, fuzzy logic and PSO evolutionary strategy in modelling and adaptively controlling the process of ball-end milling. An overall procedure for the hybrid modelling of the cutting process (ANfis-system) used for working out the CNC milling simulator has been prepared. On the basis of the hybrid process modelling, off-line optimization and feed-forward neural control scheme (UNKS) the combined system for off-line optimization and adaptive adjustment of the cutting parameters is built. This is an adaptive control system controlling the cutting force and maintaining the constant roughness of the surface being milled by digital adaptation of the cutting parameters. In this way it compensates for all the disturbances during the cutting process: tool wear, non-homogeneity of the workpiece material, vibrations, chatter etc. The basic control principle is based on a control scheme (UNKS) consisting of two neural identificators of the process dynamics and the primary controller. The CNC milling simulator tests the system stability and tunes the control-scheme parameters. The approach was successfully applied to a Heller CNC milling machine. Experiments have confirmed the efficiency of the adaptive control system, which was reflected in improved surface quality and decreased tool wear.

(Keywords: machining, force control, adaptive control systems, optimization, ball-end mill)

0 UVOD

Pomanjkljivost modernih RNK sistemov je, da se rezalni parametri, kakor so podajanje, rezalna hitrost in globina reza, še vedno programirajo v ločenem načinu. Rezalni parametri so običajno izbrani

0 INTRODUCTION

A drawback of modern CNC systems is that the machining parameters, such as feedrate, cutting speed and depth of cut, are still programmed off-line. The machining parameters are usually selected pred obdelavo na podlagi programerjevih izkušenj in tehnoloških priročnikov. Da bi preprečili poškodbe orodja in se izognili lomu orodja, so rezalne razmere običajno izbrane skrajno zadržano, kar pomeni, da so vrednosti podajanja in rezalne hitrosti mnogo nižje od priporočenih vrednosti, ki jih je podal proizvajalec orodja. S tem so sicer izpolnjene omejitve obdelave, vendar pa stroj in orodje nista popolnoma izkoriščena.

Zato so mnogi RNK sistemi neučinkoviti in obratujejo v rezalnih razmerah, ki so daleč od optimalnih. Četudi so rezalni parametri določeni v ločenem načinu z ne-determinističnimi optimizacijskimi algoritmi, ki temeljijo na umetni inteligenci (nevronske mreže) [1], jih pozneje med obdelavo ni več mogoče popraviti.

Da bi zagotovili kakovost obdelanih kosov, zmanjšali stroške obdelave in povečali učinkovitost obdelave, je treba prilagajati rezalne parametre med postopkom obdelave (v dejanskem času), tako da so izpolnjeni optimalni kriteriji obdelave. Zato raziskovalci intenzivno preučujejo prilagodne sisteme krmiljenja (PKS - AC), ki omogočajo sprotno prilagajanje rezalnih razmer [2]. V našem PKS se podajanje nastavlja v sprotnem načinu z namenom, da se ohranja stalna rezalna sila kljub spremembam rezalnih razmer.

V središču te raziskave je krmiljenje največje sile pri 4-osni RNK obdelavi z uporabo ločenih optimiranih hitrosti podajanja in prilagodnega krmiljenja. V tem prispevku je razvit nevronski prilagodni sistem krmiljenja in izvedeno je nekaj simulacij ter preizkusov z nevronsko strategijo krmiljenja. Rezultati prikazujejo zmožnost predlaganega sistema za učinkovito krmiljenje največjih rezalnih sil v rezalnih razmerah, ki so pogoste pri opravilih oblikovnega frezanja.

Številni raziskovalci so razvijali in ocenjevali algoritme za krmiljenje rezalne sile. Med najbolj razširjenimi je PI krmilnik s stalnim ojačanjem, ki sta ga za frezanje prvotno predlagala Tlusty in Elbestawi [3]. Stute in Goetz [4] sta predlagala PI krmilnik z nastavljivim ojačanjem, kjer se ojačanje krmilnika prilagaja kot odziv na spremembe rezalnih razmer. Čisti prilagodni modelno podprt referenčni sistem krmiljenja (MPRKS - MRAC) je prvotno raziskoval Tomizuka [5]. Liu [6] je te sisteme simuliral, ocenil ter fizično uresničil. V obeh raziskavah je ugotovljeno, da vsi trije prilagodni sistemi krmiljenja delujejo bolje kakor PI krmilnik s stalnim ojačanjem. Žal samo prilagodno krmiljenje ne more učinkovito krmiliti

before machining according to the programmer's experience and machining handbooks. To prevent tool damage and to avoid machining failure the operating conditions are usually set extremely conservatively, which means that the values of the feeding and the cutting speed are much lower than the recommended values specified by the tool maker. Thus, although the machining constraints are fulfilled, the tool and the machine are not fully utilized.

As a result, many CNC systems are inefficient and run under operating conditions that are far from optimised. Even if the machining parameters are determined off-line by non-deterministic optimisation algorithms based on artificial intelligence (neural networks) [1], they cannot be adjusted further during the machining process.

To ensure the quality of machining products, to reduce the machining costs and increase the machining efficiency, it is necessary to adjust the machining parameters during the machining process (in real-time), to satisfy the optimal machining criteria. For this reason, adaptive control (AC), which provides on-line adjustment of the operating conditions, is being studied with interest [2]. In our AC system, the feedrate is adjusted on-line in order to maintain a constant cutting force in spite of variations in the cutting conditions.

The focus of this research is peak-force regulation in 4-axis CNC machining through the use of off-line optimized feedrates and adaptive control. In this paper, a neural adaptive controller is developed and some simulations and experiments with the neural control strategy are carried out. The results demonstrate the ability of the proposed system to effectively control peak forces for the cutting conditions commonly encountered in end-milling operations.

Force-control algorithms have been developed and evaluated by numerous researchers. Among the most common is the fixed-gain proportional integral (PI) controller, originally proposed for milling by Tlusty & Elbestawi [3]. Stute & Goetz [4] proposed an adjustable-gain PI controller, where the gain of the controller is adjusted in response to variations in the cutting conditions. The purely adaptive model reference adaptive controller (MRAC) approach was originally investigated by Tomizuka [5]. These controllers were simulated and evaluated and physically implemented by Liu [6]. Both studies found all three parameter adaptive controllers to perform better than the fixed-gain PI controller. Unfortunately, adaptive control alone cannot effectively control the cutting forces.

rezalnih sil. Do zdaj ni takega krmilnika, ki bi se lahko dovolj hitro odzval na nenadne spremembe geometrijske oblike reza in odpravil velike konice rezalnih sil. Zato uporabimo sprotno prilagodno krmilje v povezavi z ločenim optimiranjem. Optimiranje se izvede z algoritmom, ki ga je izdelal Župerl [7].

Mnogo dela je bilo opravljenega na področju prilagodnega krmiljenja rezalnih sil pri frezanju ([8] in [9]). Vendar se v večini predhodnih del problem frezanja poenostavi v enorazsežno frezanje. V tem prispevku bomo obravnavali problematiko krmiljenja sile pri trirazsežnem frezanju.

V naslednjem poglavju je na kratko opisana celovita strategija krmiljenja rezalne sile. Četrto poglavje obravnava simulator RNK frezanja. V petem poglavju je s preizkusi ocenjen kombiniran prilagodni sistem krmiljenja. Na koncu so v sedmem in osmem poglavju podani rezultati preizkusov, sklepi in priporočila za nadaljnje raziskave.

1 KOMBINIRAN SISTEM ZA LOČENO OPTIMIZACIJO IN PRILAGODNO KRMILJENJE REZALNE SILE

Poglavitna zamisel tega postopka je združiti algoritem ločene optimizacije rezalnih razmer in prilagodnega krmiljenja sile (sl. 1). Na podlagi tega novega kombiniranega sistema vodenja je mogoče laže in natančneje nadzorovati zapletene postopke kakor s standardnimi postopki krmiljenja. Cilj razvitega kombiniranega sistema krmiljenja je zagotavljati čim večjo stopnjo odvzemanja materiala (SOM - MRR) in ohranjati rezalno silo na ravni primerjalne vrednosti. Kombinirani sistem krmiljenja se s prilagoditvijo podajanja avtomatsko prilagaja trenutnim rezalnim razmeram. Kadar so obremenitve vretena majhne, sistem poveča podajanje prek predprogramiranih vrednosti, kar ima za posledico znatno zmanjšanje časa obdelave in proizvodnih stroškov. Kadar so obremenitve vretena velike, se podajanje zmanjša, kar zavaruje rezalno orodje pred poškodbami in lomom. Kadar sistem zazna skrajne sile, avtomatsko zaustavi stroj, da zaščiti rezalno orodje. Sistem zmanjša potrebo po nenehnem nadzoru operaterja. Spodaj je podano zaporedje korakov pri sprotni optimizaciji postopka frezanja.

1. Priporočene rezalne razmere se določijo z ANfis (prilagodni nevromehki sklepni sistem) modeli, ki so glavni elementi programske opreme za izbiro priporočenih rezalnih razmer.

There is no controller that can respond quickly enough to sudden changes in the cut geometry to eliminate large spikes in the cutting forces. Therefore, we have implemented on-line adaptive control in conjunction with off-line optimization. The optimization is performed with an algorithm developed by Župerl [7].

Much work has been done on adaptive cutting-force control for milling [8] and [9]. However, most of the previous work has simplified the problem of milling into one-dimensional motion. In this contribution we will consider force control for three-dimensional milling.

The following section briefly describes the overall cutting-force control strategy. Section four covers the CNC milling simulator. Section five describes the experimental evaluation of the combined adaptive-control system. Finally, sections seven and eight present the experimental results, the conclusions, and the recommendations for future research.

1 COMBINED SYSTEM FOR OFF-LINE OPTIMIZATION AND ADAPTIVE CUTTING-FORCE CONTROL

The basic idea of this approach is to merge the off-line cutting condition optimization algorithm and adaptive force control (Fig. 1). Based on this new, combined control system, very complicated processes can be controlled more easily and accurately compared to standard approaches. The objective of the developed combined control system is keeping the metal removal rate (MRR) as high as possible and maintaining the cutting force as close as possible to a given reference value. The combined control system is automatically adjusted to instant cutting conditions by adaptation of the feedrate. When spindle loads are low, the system increases feeds above and beyond pre-programmed values, resulting in considerable reductions in the machining time and production costs. When spindle loads are high the feedrates are lowered, safeguarding the cutting tool from damage and breakage. When the system detects extreme forces, it automatically stops the machine to protect the cutting tool. This reduces the need for constant operator supervision. The sequence of steps for on-line optimization of the milling process is presented below.

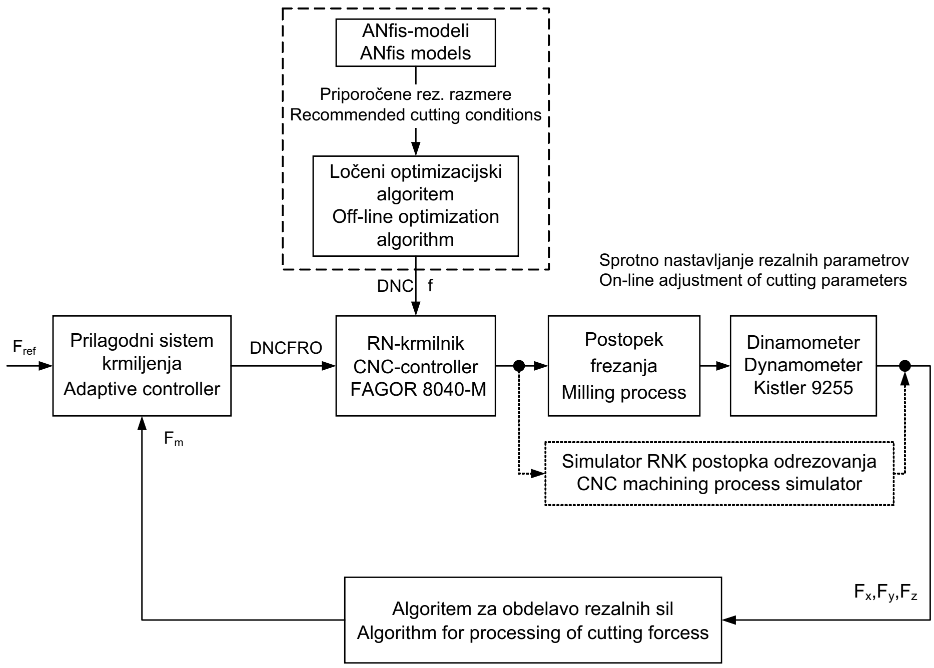
1. The recommended cutting conditions are determined by ANfis (adaptive neuro-fuzzy inference system) models, which are basic elements of the software for selecting the recommended cutting conditions.

2. Predprogramirane vrednosti podajanja, določene z algoritmom ločene optimizacije, se pošljejo RN krmilniku frezalnega stroja. Optimizacijski algoritem [1] deluje na podlagi usmerjenih in radialnih mrež ob hkratni uporabi novih sodobnih algoritmov učenja, ki se avtomatično prilagajajo trenutnim razmeram med postopkom učenja. Glavni cilj algoritma je določiti takšne optimalne rezalne razmere (rezalno hitrost, podajanje in globino reza), ki čimbolj povečajo obseg proizvodnje, zmanjšajo obdelovalne stroške in izboljšajo kakovost izdelka.
3. Izmerjene rezalne sile se sporočajo nevronski krmilni shemi,
4. Nevronska krmilna shema prilagodi optimalne vrednosti podajanja in jih pošlje nazaj stroju.
5. Koraki 1 do 3 se ponavljajo do konca obdelave.

Nevronski prilagodni krmilnik sile prilagodi podajanje, tako da predpiše popravek vrednosti podajanja RN krmilniku 4-osnega Hellerja na temelju izmerjene največje vrednosti sile (sl. 1). Dejanska vrednost podajanja je zmnožek popravka podajanja (DNCFRO) in programirane stopnje podajanja. Če bi bila programska oprema za optimiranje rezalnih razmer popolna, bi optimirana vrednost podajanja

2. The pre-programmed feedrates determined by the off-line optimization algorithm are sent to the CNC controller of the milling machine. The optimization algorithm works on the basis of feed-forward and radial basis networks with the simultaneous use of a new, advanced learning algorithm that automatically adapts to current conditions during the training process. The main objective of the paper is to determine the optimal machining parameters (cutting speed, feedrate, depth of cut) that maximize the extent of production, reduce the manufacturing costs and finally improve the product quality.
3. The measured cutting forces are sent to the neural control scheme,
4. The neural control scheme adjusts the optimal feedrates and sends details back to the machine,
5. Steps 1 to 3 are repeated until the termination of the machining.

The neural adaptive force controller adjusts the feedrate by assigning a feedrate override percentage to the CNC controller on a 4-axis Heller, based on a measured peak force (see Figure 1). The actual feedrate is the product of the feedrate override percentage (DNCFRO) and the programmed feedrate. If the software for optimization of the cutting conditions was per-



Sl. 1. *Zgradba kombiniranega sistema za ločeno optimiranje in prilagodno nastavljanje rezalnih parametrov*

Fig. 1. *Structure of combined system for off-line optimization and adaptive adjustment of the cutting parameters*

vedno ustrezala primerjalni največji sili. V tem primeru bi bil popravek podajanja 100-odstoten. Da bi lahko krmilnik vodil največjo silo, mora biti podatek o sili na voljo algoritmu vsakih 20 ms. Ta podatek zagotavlja programska oprema za zbiranje podatkov (LabVIEW) in algoritem za obdelavo rezalnih sil. Čas optimiranja z ločenim optimizacijskim algoritmom, ki temelji na usmerjeni nevronski mreži, znaša 0,001 s. Kombinirani sistem krmiljenja najkasneje v 4 iteracijah (2ms) vrne vrednost rezalne sile na raven primerjalne - želene vrednosti.

2 USMERJENA NEVRONSKA KRMILNA SHEMA (UNKS)

Poglavitno načelo krmiljenja sloni na krmilni shemi (UNKS), ki je sestavljena iz treh delov (sl. 2). Prvi del je zanka, znana kot zunanja krmilna zanka s povratno zvezo (klasična krmilna zanka). Klasična krmilna zanka temelji na napaki med izmerjeno (F_m) in želeno rezalno silo (F_{ref}). Primarno krmilje klasične krmilne zanke je nevronska mreža (NM-R), ki posnema delovanje delilnega krmilnika.

Drugi del je zanka, povezana z nevronsko mrežo 1 (NM-1), ki predstavlja notranji model dinamike postopka. Deluje kot identifikator dinamike postopka. Ta del predstavlja notranjo zanko s povratno zvezo, ki je mnogo hitrejša od zunanje krmilne zanke, kajti slednja vsebuje zakasnitve merilnega člena.

Tretji del sistema je nevronska mreža 2 (NM-2). NM-2 se uči inverzne dinamike postopka.

UNKS deluje po naslednjem načelu: Zaznavna povratna zveza je učinkovita v glavnem v fazi učenja. Ta zanka daje klasični signal povratne zveze za krmiljenje postopka. Med fazo učenja se NM-2 uči obrnjene dinamike. Med učenjem notranja zanka postopoma prevzame vlogo zunanje krmilne zanke in primarnega krmilnika. Z napredovanjem učenja bo obrnjeni dinamični del nadomestil zunanjo krmilno zanko. Končni rezultat je, da je postopek krmiljen v glavnem z NM-1 in NM-2, ker je izhodna napaka postopka skoraj enaka nič.

To je prilagodni sistem krmiljenja, ki uravnava rezalno silo in ohranja stalno hrapavost frezane površine z digitalno prilagoditvijo rezalnih parametrov. Tako izravna vse motnje med postopkom odrezovanja: obrabo orodja, nehomogenost materiala obdelovanca, vibracije, drdranje itn.

fect, the optimized feedrate would always be equal to the reference peak force. In this case the correct override percentage would be 100%. In order for the controller to control the peak force, force information must be available to the control algorithm every 20ms. Data acquisition software (LabVIEW) and the algorithm for processing the cutting forces are used to provide this information. The optimization time with the use of the off-line optimization algorithm based on a feed-forward neural network, is equal to 0.001s. The combined control system returns the cutting-force value to the desired value level within four or less iterations at the latest.

2 FEED-FORWARD NEURAL CONTROL SCHEME (UNKS)

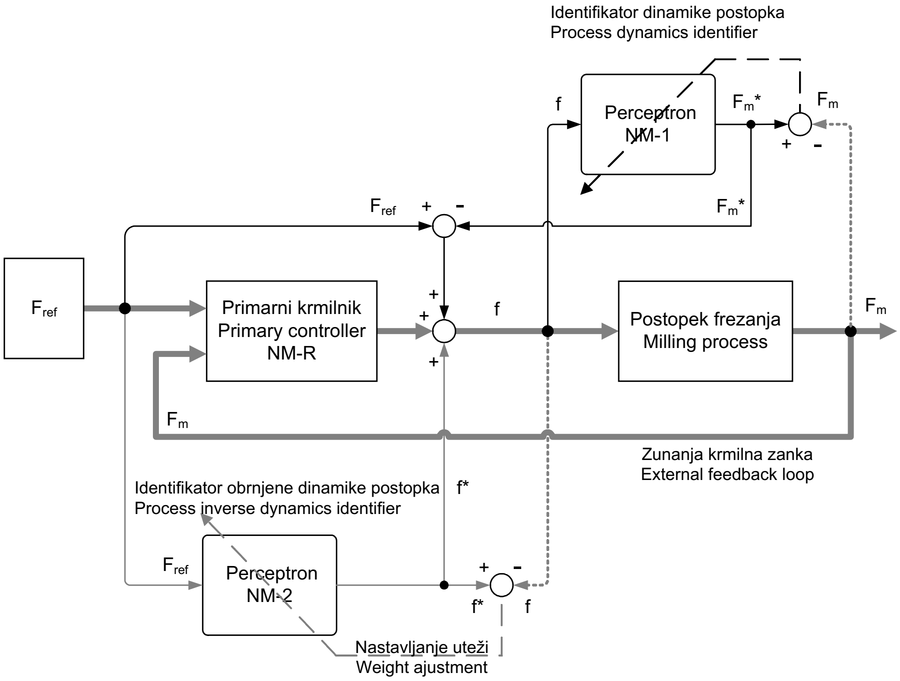
The basic control principle is based on a control scheme (UNKS) consisting of three parts (Fig. 2). The first part is the loop known as external feedback (conventional control loop). The feedback control is based on the error between the measured (F_m) and desired (F_{ref}) cutting force. The primary feedback controller is a neural network (NM-R) that imitates the work of the division controller.

The second part is the loop connected with neural network 1 (NM-1), which is an internal model of the process dynamics. It acts as the process dynamics identifier. This part represents an internal feedback loop, which is much faster than the external feedback loop, as the latter usually has sensory delays.

The third part of the system is neural network 2 (NM-2). The NM-2 learns the process inverse dynamics.

The UNKS operates according to the following procedure. The sensory feedback is effective mainly in the learning stage. This loop provides a conventional feedback signal to control the process. During the learning stage, NM-2 learns the inverse dynamics. As the learning proceeds, the internal feedback gradually takes over the role of the external feedback and the primary controller. Then, as learning proceeds further, the inverse dynamics part will replace the external feedback control. The final result is that the plant is controlled mainly by NM-1 and NM-2, since the process output error is nearly zero.

This is an adaptive control system controlling the cutting force and maintaining the constant roughness of the surface being milled by digital adaptation of the cutting parameters. In this way it compensates for all the disturbances during the cutting process: tool wear, non-homogeneity of the workpiece material, vibrations, chatter, etc.



Sl. 2. *Usmerjena nevronska krmilna shema (UNKS)*
Fig. 2. *Feed-forward neural control scheme (UNKS)*

3 SIMULATOR RNK FREZANJA

S simulatorjem RNK frezanja ocenimo izvedbo krmilnika še pred izvedbo eksperimentalnih preizkusov. S simulatorjem RNK frezanja preizkušamo stabilnost sistema in uglasimo parametre krmilne sheme vodenja. Simulator sestavlja nevronski model sil, model podajalnega pogona in model elastičnosti (sl. 3). Nevronski model napove rezalne sile na podlagi rezalnih razmer in geometrijske oblike reza, kakor je opisal Župerl [10]. Model podajalnega servopogona simulira odziv stroja na spremembe želenega podajanja. Model elastičnosti poda upogibanje orodja (sl. 3). Model je prirejen po Muršecu [11]. Elastičnost sistema je modelirana kot statični odklon frezala. Enačba elastičnosti za smer X poti orodja je:

3 CNC MILLING SIMULATOR

A CNC milling simulator is used to evaluate the controller design before conducting the experimental tests. The CNC milling simulator tests the system stability and tunes the control scheme parameters. The simulator consists of a neural force model, a feed-drive model and a model of elasticity (Fig. 3). The neural model predicts the cutting forces based on the cutting conditions and the cut geometry, as described by Župerl [10]. The feed-drive model simulates the machine response to changes in the desired feedrate. The elasticity model represents the deflection between the tool and the workpiece (Fig. 3). The model is adapted from Muršec [11]. The system elasticity is modelled as a static deflection of the cutter. The elasticity equation for the X direction of tool travel is:

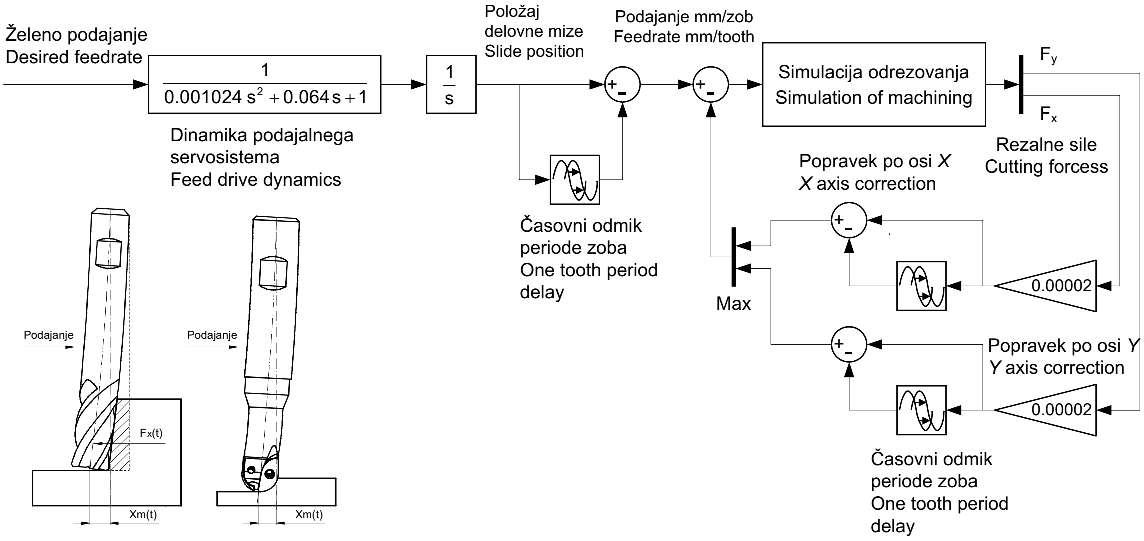
$$X_m(t) = (-F_x(t)) + F_x(t - T_{tp})) \cdot G_x \quad (1),$$

kjer je X_m elastični odklon orodja, ki vpliva na debelino odrezka, F je rezalna sila, G_x je elastičnost, t je čas in T_{tp} je časovni odmik periode zoba.

Model podajalnega servopogona je določen s preizkusi, s preučevanjem odzivov sistema na skočne spremembe želene podajalne hitrosti. Model se najbolje ujema s sistemom drugega reda z

where X_m is the tool's elastic deflection affecting the chip thickness, F is the cutting force, G_x is the compliance, t is time and T_{tp} is the tool passing period.

The feed-drive model was determined experimentally by examining the responses of the system to step changes in the desired feed velocity. The best model fit was found to be a second-order



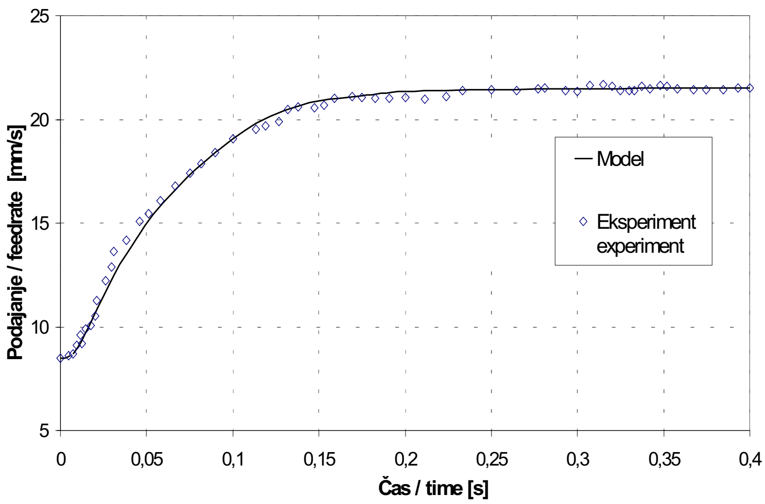
Sl. 3. *Simulator RNK frezanja*
Fig. 3. *CNC milling simulator*

lastno frekvenco 3 Hz in odzivnim časom 0,4 s. Na sliki 4 je podana primerjava preizkusnih in simulacijskih rezultatov za skočno spremembo hitrosti od 7 na 22 mm/s.

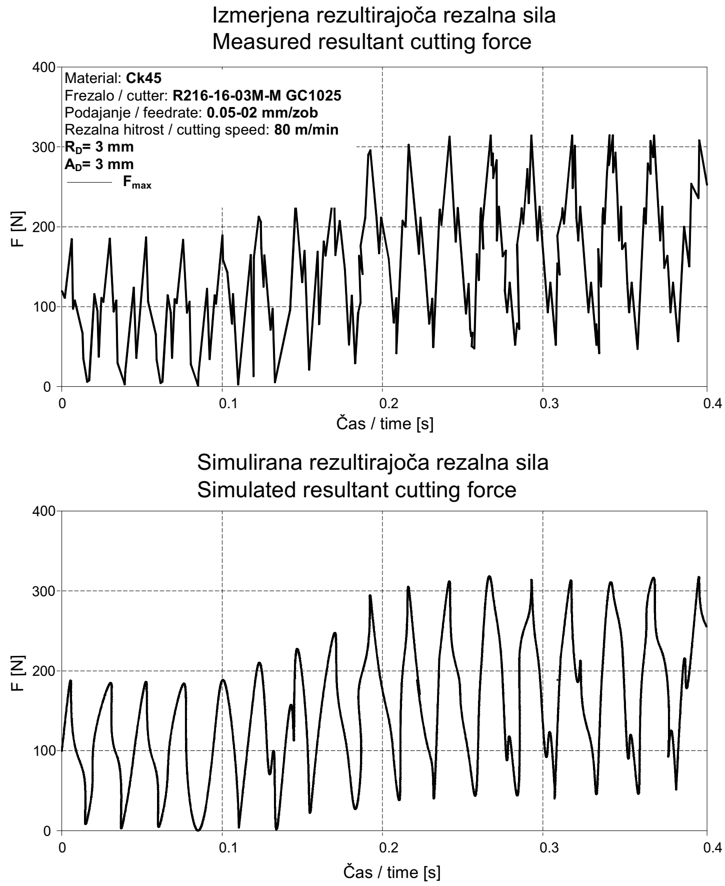
Kombinacija modela podajalnega servopogona, nevronskega modela sil in modela elastičnosti sestavlja simulator RNK frezanja. Vhod v simulator je želeno podajanje, izhod pa rezultirajoča rezalna sila *X*, *Y*. Geometrijska oblika reza je definirana v nevronskem modelu sil. Simulator je potrjen s primerjanjem preizkusnih in simulacijskih rezultatov. Za potrditev smo izvedli vrsto rezov s spremenljivim

system with a natural frequency of 3 Hz and a settling time of 0.4sec. A comparison of the experimental and simulation results for a velocity step change from 7mm/sec to 22mm/sec is shown in Figure 4.

The feed-drive model, the neural force model and the elasticity model are combined to form the CNC milling simulator. The simulator input is the desired feedrate, and the output is the *X, Y* resultant cutting force. The cut geometry is defined in the neural force model. The simulator is verified by a comparison of the experimental and model simulation results. A variety of cuts with feedrate changes



Sl. 4. *Primerjava dejanskega in simuliranega podajanja*
Fig. 4. *Comparison of actual and simulated feedrate*



Sl. 5. *Primerjava simulirane in izmerjene rezalne sile*
Fig. 5. *Comparison of simulated and measured cutting force*

podajanjem. Na sliki 5 je prikazana izmerjena in simulirana rezultirajoča sila pri skočni spremembi podajanja iz 0,05 na 2 mm/zob. Eksperimentalni rezultati se dobro ujemajo z rezultati modelov tako za povprečne sile kakor tudi za največje sile. Do očitnih neskladnosti je lahko prišlo zaradi nenatančnosti nevronskega modela sil in nemodelirane dinamike sistema.

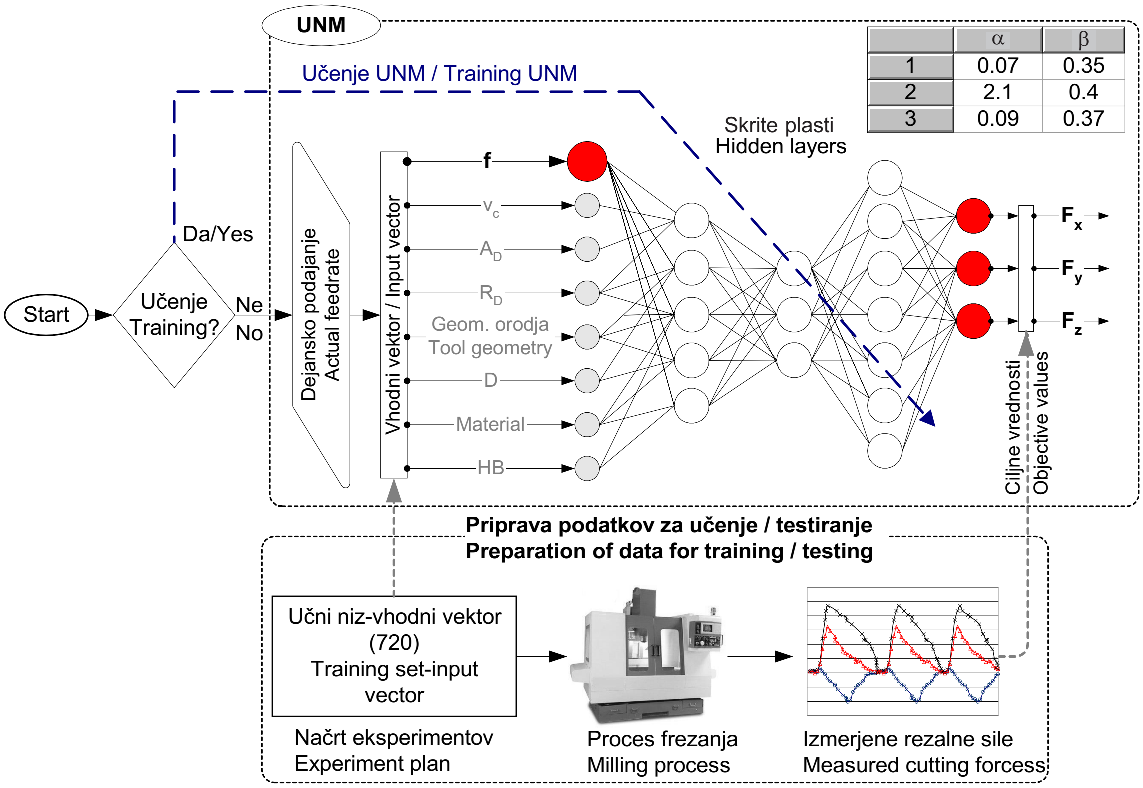
3.1 Simulator dinamike odrezovanja

Za izvedbo sprotnega modeliranja postopka odrezovanja, je predlagana standardno BP nevronska mreža (UNM), ki temelji na dobro znanem učnem pravilu vzvratnega širjenja napake. Pri predhodnih preizkusih se je izkazalo, da je zmožna izvleči model dinamike sil neposredno iz podatkov preizkusov. Namenjena je za simulacijo dinamike postopka. UNM za modeliranje potrebuje osem vhodnih nevronov: za podajanje (*f*), rezalno hitrost (v_c), prečno in

were made for the validation. The measured and simulated resultant force for a step change in the feedrate from 0.05mm/tooth to 2 mm/tooth is presented in Figure 5. The experimental results correlate well with the model results in terms of average and peak force. The obvious discrepancy might be due to inaccuracies in the neural force model and the unmodelled system dynamics.

3.1 Simulator of the Cutting Dynamics

To realise the on-line modelling of the cutting process, a standard BP neural network (UNM) is used, based on the popular back-propagation learning rule. During preliminary experiments it proved to be sufficiently capable of extracting the force dynamics model directly from the experimental machining data. It is used to simulate the dynamics of the cutting process. The UNM for modelling needs eight input neurons: for federate (*f*), cutting speed



Sl. 6. *Topologija modela za napovedovanje rezalnih sil*
Fig. 6. *Predictive cutting-force model topology*

vzdolžno globino reza (A_D/R_D), vrsto obdelovanega materiala, trdoto obdelovanega materiala, premer frezala (D) in geometrijsko obliko orodja. UNM beleži vhodne podatke samo v numerični obliki, zato je treba podatke o geometrijski obliki orodja in materialu spremeniti v numerično kodo. Geometrijska oblika frezala je nakazana z osemštevilčno sistematizacijsko kodo, ki vsebuje podatke o obliki rezalnega roba, cepilnem kotu, prostem kotu, polmeru konice, osnovnem materialu, oplaščenju ploščice in dolžini rezalnega roba. Izhod iz UNM so komponente rezalne sile, zato so potrebni trije izhodni nevroni. Za poenostavitev simulatorja frezanja se priredi UNM tako, da med napovedovanjem prezre vse parametre vhodnega vektorja razen podajanja. Večina parametrov vhodnega vektorja se namreč med simulacijo ne spreminja (npr. premer in geometrijska oblika frezala, material itn.).

Podrobna topologija uporabljene UNM z optimalnimi učnimi parametri je podana na sliki 6. Optimalna UNM vsebuje 5, 3 in 7 nevronov v skritih nivojih.

(v_c), radial and axial depth of cut (A_D/R_D), type of machined material, hardness of the machined material, cutting-tool diameter (D), and tool geometry. The ANN registers the input data only in numerical form; therefore, the information about the tool, the cutting geometry and the material must be transformed into a numerical code. The geometry of the cutter is indicated with an 8-digit systematization code containing data on the cutting-edge shape, the rake angle, the free angle, the tip radius, the base material, the cutting coating and the length of the cutting edge. The outputs from the UNM are the cutting force components, and so three output neurons are necessary. For simplification of the milling simulator the neural network is so adapted that during prediction it overlooks all the input parameters except feeding. During the simulation most of the input vector parameters do not change (e.g., cutter diameter and geometry, material etc.).

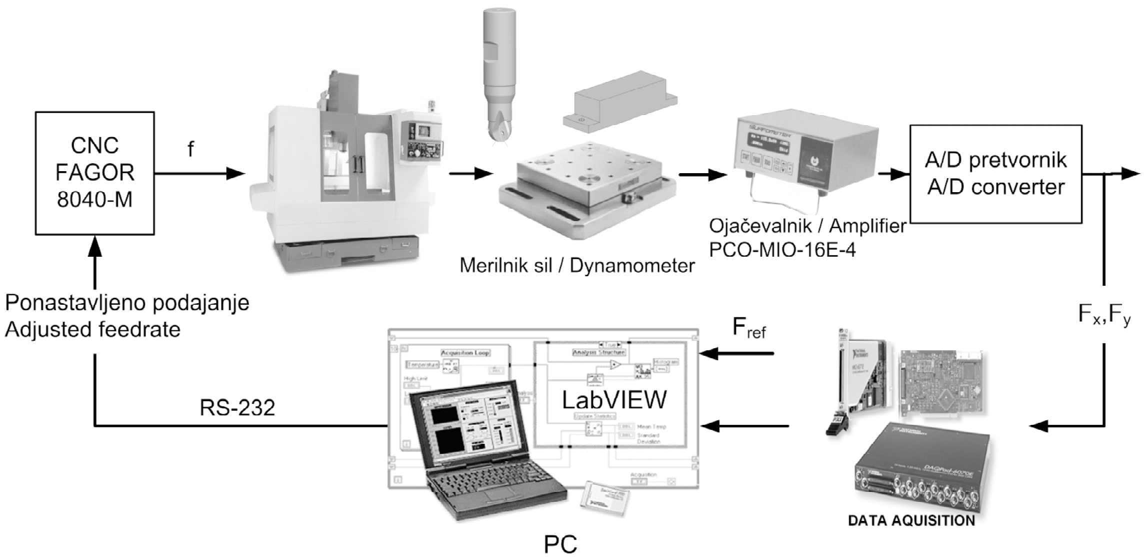
A detailed topology of the used NN with optimal training parameters is shown in Figure 6. The optimal UNM configuration contains 5, 3 and 7 neurons in hidden layers.

4 SISTEM ZA ZBIRANJE PODATKOV IN PREIZKUSNA OPREMA

Slika 7 prikazuje opremo za zbiranje podatkov, ki sestoji iz dinamometra, vpenjalne priprave in programskega modula. Rezalne sile so izmerjene s piezoelektričnim dinamometrom (Kistler 9255), nameščenim med obdelovancem in mizo stroja. Med obdelavo se rezalna sila prenese na dinamometer prek obdelovanca. Piezoelektrični kremen v dinamometru bo obremenjen in nastal bo električni naboj. Električni naboj se nato prenese na večkanalni nabojni ojačevalnik prek priključnega kabla. Nato večkanalni nabojni ojačevalnik ojača naboj (Kistler 5019A). V nabojnem ojačevalniku je mogoče nastaviti različne parametre, tako da dobimo zahtevano ločljivost. Na izhodu ojačevalnika se bo električna napetost ujemala s silo glede na nastavljene parametre nabojnega ojačevalnika. Modul vmesnikove strojne opreme je sestavljen iz povezovalnega bloka, modula za obdelavo analognega signala in 16-kanalnega analogno-digitalnega pretvornika A/D (PC-MIO-16E-4). V pretvorniku A/D bo analogni signal spremenjen v digitalni signal, tako da programska oprema LabVIEW lahko sprejme in prebere podatke. S programom LabVIEW so nato električne napetosti spremenjene v komponente sil X, Y in Z. S tem programom je mogoče hkrati pridobiti tri komponente sile in jih prikazati na zaslonu za nadaljnje analize. Za obdelavo izberemo oblikovno frezalo z izmenljivimi

4 DATA-ACQUISITION SYSTEM AND EXPERIMENTAL EQUIPMENT

The data-acquisition equipment consists of a dynamometer, a fixture and a software module, as shown in Figure 7. The cutting forces were measured with a piezoelectric dynamometer (Kistler 9255) mounted between the workpiece and the machining table. When the tool is cutting the workpiece, the force is applied to the dynamometer through the workpiece. The piezoelectric quartz in the dynamometer will be strained and an electric charge will be generated. The electric charge is then transmitted to the multi-channel charge amplifier through the connecting cable. The charge is then amplified using a multi-channel charge amplifier (Kistler 5019A). In the charge amplifier, different parameters can be adjusted so that the required resolution can be achieved. Essentially, at the output of the amplifier, the voltage will correspond to the force depending on the parameters set in the charge amplifier. The interface hardware module consists of a connecting plan block, analogue signal conditioning modules and a 16-channel A/D interface board (PC-MIO-16E-4). In the A/D board, the analogue signal will be transformed into a digital signal so that the LabVIEW software is able to read and receive the data. The voltages are then converted into forces in X, Y and Z directions using the LabVIEW program. With this program, the three axial force components can be obtained simultaneously, and can be displayed on the screen for further analysis. The ball-end milling cutter with interchangeable cutting inserts of type R216-16B20-040 with



Sl. 7. *Preizkusna oprema*
Fig. 7. *The experimental equipment*

rezalnimi ploščicami tipa R216-16B20-040 z dvema rezalnima roboma, premera 16 mm in s kotom vijačnice 10°. Izbrali smo rezalno ploščico R216-16 03 M-M s cepilnim kotom 12°. Material rezalne ploščic je P10-20 oplaščen s TiC/TiN, z oznako GC 1025. Komunikacija med sistemom krmiljenja in krmiljem NK stroja je izvedena prek RS-232 protokola. Spremenljivka popravka podajanja DNCFRO je na voljo sitemu vodenja s frekvenco 1 kHz.

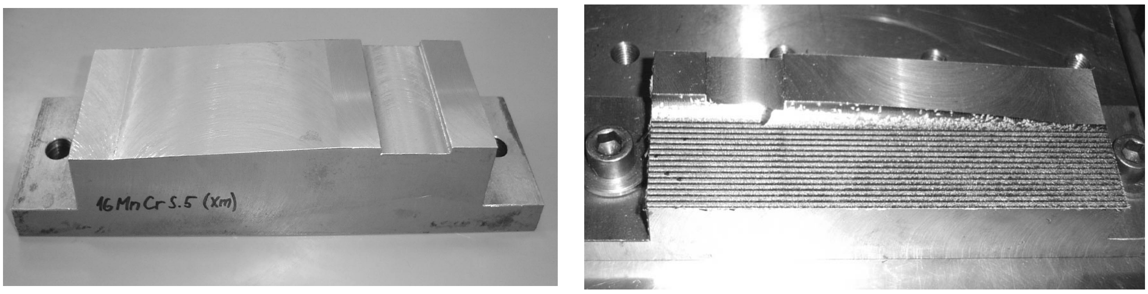
5 PREIZKUSNO TESTIRANJE KOMBINIRANEGA PRILAGODNEGA SISTEMA KRMILJENJA

Da bi preverili stabilnost in robustnost predlagane strategije krmiljenja, sistem najprej analiziramo s simulacijami na LabVIEW-ovem simulatorju Simulink [12]. Nato sistem testiramo z dvema preizkusoma na RNK frezalnem stroju (tipa HELLER BEA1) za jeklena obdelovanca Ck 45 in 16MnCrSi5 XM pri variabilni vzdolžni globini reza. (Preizkus 1- prizmatični obdelovanec; preizkus 2- obdelovanec z nepravilnim profilom, glej sliki 8, 9). Vrednosti podajanja za vsak rez se najprej določi z

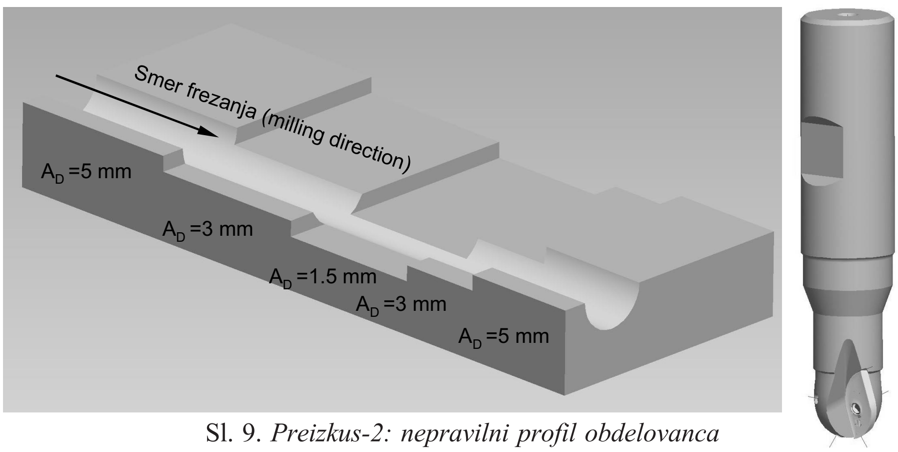
two cutting edges of 16 mm diameter and a 10° helix angle was selected for machining. The cutting inserts R216-16 03 M-M with a 12° rake angle were selected. The cutting insert material is P10-20 coated with TiC/TiN, designated GC 1025. Communication between the control system and the CNC machine controller is via the RS-232 protocol. The feedrate override percentage variable DNCFRO is available to the control system at a frequency of 1 kHz.

5 EXPERIMENTAL TESTING OF THE COMBINED ADAPTIVE CONTROL SYSTEM

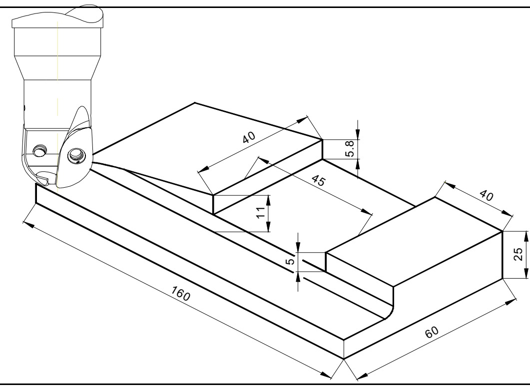
To examine the stability and robustness of the proposed control strategy, the system is first analysed by simulations using LabVIEW´s simulation package Simulink [12]. Then the system is verified by two experiments on a CNC milling machine (type HELLER BEA1) for Ck 45 and 16MnCrSi5 XM steel workpieces with a variation of the axial cutting depth (Experiment 1- prismatic workpiece; experiment 2- workpiece with irregular profile, see Figure 8, 9). The feed rates for each cut are first optimized off-

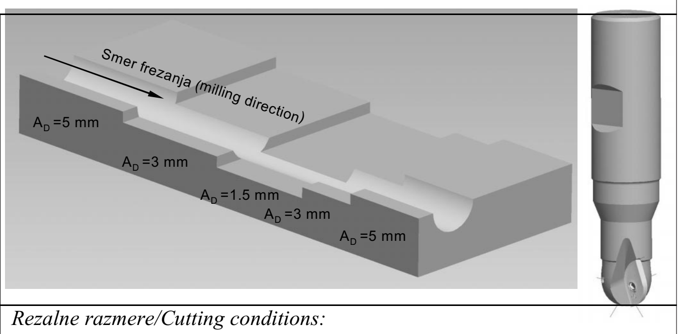


Sl. 8. *Preizkus-1: prizmatični obdelovanec*
Fig. 8. *Experiment-1: prismatic workpiece*



Sl. 9. *Preizkus-2: nepravilni profil obdelovanca*
Fig. 9. *Experiment-2: irregular workpiece profile*

a)	
Preizkus 1/Experiment 1: Prizmatični obdelovanec/ Prismatic Workpiece	
Test_A (Stalno podajanje / Constant feedrate)	*Rezalne razmere/Cutting conditions:* Podajanje/Feedrate: 0,08 mm/zob / 0.08 mm/tooth Rezalna hitrost /Cutting speed: v=80 m/min Predprogramirana vzdolžna globina reza / Pre-programed axial depth of cut A_D=2 mm Prečna globina reza R_D =4mm F_{ref}=280 N Rezultat /Result: Slika/Figure: 11a
Test_B (Predlagani kombinirani sistem krmiljenja / Proposed combined control system)	Startno podajanje/Starting feedrate: 0,08mm/zob / 0.08 mm/tooth Dopustno nastavljivo območje/Allowable adjusting rate 0,08-0,2 mm/zob / 0.08-0.2 mm/tooth Rezalna hitrost/Cutting speed: v=80 m/min Vzdolžna globina reza / Axial depth of cut A_D=2-8 mm Prečna globina reza R_D =4 mm F_{ref}=280 N Rezultat /Result: Slika / Figure: 11b

b)	
Preizkus 2/Experiment 2: Nepravilni profil obdelovanca / Irregular workpiece profile	
Test_A (Stalno podajanje / Constant feedrate)	*Rezalne razmere/Cutting conditions:* Podajanje/Feedrate: 3 mm/s Vrtljaji vretena / Spindle speed: 2400 min^{-1} Vzdolžna globina reza / Axial depth of cut A_D=2 -5 mm Prečna globina reza R_D =16 mm F_{ref}=650 N
Test_B (Predlagani kombinirani sistem krmiljenja / Proposed combined control system)	Startno podajanje / Starting Feedrate: 2,5 mm/s Dopustno nastavljivo območje podajanja /Allowable adjusting rate of federate: 2,5-11 mm/s Vrtljaji vretena / Spindle speed: 2400 min^{-1} Vzdolžna globina reza / Axial depth of cut A_D=2 -5 mm Prečna globina reza R_D =16 mm F_{ref}=650 N Rezultat /Result: Slika / Figure: 12

Sl. 10. *Načrt preizkusov: a)rezalne razmere za prizmatični obdelovanec, b) rezalne razmere za nepravilni profil obdelovanca*

Fig. 10. *Plan of experiments: a) cutting conditions for prismatic workpiece, b) cutting conditions for irregular workpiece profile.*

ločeno optimizacijo, nato se izvede obdelava s prilagodnim krmiljenjem.

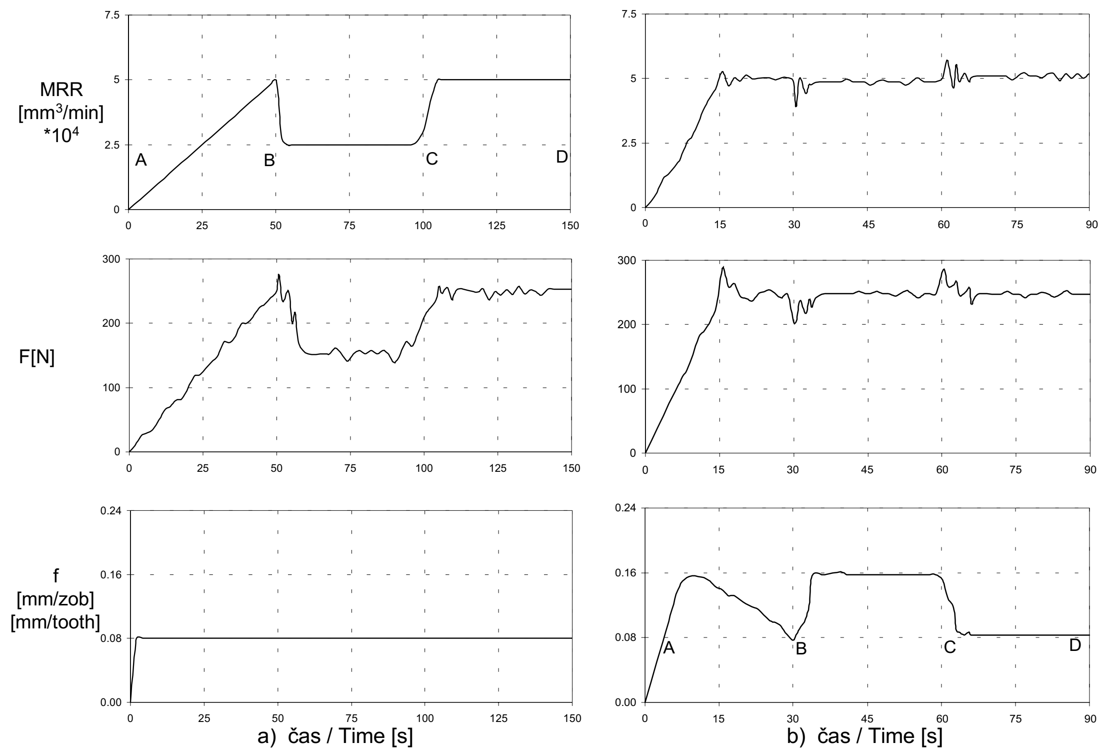
Izvedli smo dve glavni seriji preizkusov, pri katerih smo obdelali dva obdelovanca različnih profilov. Podrobni preizkusni pogoji in izmere obdelovanca so prikazani na sliki 10. Prvi test je klasično odrezovanje s stalnim podajanjem (Test_A). V drugem testu smo predlagani kombinirani sistem uporabili pri frezanju, da bi dokazali njegovo učinkovitost (Test_B).

Za preizkuse izberemo oblikovno frezalo (R216-16B20-040) z dvema rezalnima robovoma, premera 16 mm in s kotom vijačnice 10°. Rezalne razmere so: širina frezanja R_D=3 mm, startna globina frezanja A_D=2 mm in rezalna hitrost v_c=80 m/min. Pri prilagodnem krmiljenju uporabimo enake parametre kakor pri preizkusih pri klasičnem frezanju. Da bi z zgradbo kombiniranega sistema na sliki 1 optimirali vrednost podajanja, izberemo želeno rezalno silo (F_{ref}=280 N), predprogramirano podajanje 0,08 mm/zob in njegovo dopustno nastavljivo območje (0 - 150%).

line, and then machining runs are made with a controller action.

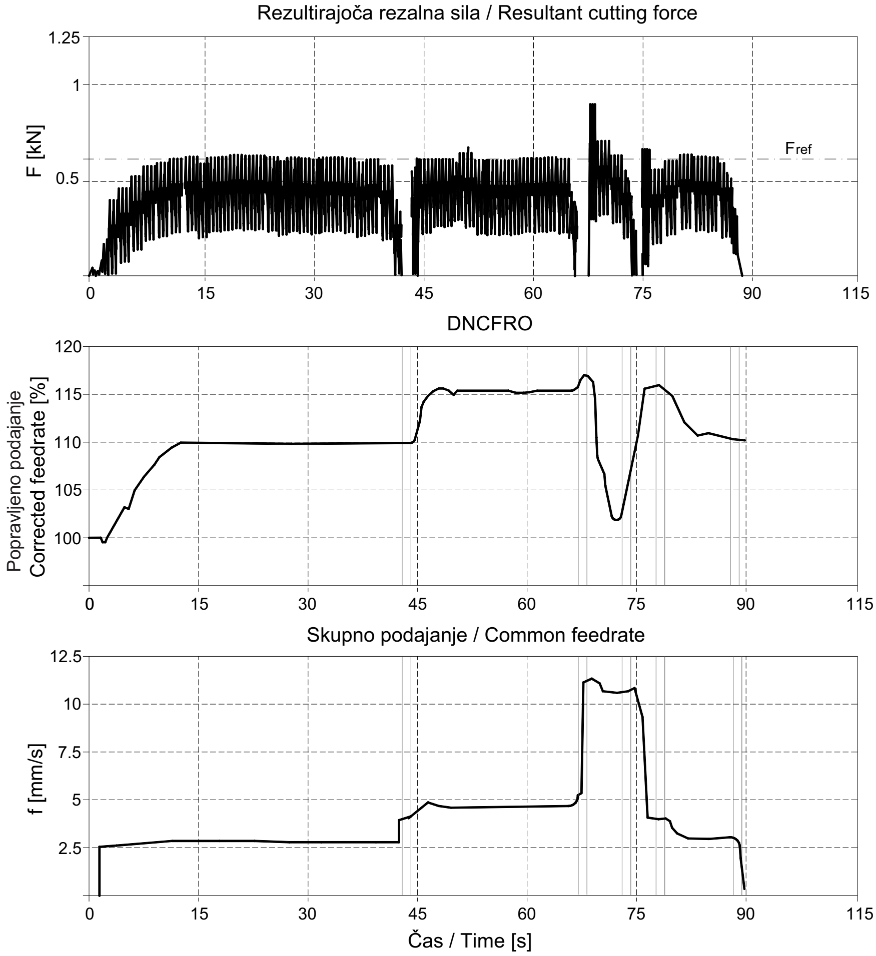
We conducted two main series of tests, in which two differently shaped workpieces were machined. The details of the experimental conditions and the dimensions of the workpiece are shown in Fig. 10. The first test is conventional cutting with a constant feedrate (Test_A). In the second test, the proposed combined system was applied during milling to demonstrate its performance (Test_B).

The ball-end milling cutter (R216-16B20-040) with two cutting edges of 16 mm diameter and a 10° helix angle was selected for the experiments. The cutting conditions are as follows: milling width R_D=4 mm, starting milling depth A_D=2 mm and cutting speed v_c=80 m/min. The parameters for adaptive control are the same as for the experiments in conventional milling. To use the structure of the combined system in Figure 1 and to optimise the feedrate, the desired cutting force is (F_{ref} =280 N), the pre-programmed feed is 0.08 mm/teeth and its allowable adjusting rate is (0–150%).



Sl. 11. *Preizkus-1: odziv MRR, rezultirajoče rezalne sile in podajanja, a) klasično frezanje-Test_A, b) frezanje s predlaganim sistemom prilagodnega krmiljenja-Test_B*

Fig. 11. *Experiment-1: response of MRR, resulting cutting force and feedrate, a) Conventional milling-Test_A, b) Milling with proposed adaptive control system-Test_B*



Sl. 12. *Preizkus-2: obdelava nepravilnega profila z ločenim optimiranjem rezalnih pogojev in prilagodnim nastavljanjem podajanja*
Fig. 12. *Experiment-2: machining of irregular profile by off-line optimizing of the cutting conditions and adaptive adjusting of the feedrate*

Na sliki 11 so prikazani odziv MRR, rezalne sile in podajanja, pri spremenljivi globini rezanja (preizkus-1). Slika prikazuje rezultate preizkusa, pri katerem se s sprotnim nastavljanjem podajanja ohranja največjo rezalno silo na ravni želene vrednosti.

Drugi preizkus je obdelava nepravilnega profila obdelovanca (sl. 9), ki jo sestavlja pet ravnih rezov z različnimi vzdolžnimi in prečnimi globinami. Ta preizkus prikazuje zmožnost prilagodnega sistema za vzdrževanje stalne rezalne sile med odrezovanjem. Želena rezalna sila je 650 N. Čas vzorčenja je 20 ms in hitrost zajemanja je 28,8 kHz. Slika 12 podaja rezultate drugega preizkusa, pri katerem uporabimo optimirane vrednosti podajanja in UNKS.

Figure 11 is the response of the cutting force and the feedrate when the cutting depth is changed (Experiment-1). It shows the experimental result where the feedrate is adjusted on-line to maintain the maximum cutting force at the desired value.

The second experiment is machining of an irregular workpiece (Fig. 9) consisting of five straight cuts with different axial and radial depths of cut. This experiment demonstrates the ability of the adaptive system to maintain a constant cutting force during machining. The desired cutting force is 650N. The sample time is 20ms and the scanning rate is 28.8 kHz. The results of the second experiment using optimized feedrates and UNKS are presented in Figure 12.

6 REZULTATI IN RAZPRAVA

V prvem preizkusu s stalnim podajanjem (Test_A - slika 11a) doseže MRR največjo vrednost šele v zadnjem odseku obdelave. Medtem ko v drugem preizkusu (sl. 11b) obdelujemo isti obdelovanec s prilagodnim krmiljenjem, pri katerem se povprečna dosežena vrednost MRR bolj približa največji vrednosti. Če primerjamo sliki 11a in 11b, vidimo, da se rezalna sila pri sistemu frezanja z nevronskim krmiljenjem ohranja v bližini vrednosti 650 N in je podajanje od točke C do D skoraj identično kakor pri klasičnim frezanju. Od točke A do točke C je vrednost podajanja pri prilagodnem sistemu frezanja višja kakor pri klasičnem RNK sistemu, zato se učinkovitost prilagodnega frezanja izboljša. Rezultati preizkusov kažejo, da je mogoče MRR izboljšati za 27 odstotkov. Izvedena je časovna analiza obdelave za klasično in za prilagodno frezanje. S prilagodnim sistemom krmiljenja dosežemo v enem rezu 40-odstotni časovni prihranek. Za celotno obdelavo je potrebnih 15 rezov; s tem skrajšamo obdelavo zelo preprostega obdelovanca za 15 minut.

Drugi preizkus z majhnimi in velikimi skočnimi spremembami izvedemo zato, da testiramo stabilnost sistema v širokem območju rezalnih razmer. Sistem ostane stabilen pri vseh preizkusih, z le majhnimi odstopanji lastnosti. V drugem preizkusu UNKS s povečevanjem podajanja ohranja največje sile na ravni vrednosti 650 N. Počasnejši odziv nevronske krmilne sheme je opažen le na začetku reza ena in tri.

Lastnosti kombiniranega sistema so ocenjene s tremi parametri: čas obdelave, absolutna vrednost največje rezalne sile in normalizirana standardna napaka Nsn:

6 RESULTS AND DISCUSSION

In the first experiment using constant feedrates (Test_A-Figure 11a) the MRR reaches its proper value only in the last section. However, in the second test (Figure 11b), machining the same piece but using adaptive control, the average MRR achieved is much closer to the maximum MRR. Comparing Fig. 11a to Fig. 11b, the cutting force for the neural control milling system is maintained at about 650N, and the feedrate of the adaptive milling system is close to that of the conventional milling from point C to point D. From point A to point C the feedrate of the adaptive milling system is higher than for the classical CNC system, so the milling efficiency of the adaptive milling is improved. The experimental results show that the MRR can be improved by 27%. A time analysis for the conventional and adaptive control systems has been curried out. With the adaptive control system a time saving of 40% with one cut was achieved. The complete machining requires 15 cuts; thus the machining of a simple workpiece is shortened by about 15 minutes.

The second experiment with small and large step changes is run to test the system stability over a range of cutting conditions. The system remains stable in all experiments, with little degradation in performance. In the second experiment, the UNKS increases the feedrates to obtain peak forces close to 650N. The slower response of the neural control scheme is noticeable at the beginning of cuts one and three.

The combined system performance for the irregular workpiece is evaluated by the time of cut, the maximum cutting force and the normalized standard error:

$$Nsn = \frac{\sqrt{\frac{\sum_{k=0}^{n}(F(k) - F_{ref})^2}{n-1}}}{F_{ref}} \qquad (2),$$

kjer sta: n - število testov (20), F_{ref} - želena rezalna sila. Zmožnost UNKS za nadzor največje sile številčno izrazimo z normalizirano standardno napako.

Rezultati primerjav za preizkus-2 so podani v preglednici 1.

S prilagodnim sistemom krmiljenja dosežemo v enem rezu 24-odstotni časovni prihranek proti frezanju s stalnim podajanjem. Z uporabo UNKS se konice rezalnih sil pomembno zmanjšajo.

where n is the number of samples (20), and F_{ref} is the desired cutting force. The normalized standard error quantifies the ability of the UNKS to regulate the reference peak force.

The results of the comparison for Experiment 2 are tabulated in Table 1.

With the adaptive control system a time saving of 24% with one cut was achieved in comparison with the constant feedrate. With the use of UNKS the peak forces are reduced significantly.

Preglednica 1. *Primerjava lastnosti krmilnikov pri obdelavi obdelovanca z nepravilnim profilom*
Table 1. *Comparison of controller performance for the machining of a workpiece with an irregular profile*

Nepravilni profil Irregular profile	Normalizirana standardna napaka Normalized Standard Error– *Nsn*	Čas obdelave Time of cut [s]	Čas optimiranja [s] /število iteracij Optimization time [s] /number of iterations	Želena sila Desired Force [kN]	Največja rezalna sila Maximal cutting force [kN]
Običajno frezanje-ločena optimizacija Conventional milling-off-line optimization	0,35	115	0,001/18	0,665	1,4
Delilni krmilnik Divisional controller	0,29	98	0,007/23	0,665	1,25
P krmilnik P-controller	0,2	95	0,006/22	0,665	1,1
Nastavljivi PI krmilnik Adjustable PI-controller	0,19	94	0,006/20	0,665	1,0
MPRKS / MRAC	0,22	92	0,012/34	0,665	0,9
Kombiniran sistem Combined system	**0,18**	**88**	**0,001/18**	**0,665**	**0,91**

Delilni krmilnik ima hiter odziv in ga je najpreprosteje izvesti. Nastavljivi PI krmilnik je nekoliko bolj zapleteno, vendar tudi prikazuje kratke odzivne čase. MPRKS je najbolj zapleten, njegov odzivni čas je znatno daljši (8%). Vsa prilagodna krmilja so zmožna nadzorovati rezalno silo in ostati stabilna prek velikega območja geometrijskih variacij.

Dobljeni rezultati se ujemajo s cilji raziskave, po katerih odstopanje krmiljene rezalne sile ne sme odstopati od primerjalne vrednosti za več ko 10 odstotkov.

V primerjavi z večino znanih sistemov krmiljenja oblikovnega frezanja ima predlagani kombinirani sistem naslednje prednosti: 1. računska zapletenost UNKS se bistveno ne povečuje s zapletenostjo postopka; 2. UNKS ima večjo zmožnost učenja kakor klasično prilagodno krmilje; 3. UNKS ima zmožnost posploševanja; 4. Sistem je neobčutljiv za spremembe geometrijske oblike obdelovanca, geometrijske oblike frezala in materiala obdelovanca; 5. Je stroškovno ugoden in ga je preprosto izdelati; in 6. Ne terja matematičnega modeliranja.

Preizkusni rezultati pokažejo, da ima postopek frezanja z zasnovanim prilagodnim sistemom krmiljenja veliko grobost, stabilnost in je bolj učinkovit kakor z uporabljenimi standardnimi krmilniki.

The divisional controller has a quick response and is the simplest to implement. The adjustable PI controller is slightly more complicated, but also demonstrates a short response time. The MRAC is the most complicated and the response time is considerably longer (8%). All of the parameter adaptive controllers are able to control the peak force and remain stable over a large range of geometric variations.

The results achieved are in accordance with the objectives of the research, according to which the controlled cutting force must not deviate from the desired value by more than 10%.

In comparison to most of the existing end-milling control systems, the proposed combined system has the following advantages: 1. the computational complexity of UNKS does not increase much with the complexity of the process; 2. the learning ability of UNKS is more powerful than that of a conventional adaptive controller; 3. UNKS has a generalisation capability; 4. it is insensitive to changes in the workpiece geometry, the cutter geometry, and the workpiece material; 5. it is cost efficient and easy to implement; and 6. it is mathematically modelling-free.

The experimental results show that the milling process with the designed adaptive controller is highly robust, stable, and also has a higher machining efficiency than standard controllers.

Trenutne raziskave kažejo, da ima nevronska krmilna shema znatne prednosti v primerjavi s klasičnimi krmilniki. Prva prednost je, da lahko učinkovito uporabi več zaznavnih informacij pri načrtovanju in izvajanju dejavnosti krmiljenja kakor industrijski krmilnik. Druga prednost je, da se nevronska krmilna shema hitro odziva na zapletene zaznavne vhode, medtem ko je hitrost izvajanja zahtevnih krmilnih algoritmov pri klasičnem krmilniku mnogo manjša.

Current research has shown that a neural control scheme has important advantages over conventional controllers. The first advantage is that it can efficiently utilize a much larger amount of sensory information in planning and executing a control action than an industrial controller can. The second advantage is that a neural control scheme responds quickly to complex sensory inputs while the executing speed of sophisticated control algorithms in a conventional controller is severely limited.

7 SKLEP

Na temelju modeliranja postopka rezanja, ločene optimizacije in usmerjene nevronske krmilne sheme (UNKS) je sestavljen kombiniran sistem za ločeno optimiranje in prilagodno nastavljanje rezalnih parametrov. To je sistem prilagodnega krmiljenja, ki z digitalnim nastavljanjem rezalnih parametrov krmili rezalno silo in ohranja stalno hrapavost frezane površine.

Uporabnost metodologije prilagodnega nastavljanja rezalnih parametrov je s preizkusi prikazana in preizkušena na 4-osnem frezalnem RNK stroju Heller. Rezultati preizkusov inteligentnega frezanja s strategijo prilagodnega krmiljenja kažejo, da ima razviti sistem veliko grobost in globalno stabilnost. Preizkusi so potrdili učinkovitost prilagodnega sistema krmiljenja, ki se kaže v izboljšani kakovosti površine in manjši obrabi orodja. V tem prispevku je predlagana zgradba sprotnega določevanja optimalnih rezalnih razmer uporabljena pri oblikovnem frezanju, vendar je očitno, da je sistem mogoče razširiti na druge obdelovalne stroje in jim tako povečati učinkovitost.

7 CONCLUSION

On the basis of the cutting process modelling, off-line optimization and feed-forward neural control scheme (UNKS) a combined system for off-line optimization and adaptive adjustment of the cutting parameters has been built. This is an adaptive control system controlling the cutting force and maintaining the constant roughness of the surface being milled by introducing digital adaptation of the cutting parameters.

The applicability of the methodology of adaptive adjustment of the cutting parameters is experimentally demonstrated and tested on a 4-axis Heller CNC milling machine. The results of the intelligent milling experiments with an adaptive control strategy show that the developed system has high robustness and global stability. Experiments have confirmed the efficiency of the adaptive control system, which is reflected in an improved surface quality and decreased tool wear. The proposed architecture for an on-line determination of the optimal cutting conditions is applied to ball-end milling in this paper, but it is obvious that the system can be extended to other machines to improve the cutting efficiency.

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Viskozno dušene prečne vibracije osno gibajoče se strune

Viscously Damped Transverse Vibrations of an Axially-Moving String

Nikola Jakšić - Miha Boltežar

V tem prispevku predstavljamo analizo delovanja viskoznega dušenja na prečna nihanja osno gibajoče se strune. Analizirani linearni model viskoznega dušenja je zapisan v obliki $b_1\frac{\partial w}{\partial t}+b_2 v\frac{\partial w}{\partial x}$. *Najprej smo rešili gibalno enačbo lastnega nihanja - linearno parcialno diferencialno enačbo. Nato smo analizirali vplive vrednosti koeficientov viskoznega dušenja* b_1 *in* b_2 *na lastne frekvence in na odziv sistema pri lastnih nihanjih. Pokazali smo, da je potrebno vrednosti koeficientov izbrati previdno, da bi se izognili fizikalno neustreznim odzivom.*

(Ključne besede: enačbe diferencialne, enačbe hiperbolične, nihanja dušena, strune gibajoče)

In this paper the linear viscous-damping mechanism acting on an axially-moving string is analyzed. The analyzed damping model is in the form $b_1\frac{\partial w}{\partial t}+b_2 v\frac{\partial w}{\partial x}$. *The equation of motion, i.e., the linear partial differential equation, of the free, transverse vibrations of the string's span is solved first. Then the influence of the coefficients* b_1 *and* b_2 *on the natural frequencies and the free responses is studied. It was found that the values of the coefficients should be carefully selected in order to avoid physically unrealistic responses.*

(Keywords: partial differential equations, hyperbolic equations, free damped vibrations, moving string systems)

0 UVOD

Modeliranje osno premikajočih se struktur je deležno nezmanjšane pozornosti že zadnjih 50 let. Pri tem gre za modeliranje verig v verižnih gonilih [1], modeliranje lista pri žagah [2], ali pa modeliranje vej pri jermenskih pogonih [3]. Obsežen pregled modeliranja jermenov in jermenskih pogonov do leta 1992 je podan v prispevku [3]. Problematika osno gibajočega se modela strune je obravnavana v številnih virih, naj izpostavimo le nekatere: [4] do [10].

Prispevek [1] analizira prečna nihanja verig verižnih gonil. Analiza je pokazala, da se amplituda nihanja točke na sredini veje verige poveča, če se poveča osna hitrost potovanja verige, če upoštevamo le $\partial w/\partial t$ del modela viskoznega dušenja. Enak pojav sta odkrila avtorja v prispevku [2]. Prispevek [3] ga na kratko povzame.

Jermeni, ki so v rabi, so v glavnem zahtevne nekovinske strukture, pri katerih je modeliranje disipacije energije praktično neizogibno. Uporabimo

0 INTRODUCTION

The modelling of moving continua has received constant attention over the past 50 years; studies have included the modelling of the vibrations of transmission chains [1], the modelling of band saws [2], and the modelling of belts [3]. A comprehensive review of the modelling of belts and belt drives up until 1992 is presented in [3]. There are many papers dealing with the problem of the moving string: [4] to [10].

The paper of Mahalingam [1] deals with the transverse vibrations of power-transmission chains. It was reported that the mid-span amplitude of the chain span, when kinematically excited at one end of the span, increases when the chain's axial velocity increases if only the $\partial w/\partial t$ part of the chain's velocity is taken into account. The same phenomenon is reported in [2] and recapitulated in [3].

The modelling of energy dissipation in the form of viscous damping, or another more sophisticated energy-dissipation or rheological model, is lahko viskozni model disipacije energije ali pa katerega od bolj izpopolnjenih reoloških modelov ali modelov disipacije energije. Modeli, ki popisujejo viskoelastične lastnosti jermenov, se že uporabljajo pri modeliranju vej jermenov ([9] do [14]).

Viskozni model dušenja lahko služi kot ekvivalentni model disipacije energije še posebej v primerih kompozitnih struktur. Tu se lahko skriva fizikalno ozadje raziskovanega viskoznega modela.

Čeprav so bolj izpopolnjeni materialni modeli že vstopili v domeno modeliranja vej jermenov, pa pojav, opisan v delih [1] in [2], še ni bi deležen večje pozornosti. Slednje je cilj tega prispevka.

practically unavoidable when dealing with modern belts. These are mainly complex non-metal structures, where viscoelasticity plays an important role. The modelling of viscoelastic properties is presented in [9] to [14].

Viscous damping can provide a suitable way of equivalent energy-dissipation modelling, particularly when dealing with composite structures, and this can provide a physical background for the viscous model under consideration.

Although more sophisticated material models have been introduced for belt modelling, the viscous-damping model used in [1] and [2] has not been analyzed in detail. Such an analysis is the aim of this paper.

1 GIBALNA ENAČBA PREČNIH NIHANJ OSNO GIBAJOČE SE STRUNE

Prečni odmik strune od statične ravnovesne lege popisuje koordinata $w = w(x,t)$ (sl. 1).

Predpostavimo, da se struna osno giblje z osno hitrostjo $v = v(t)$. Diferencial koordinate prečnega pomika podaja enačba (1). Uporabimo jo za izpeljavo hitrosti strune v prečni smeri, enačba (2):

1 THE EQUATION OF MOTION OF THE TRANSVERSE VIBRATIONS OF AN AXIALLY-MOVING STRING

The transverse vibrations of a string are represented by the transverse displacement $w = w(x,t)$ (Fig. 1).

Let us suppose that the string is moving with an axial velocity $v = v(t)$. The differential of the displacement, Eq. (1), is used to deduce the transverse velocity of the string, Eq. (2):

$$\mathrm{d}w = \frac{\partial w}{\partial x}\mathrm{d}x + \frac{\partial w}{\partial t}\mathrm{d}t \tag{1}$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} = \dot{w} = \frac{\partial w}{\partial x}\frac{\mathrm{d}x}{\mathrm{d}t} + \frac{\partial w}{\partial t} = \frac{\partial w}{\partial x}v + \frac{\partial w}{\partial t} \tag{2}$$

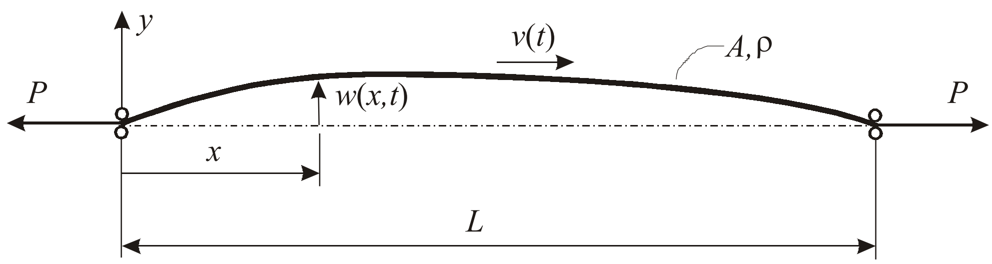
Tako zapišemo diferencialna operatorja:

Hence, the differential operators can be deduced as

$$\frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial x}v + \frac{\partial}{\partial t} \quad \text{in/and} \quad \frac{\mathrm{D}^2}{\mathrm{D}t^2} = v^2\frac{\partial^2}{\partial x^2} + 2v\frac{\partial^2}{\partial x \partial t} + \frac{\partial^2}{\partial t^2} + \dot{v}\frac{\partial}{\partial x} \tag{3}$$

Gibalno enačbo prečnih nihanj (4) osno gibajoče se strune izpeljemo z uporabo 2. Newtonovega zakona:

The equation of motion (4) can be deduced from Newton's second law for a differentially small section of the string, and written as:



Sl. 1. *Osno gibajoča se struna*
Fig. 1. *The axially-moving string*

$$\rho A \frac{\mathrm{D}^2 w(x,t)}{\mathrm{D}t^2} = P \frac{\partial^2 w(x,t)}{\partial x^2} - d \frac{\mathrm{D}\, w(x,t)}{\mathrm{D}t} \tag{4}$$

kjer popisujejo: ρ gostoto gradiva strune, A velikost prečnega prereza strune, P natezno obremenitev strune in d koeficient viskoznega dušenja. Leva stran enačbe (4) pomeni vztrajnostno silo v sistemu. Prvi člen na desni strani iste enačbe popisuje aktivno silo zaradi natezanja strune. Drugi člen popisuje silo viskoznega dušenja. Z uporabo diferencialnih operatorjev (3) dobimo gibalno enačbo v obliki:

where ρ is the density of the string material, A is the area of the cross-section of the string, P is the tension force and d is the viscous damping coefficient. The left-hand side of Equation (4) represents the inertial forces of the system. The first part of the right-hand side of the same equation stands for the active force due to the string's tension, and the second part stands for the viscous damping force acting on the string. By considering the differential operators, Eq. (3), the equation of motion can be rewritten as:

$$P \frac{\partial^2 w}{\partial x^2} - \rho A v^2 \frac{\partial^2 w}{\partial x^2} - 2\rho A v \frac{\partial^2 w}{\partial x \partial t} - \rho A \frac{\partial^2 w}{\partial t^2} - d \frac{\partial w}{\partial t} - \left(\rho A \frac{\mathrm{d}v}{\mathrm{d}t} + d\, v \right) \frac{\partial w}{\partial x} = 0 \tag{5}$$

Upoštevaje nespremenljivo osno hitrost strune, $\mathrm{d}v/\mathrm{d}t = 0$, ter z deljenjem enačbe s konstanto ρA, dobimo gibalno enačbo v obliki:

Taking the constant velocity into account, $\mathrm{d}v/\mathrm{d}t = 0$, and dividing the equation by ρA, the equation becomes:

$$(c^2 - v^2) \frac{\partial^2 w}{\partial x^2} - 2v \frac{\partial^2 w}{\partial x \partial t} - \frac{\partial^2 w}{\partial t^2} - b \frac{\partial w}{\partial t} - b v \frac{\partial w}{\partial x} = 0 \quad ; \quad c = \sqrt{\frac{P}{\rho A}} \quad ; \quad b = \frac{d}{\rho A} \tag{6}$$

Namen tega prispevka je analizirati gibalno enačbo lastnega nihanja osno gibajoče se strune, če imata koeficienta b različne vrednosti. Tako dobimo enačbo, ki nas zanima:

The aim of this paper is to analyze the equation of motion for different values of b. Hence, the equation of interest is:

$$(c^2 - v^2) \frac{\partial^2 w}{\partial x^2} - 2v \frac{\partial^2 w}{\partial x \partial t} - \frac{\partial^2 w}{\partial t^2} - b_1 \frac{\partial w}{\partial t} - b_2 v \frac{\partial w}{\partial x} = 0 \tag{7}$$

kjer so $b_1 \geq 0$, $b_2 \geq 0$ in $0 \leq v < c$, kar predpostavlja podkritično osno hitrost strune.

where $b_1 \geq 0$, $b_2 \geq 0$ and $0 \leq v < c$ applying the subcritical string's axial velocity.

2 ANALITIČNA REŠITEV GIBALNE ENAČBE PREČNIH NIHANJ OSNO GIBAJOČE SE STRUNE

2 AN ANALYTICAL SOLUTION OF THE EQUATION OF MOTION FOR THE TRANSVERSE VIBRATIONS OF AN AXIALLY-MOVING STRING

Enačbo (7) preslikamo v drugo kanonično obliko s preslikavo:

Equation (7) can be transformed into the second canonical form by the transformation:

$$\begin{aligned} \zeta &= \alpha x + \beta t \\ \eta &= \gamma x + \delta t \end{aligned} \quad ; \quad \begin{vmatrix} \alpha & \beta \\ \gamma & \delta \end{vmatrix} \neq 0 \tag{8}$$

Če se hočemo znebiti mešanega odvoda v enačbi (7), morajo parametri preslikave zasesti naslednje vrednosti: $\alpha = 1$, $\beta = 0$, $\gamma = v/(c^2 - v^2)$ in $\delta = 1$, preslikavo zapišemo kot:

To get rid of the second mixed derivative in Eq. (7) the values of the transformation parameters should be $\alpha = 1$, $\beta = 0$, $\gamma = v/(c^2 - v^2)$ and $\delta = 1$, and the transformation can be written as:

$$\begin{aligned} \zeta &= x \\ \eta &= x v/(c^2 - v^2) + t \end{aligned} \tag{9}$$

Tako lahko gibalno enačbo zapišemo v drugi kanonični obliki kot:

The equation of motion is thus given in the second canonical form as:

$$(c^2 - v^2) \frac{\partial^2 w}{\partial \zeta^2} - \frac{c^2}{c^2 - v^2} \frac{\partial^2 w}{\partial \eta^2} - b_2 v \frac{\partial w}{\partial \zeta} - \left(\frac{v^2}{c^2 - v^2} b_2 + b_1 \right) \frac{\partial w}{\partial \eta} = 0 \tag{10}$$

Enačbo (10) rešujemo z Euler-Fourierjevim nastavkom, ki loči časovno in krajevno spremenljivko:

Equation (10) can be solved by using the Euler-Fourier approach of variables separation,

$$w(\zeta,\eta) = W(\zeta)T(\eta) \tag{11}$$

Nastavek (11) vnesemo v enačbo (10) in delimo z nastavkom. Tako lahko enačbo (10) zapišemo kot:

By putting the supposed solution (11) into (10) and dividing the latter by the solution itself, Eq. (10) can be rewritten as:

$$(c^2-v^2)\frac{W''}{W} - b_2 v\frac{W'}{W} = \frac{c^2}{c^2-v^2}\frac{\ddot{T}}{T} + \left(\frac{v^2}{c^2-v^2}b_2 + b_1\right)\frac{\dot{T}}{T} = -\omega^2 \tag{12}$$

In na tej podlagi sestavimo dve navadni diferencialni enačbi:

And thus two ordinary differential equations are formed:

$$(c^2-v^2)W'' - b_2 v W' + \omega^2 W = 0 \tag{13}$$

$$\frac{c^2}{c^2-v^2}\ddot{T} + \left(\frac{v^2}{c^2-v^2}b_2 + b_1\right)\dot{T} + \omega^2 T = 0 \tag{14}$$

Prvo rešujemo navadno diferencialno enačbo (13), da bi določili izraz za parameter ω. Rešitev predpostavimo v obliki $W(\zeta) = Ce^{\lambda\zeta}$ in dobimo karakteristični polinom:

The ordinary differential equation (13) should be solved first in order to get the expression for the parameter ω. The solution is assumed to be in the form $W(\zeta) = Ce^{\lambda\zeta}$, and the characteristic polynomial is formed as:

$$\lambda^2 - \frac{b_2 v}{c^2-v^2}\lambda + \frac{\omega^2}{c^2-v^2} = 0 \tag{15}$$

s koreni

with the roots

$$\lambda_{1,2} = \frac{1}{2}\left[\frac{b_2 v}{c^2-v^2} \pm \sqrt{\left(\frac{b_2 v}{c^2-v^2}\right)^2 - 4\frac{\omega^2}{c^2-v^2}}\right] = \frac{1}{2}\tilde{\alpha} \pm i\tilde{\gamma} \tag{16}$$

kjer so $\tilde{\alpha} = b_2 v/(c^2-v^2)$, $\tilde{\beta} = \omega^2/(c^2-v^2)$ in $\tilde{\gamma} = \sqrt{\tilde{\beta} - (\tilde{\alpha}/2)^2}$. Izraz pod korenom enačbe za $\tilde{\gamma}$ je vedno pozitiven, če le velja $v \le c$. Ta izraz lahko zapišemo tudi kot $\omega^2 > \left(\frac{b_2}{2}\right)^2 \frac{v^2}{c^2-v^2}$, njegovo veljavo pa ocenimo na podlagi enačbe (20).

Rešitev enačbe (13) je linearna kombinacija rešitve obeh korenov:

where $\tilde{\alpha} = b_2 v/(c^2-v^2)$, $\tilde{\beta} = \omega^2/(c^2-v^2)$ and $\tilde{\gamma} = \sqrt{\tilde{\beta} - (\tilde{\alpha}/2)^2}$. The expression under the square root in $\tilde{\gamma}$ is non-negative as long as $v \le c$. This expression can also be rewritten as $\omega^2 > \left(\frac{b_2}{2}\right)^2 \frac{v^2}{c^2-v^2}$. Its validity can be verified on the basis of Eq. (20).

The solution of (13) is a linear combination of both roots:

$$W(\zeta) = e^{\tilde{\alpha}L/2}(C_1 \cos\tilde{\gamma}\zeta + C_2 \sin\tilde{\gamma}\zeta) \tag{17}$$

kjer sta C_1 in C_2 konstanti. Funkcija (17) mora zadostiti robnim pogojem:

where C_1 and C_2 are constants. The function (17) must satisfy the boundary conditions

$$\begin{aligned} w(0,t)=0 \quad &\Rightarrow \quad W(0)T(t)=0 \quad &\Rightarrow \quad W(0)=0=C_1 \\ w(L,t)=0 \quad &\Rightarrow \quad W(L)T(Lv/(c^2-v^2)+t)=0 \quad &\Rightarrow \quad W(L)=0=C_2 e^{\tilde{\alpha}L/2}\sin\tilde{\gamma}L \end{aligned} \tag{18}$$

iz česar izhaja:

which yields

$$\sin\tilde{\gamma}L = 0 \quad \Rightarrow \quad \tilde{\gamma}_k = \frac{k\pi}{L} = \sqrt{\tilde{\beta} - \tilde{\alpha}^2/2} \quad ; \quad k = 1,2,3,... \tag{19}$$

Iz enačbe (19) dobimo izraz za ω_k; $k = 1,2,3, \ldots$

It is straightforward to derive an expression for ω_k; $k = 1,2,3, \ldots$ from Eq. (19).

$$\omega_k^2 = (c^2 - v^2)\frac{k^2\pi^2}{L^2} + \frac{v^2}{c^2 - v^2}\left(\frac{b_2}{2}\right)^2 \quad (20).$$

Nabor navadnih diferencialnih enačb (14) lahko, glede na funkcijo $T_k(t)$, zapišemo kot:

With respect to the time function $T_k(t)$, the set of the ordinary differential equations (14) can be rewritten as:

$$\ddot{T}_k + \left(\frac{v^2}{c^2}(b_2 - b_1) + b_1\right)\dot{T}_k + \frac{c^2 - v^2}{c^2}\omega_k^2 T_k = 0 \quad (21).$$

Pri reševanju diferencialne enačbe (21) uporabimo nastavek v obliki $T_k(\eta) = C_k\, e^{\lambda_k \eta}$ in dobimo karakteristični polinom:

The solution is assumed to be in the form $T_k(\eta) = C_k\, e^{\lambda_k \eta}$, and the characteristic polynomial is formed as:

$$\lambda_k^2 + \left(\frac{v^2}{c^2}(b_2 - b_1) + b_1\right)\lambda_k + \frac{c^2 - v^2}{c^2}\omega_k^2 = 0 \quad (22)$$

s koreni

with the roots

$$\lambda_{k_{1,2}} = \frac{1}{2}\left[-\left(\frac{v^2}{c^2}(b_2 - b_1) + b_1\right) \pm \sqrt{\left(\frac{v^2}{c^2}(b_2 - b_1) + b_1\right)^2 - 4\omega_k^2\frac{c^2 - v^2}{c^2}}\right] = \frac{1}{2}\left[-\hat{\alpha} \pm \sqrt{\hat{\alpha}^2 - 4\hat{\beta}_k}\right] \quad (23),$$

kjer sta $\hat{\alpha} = \frac{v^2}{c^2}(b_2 - b_1) + b_1$ in $\hat{\beta}_k = \omega_k^2\frac{c^2 - v^2}{c^2}$.
Če velja:

where $\hat{\alpha} = \frac{v^2}{c^2}(b_2 - b_1) + b_1$ and $\hat{\beta}_k = \omega_k^2\frac{c^2 - v^2}{c^2}$.
If the relation:

$$\hat{\beta}_k > \frac{1}{4}\hat{\alpha}^2 \quad \Rightarrow \quad \omega_k^2 > \frac{1}{4}\frac{c^2 - v^2}{c^2}\left(\frac{v^2}{c^2 - v^2}b_2 + b_1\right)^2, \quad (24),$$

potem imamo opravka z nihanjem, torej s podkritičnim dušenjem. Če pa neenačbi (24) ni zadoščeno, nihanja ni in opredelimo dušenje kot kritično ali nadkritično.

is satisfied, then vibrations exist and the system is underdamped. Otherwise, the system is overdamped or critically damped.

2.1 Podkritično dušenje

2.1 The underdamped system

V tem primeru je izrazu (24) zadovoljeno. Rešitev karakterističnega polinoma (22) zapišemo kot:

In this case Expression (24) is satisfied. The roots of the characteristic polynomial (22) are:

$$\lambda_{k_{1,2}} = -\frac{1}{2}\hat{\alpha} \pm i\hat{\gamma}_k \quad (25),$$

kjer je $\hat{\gamma}_k = \sqrt{\hat{\beta}_k - (\hat{\alpha}/2)^2}$. Rešitev diferencialne enačbe (21) zapišemo kot:

where $\hat{\gamma}_k = \sqrt{\hat{\beta}_k - (\hat{\alpha}/2)^2}$. The solution of the ordinary differential equation (21) can be written as:

$$T_k(\eta) = e^{-\hat{\alpha}\eta/2}\left(A\cos(\hat{\gamma}_k\eta) + B\sin(\hat{\gamma}_k\eta)\right) \quad (26).$$

Iz enačbe (26) vidimo, da je parameter $\hat{\gamma}_k$ enak lastni frekvenci dušenega nihanja:

It can be seen in Eq. (26) that the parameter $\hat{\gamma}_k$ is equal to the damped natural frequency:

$$\omega_{d_k}^2 = \hat{\gamma}_k^2 = \left(\frac{c^2 - v^2}{c}\right)^2\frac{k^2\pi^2}{L^2} + \frac{1}{4}\frac{c^2 - v^2}{c^2}\left[\frac{v^2}{c^2}(b_2 - b_1)^2 - b_1^2\right] \quad ; \quad k = 1,2,3,\ldots \quad (27).$$

Odziv k-tega načina izpeljemo kot:

The k-th mode is as follows:

$$w_k(x,t) = e^{\frac{1}{2}\frac{v}{c^2}(b_2 - b_1)x}\sin\frac{k\pi x}{L}\, e^{-\frac{1}{2}\frac{1}{c^2}[v^2(b_2 - b_1) + c^2 b_1]t}\left[A_k\cos\left(\omega_{d_k}\left(\frac{xv}{c^2 - v^2} + t\right)\right) + B_k\sin\left(\omega_{d_k}\left(\frac{xv}{c^2 - v^2} + t\right)\right)\right] \quad (28).$$

2.2 Kritično dušenje

V primeru kritičnega dušenja velja $\hat{\beta}=\hat{\alpha}^2/4$ oziroma $\omega^2=\frac{1}{4}\frac{c^2-v^2}{c^2}\left(\frac{v^2}{c^2-v^2}b_2+b_1\right)^2$, kar pomeni, da ima karakteristični polinom (22) dve enaki realni rešitvi:

2.2 The critically damped system

In this case the equality $\hat{\beta}=\hat{\alpha}^2/4$ or $\omega^2=\frac{1}{4}\frac{c^2-v^2}{c^2}\left(\frac{v^2}{c^2-v^2}b_2+b_1\right)^2$ is established. This means that the characteristic polynomial (22) has two identical roots.

$$\lambda_{1,2}=-\frac{1}{2}\left(\frac{v^2}{c^2}(b_2-b_1)+b_1\right)=-\frac{1}{2}\hat{\alpha} \tag{29}$$

Rešitev diferencialne enačbe (21) zapišemo kot:

The solution of the ordinary differential equation (21) can be written as:

$$T(\eta)=\left(A+B\eta\right)e^{-\frac{1}{2}\hat{\alpha}\eta} \tag{30}$$

in odziv *k*-tega načina kot:

and the expression for the *k*-th mode as:

$$\begin{aligned} w_k(x,t) \;=\; & e^{\frac{1}{2}\frac{v}{c^2}(b_2-b_1)x}\sin\frac{k\pi x}{L}\,e^{-\frac{1}{2}\frac{1}{c^2}[v^2(b_2-b_1)+c^2b_1]t} \\ & \left[A_k+B_k\left(\frac{xv}{c^2-v^2}+t\right)\right] \end{aligned} \tag{31}$$

2.3 Nadkritično dušenje

V primeru nadkritičnega dušenja se nihanja ne pojavijo ker velja $\hat{\beta}_k<\hat{\alpha}^2/4$ oziroma $\omega_k^2<\frac{1}{4}\frac{c^2-v^2}{c^2}\left(\frac{v^2}{c^2-v^2}b_2+b_1\right)^2$, kar tudi pomeni, da ima karakteristični polinom (22) dve različni realni rešitvi:

2.3. The overdamped system

In the case of the overdamped system the vibrations cannot appear and $\hat{\beta}_k<\hat{\alpha}^2/4$ or $\omega_k^2<\frac{1}{4}\frac{c^2-v^2}{c^2}\left(\frac{v^2}{c^2-v^2}b_2+b_1\right)^2$, which means that the characteristic polynomial (22) has two different real roots:

$$\lambda_{k_{1,2}}=\frac{1}{2}\hat{\alpha}\pm\hat{\varepsilon}_k \tag{32}$$

kjer je $\hat{\varepsilon}_k=\sqrt{(\hat{\alpha}/2)^2-\hat{\beta}_k}=i\hat{\gamma}_k$. Rešitev diferencialne enačbe (21) zapišemo kot:

where $\hat{\varepsilon}_k=\sqrt{(\hat{\alpha}/2)^2-\hat{\beta}_k}=i\hat{\gamma}_k$. The solution of the ordinary differential equation (21) can be written as:

$$T_k(\eta)=e^{-\hat{\alpha}\eta/2}\left(A_k\cosh(\hat{\varepsilon}_k\eta)+B_k\sinh(\hat{\varepsilon}_k\eta)\right) \tag{33}$$

in odziv *k*-tega načina kot:

and the expression for the *k*-th mode as:

$$w_k(x,t)=e^{\frac{1}{2}\frac{v}{c^2}(b_2-b_1)x}\sin\frac{k\pi x}{L}\,e^{-\frac{1}{2}\frac{1}{c^2}[v^2(b_2-b_1)+c^2b_1]t}\left[A_k\cosh\left(\hat{\varepsilon}_k\left(\frac{xv}{c^2-v^2}+t\right)\right)+B_k\sinh\left(\hat{\varepsilon}_k\left(\frac{xv}{c^2-v^2}+t\right)\right)\right] \tag{34}$$

3 REZULTATI IN RAZPRAVA

Pod predpostavko oziroma pri pogojih $b_1\geq 0, b_2\geq 0$ in $0\leq v<c$ pričakujemo, da bo model viskoznega dušenja, kot model disipacije energije v sistemu, vplival na lastne frekvence dušenega nihanja strune na način, da se bodo omenjene lastne frekvence zmanjšale ob povečanju vrednosti koeficientov viskoznega dušenja. Druga domneva govori o tem, da se amplituda odziva sistema ne bi smela zmanjševati počasneje s povečanjem osne hitrosti strune.

3 RESULTS AND DISCUSSION

Assuming that $b_1\geq 0, b_2\geq 0$ and $0\leq v<c$, one can expect that the viscous-damping energy-dissipation model would influence the natural frequencies of the vibrations in such a way that the frequencies would not increase with the increasing value of the coefficient of the viscous damping model. The second assumption is that the response's amplitude should not decrease more rapidly with the string's increasing axial velocity.

3.1 Vpliv koeficientov viskoznega dušenja na lastno frekvenco prečnega nihanja strune

Nihanje strune s svojo lastno frekvenco se pojavi le pri podkritičnem dušenju. Enačba (27) lastne frekvence dušenega nihanja je sestavljena iz dveh delov. Prvi del je enak lastni frekvenci nedušenega nihanja osno gibajoče se strune. Na drugi del pomembno vpliva viskozno dušenje. Pričakujemo, da se bo lastna frekvenca dušenega nihanja zmanjšala glede na lastno frekvenco nedušenega nihanja, iz česar izhaja matematično formuliran pogoj:

3.1 The influence of the viscous damping coefficients on the natural frequency of the damped transverse string vibrations

Let us focus first on the natural frequencies whose values should not increase if the damping also increases. It is clear that the expression for the natural frequency (27) is made up of two parts. The first part is actually the undamped natural frequency of the moving string, and the second part is influenced by the damping mechanism. Since the damping should decrease the natural frequency the following relation must be satisfied:

$$\frac{v^2}{c^2}(b_2-b_1)^2-b_1^2\le 0 \qquad (35).$$

Rešitev tega pogoja je ploskev, ki jo podaja neenačba:

The solution of relation (35) is a half-plane defined by:

$$b_1\ge\frac{v}{c+v}b_2 \qquad (36),$$

le ta pa je omejena s premico:

and bounded by the straight line:

$$b_1=\frac{v}{c+v}b_2=k_1\,b_2 \qquad (37).$$

Koeficient strmine premice k_1 doseže najmanjšo vrednost pri $v=0$, $k_1\,(v=0)=0$, in največjo vrednost v mejnem primeru $v\to c$, $k_1\,(v\to c)=0{,}5$. Mejo med nihanjem strune in nadkritičnim obnašanjem slednje za vsak način posebej izpeljemo iz enačbe $\omega_k^2=\frac{1}{4}\frac{c^2-v^2}{c^2}\left(\frac{v^2}{c^2-v^2}b_2+b_1\right)^2$ (gl. 2.2).:

The coefficient k_1 reaches its minimum value at $v=0$, $k_1\,(v=0)=0$, and its maximum value in the limit case of $v\to c$, $k_1\,(v\to c)=0.5$. The border between the underdamped and overdamped systems' response for each mode can be deduced from $\omega_k^2=\frac{1}{4}\frac{c^2-v^2}{c^2}\left(\frac{v^2}{c^2-v^2}b_2+b_1\right)^2$, see subsection 2.2.:

$$b_{k_1}=f_k(b_2)=\frac{1}{c^2-v^2}\left[-b_2\,v^2+c\sqrt{b_2^2\,v^2+\left(2\frac{k\pi}{L}(c^2-v^2)\right)^2}\right] \qquad (38).$$

Enačba (38) doseže svojo najmanjšo vrednost v točki $b_{k_1}=b_{k_2}=2\frac{k\pi}{L}\sqrt{c^2-v^2}$ in se asimptotično približuje enačbi (37).

Equation (38) reaches its minimum at point $b_{k_1}=b_{k_2}=2\frac{k\pi}{L}\sqrt{c^2-v^2}$. It also asymptotically approaches Eq. (37).

3.2 Vpliv koeficientov viskoznega dušenja na amplitudo odziva strune

Druga domneva govori o tem, da se amplituda odziva sistema ne bi smela zmanjševati počasneje s povečanjem osne hitrosti strune v. Izrazi k-tega načina so podani v enačbah (28), (31) in (34). Prvo moramo najti vrh lastne oblike z zanemaritvijo faznega zaostajanja točk vzdolž dolžine strune, ki je skrito v koordinati η, kot primer naj bo enačba (28). Lastno obliko okarakterizira izraz:

3.2 The influence of the viscous damping coefficients on the response amplitude

In contrast, we expect that the response's amplitudes would not decrease more rapidly with the string's increasing axial velocity, v. The expressions for the k-th mode are given in Equations (28), (31) and (34). The maximum of the mode shape should be found first. By neglecting the different phase lags of the different points along the string's length, which are hidden in the coordinate η, e.g., see Eq. (28), the mode shapes are governed primarily by the following expression:

$$\bar{W}_k(x) = e^{\frac{v}{2c^2}(b_2-b_1)x} \sin\frac{k\pi x}{L} \quad ; \quad k = 1,2,3,... \tag{39}$$

iz katerega lahko sklepamo o legi največje amplitude nihanja strune zaradi koordinate lege v odvisnosti od predznaka izraza $b_2 - b_1$. Če je $b_2 - b_1 \geq 0$, sledi, da se vrh pojavi na zadnjem polvalu lastne oblike, ko je $x_k = (2k–1)L/(2k)$, ter če je $b_2 - b_1 < 0$, sledi, da se vrh pojavi na prvem polvalu lastne oblike, ko je $x_k = L/(2k)$.

Amplitudo odziva, glede na enačbe (28), (31) in (34), dominantno opredeljuje enačba:

which applies a different shape-maximum position, as the expression $b_2 - b_1$ can have different signs. In the case of $b_2 - b_1 \geq 0$ the shape maximum is found at $x_k = (2k–1)L/(2k)$, and in the case of $b_2 - b_1 < 0$ the shape maximum is found at $x_k = L/(2k)$.

The response's amplitude is, according to Equations (28), (31) and (34), governed by the expression:

$$Amp(w(x_k,t)) = \exp\left[\frac{1}{2c^2}\left(v[b_2-b_1]x-[v^2(b_2-b_1)+c^2 b_1]t\right)\right] \tag{40}$$

kjer x lahko zavzame dve vrednosti $x_k = (2k–1)L/(2k)$ ali $x_k = L/(2k)$, glede na predznak izraza $b_2 - b_1$. Eksponentna funkcija je monotona, zato zadošča analiza eksponenta. Zahtevamo, da se eksponent ne povečuje s povečevanjem hitrosti strune, kar matematično zapišemo kot:

where x can take only two values, $x_k = (2k–1)L/(2k)$ or $x_k = L/(2k)$, depending on the sign of $b_2 - b_1$. The exponential function is monotonous, so an analysis of the exponent is sufficient. The demand for decreasing amplitudes with the string's increasing axial velocity can be mathematically formulated as:

$$\frac{\partial}{\partial v}\left(v[b_2-b_1]x_k-[v^2(b_2-b_1)+c^2 b_1]t\right) = (x_k-2vt)(b_2-b_1) \leq 0 \tag{41}$$

Poglejmo si oba primera vrednosti $b_2 - b_1$. Če je $b_2 - b_1 \geq 0$, sledi $x_k = (2k–1)L/(2k)$ in $x_k - 2vt \leq 0$, kar velja za poljuben, dovolj velik t. Dovolj velik čas, ki zadovolji vse načine, dobimo, ko gre $k \to \infty$, je $t_{cr} = L/(2v)$, kar zadovolji enačbo (41). Če pa je $b_2 - b_1 < 0$, sledita $x_k = L/(2k)$ in $x_k - 2vt > 0$, kar pa je mogoče zagotoviti le za nekatere načine in za omejen čas. To pa v splošnem ne velja, saj je lastnih oblik neskončno veliko in ker lahko t zasede poljubne vrednosti. Sledi, da rešitev $b_2 - b_1 < 0$ ni fizikalno sprejemljiva.

Če povzamemo, dobimo sistem treh neenačb, od katerih sta pomembni le prvi dve:

Two different cases are possible again. In the first case, when $b_2 - b_1 \geq 0$, then $x_k = (2k–1)L/(2k)$ and $x_k - 2vt \leq 0$, which is true for sufficiently large t. The largest mode, $k \to \infty$, would give a time large enough, $t_{cr} = L/(2v)$, to satisfy the condition in Eq. (41). In the second case, when $b_2 - b_1 < 0$, then $x_k = L/(2k)$ and $x_k - 2vt > 0$, which can only be met for some nodes and for a limited amount of time, and cannot be met for all of the nodes. For this reason, the second case is considered to be unrealistic.

When summing together all of the constraints:

$$\begin{array}{lllcl} b_1 & \geq & k_1 b_2 & ; & k_1 = \dfrac{v}{c+v} < k_2 \\ b_1 & \leq & k_2 b_2 & ; & k_2 = 1 \\ t & \geq & t_{cr} & ; & t_{cr} = \dfrac{L}{2v} \end{array}$$

in tako je mogoče opredeliti sprejemljivo območje koeficientov b_1 in b_2. Predstavljeno je na sliki 2 kot senčeno področje.

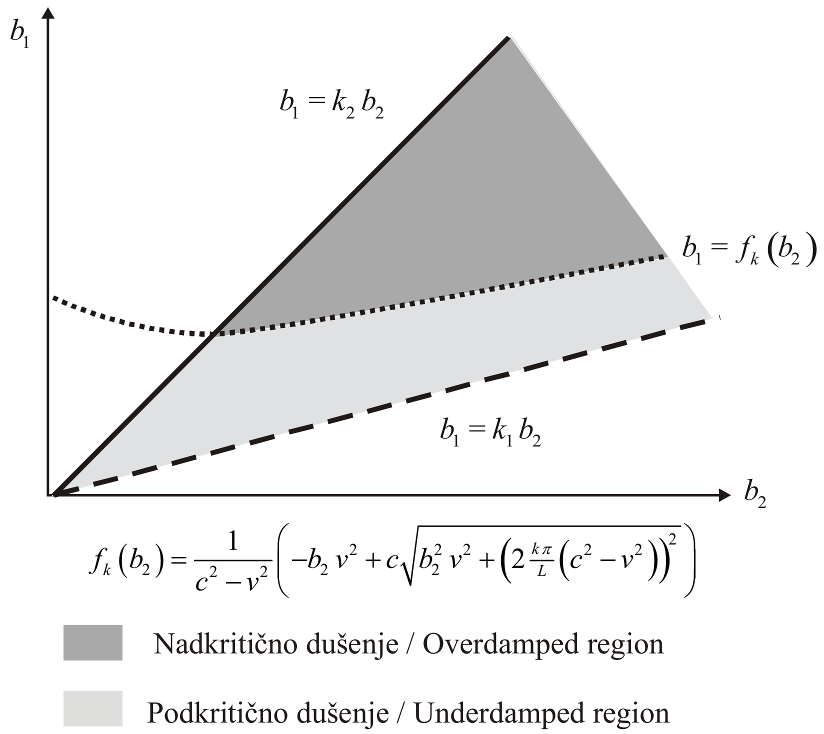
the region of acceptable values for b_1 and b_2 can be deduced. It is presented in Figure 2 as the shaded region between the solid and the dashed lines.

4 SKLEPI

V prispevku smo analizirali vplive viskoznega mehanizma dušenja na lastna prečna nihanja osno premikajoče se strune. Pokazali smo, da vrednosti parametrov b_1 in b_2 ne moremo povsem poljubno izbirati, če želimo ohraniti fizikalno korektno

4 CONCLUSIONS

The viscous-damping mechanism acting on the transverse vibrations of an axially-moving string was analyzed. It was shown that the values of the parameters b_1 and b_2 cannot be chosen completely freely if physically meaningless results are



Sl. 2. *Fizikalno sprejemljivo območje vrednosti koeficientov b_1 in b_2 leži med premicama v senčenem območju. Svetlejše senčeno območje pomeni nihanje strune, temnejše pa odziv strune z nadkritičnim dušenjem.*

Fig. 2. T*he acceptable-values region (shaded) for the viscous-damping coefficients b_1 and b_2. The lighter shaded region represents the underdamped system, and the darker shaded region represents the overdamped system.*

obnašanje sistema. Senčeno področje na sliki 2 pomeni območje dvojic vrednosti parametrov b_1 in b_2, ki daje fizikalno sprejemljive rezultate.

Kot rešitev problema predlagamo, da če je le mogoče, ne razlikujemo med vrednostmi b_1 in b_2, torej $b_1 = b_2 = b$. Tako pravilo ima močno fizikalno ozadje, saj je sila viskoznega dušenja enaka zmnožku koeficienta viskoznega dušenja in hitrosti delca strune. Slednja pa je definirana z enačbo (2) in uporabljena v zapisu gibalne enačbe (4), kjer pa ne obstaja matematični formalizem, ki bi lahko pripeljal do različnih vrednosti parametra b, kakor to srečamo v enačbi (7). Zatorej ni jasno, kaj je avtorje prispevkov [1] in [2] spodbudilo k taki uporabi modela viskoznega dušenja. Vendar, če uporabimo viskozno dušenje kot ekvivalentni mehanizem disipacije energije, na primer, v jermenih, se lahko pojavi potreba po različnih vrednostih parametra b, če želimo zajeti odtekajočo energijo vseh različnih mehanizmov disipacije energije v jermenu.

to be avoided. They are within the shaded region in Figure 2.

The solution would be not to distinguish between the values of b_1 and b_2 and to use only $b_1 = b_2 = b$, if possible. This might have a better physical explanation as the viscous damping force is proportional to the product of the viscous damping coefficient and the velocity. The latter is defined by (2) and used in (4), where there is no mathematical mechanism for obtaining different values for the coefficients b_1 and b_2, as in Eq. (7). But, if the viscous-damping model is used as an equivalent mechanism of energy dissipation in belts, as an example, the different values of b might be necessary for the viscous-damping model in order to encompass all the dissipated energy from the different mechanisms of energy dissipation in belts. The exact reason for using the notation b_1 and b_2 by the authors of [1] and [2] is unknown.

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Optimizacija oblike prostorske palične konstrukcije

Efficient Shape Optimization of Space Trusses

Boštjan Harl - Marko Kegl

Prispevek predstavlja postopek pri optimalnem projektiranju statično obremenjenih prostorskih paličnih konstrukcij. Oblika in vpetje konstrukcije, kakor tudi prerezi posameznih paličnih elementov, so odvisni od spremenljivih parametrov – projektnih spremenljivk. Spremenljivo obliko in vpetje konstrukcije smo dosegli s tehniko projektnih elementov in uporabo ustreznega projektnega elementa – Bézierjevega telesa. Spremenljive lastnosti prerezov paličnih elementov so obravnavane na običajen način. Kot končni element je uporabljen kinematično nelinearen palični element. Optimizacijsko nalogo smo oblikovali v obliki standardnega problema matematičnega programiranja. Ker so projektne spremenljivke zvezne, smo rešitve optimizacijske naloge iskali z uporabo gradientne optimizacijske metode. Za ponazoritev omenjene teorije sta podrobno predstavljena in rešena optimizacijska problema prostorske palične konstrukcije.

(Ključne besede: konstrukcije palične, optimiranje oblike, programiranje matematično, parametrizacija)

This paper describes an approach to the optimization of statically loaded space trusses. The cross-sectional properties of individual elements, the shape of the whole structure as well as the support locations depend on the design variables. The variable structural shape and the support locations are addressed by employing the design-element technique and an appropriate design element – the Bézier body. The variable cross-sectional properties of the individual truss elements are handled in the usual way. Kinematically nonlinear truss elements are employed as the finite elements. The optimization problem is defined in the form of a general nonlinear problem of mathematical programming. Since the design variables are all assumed to be continuous, a gradient-based optimization procedure is proposed. Two numerical examples of space-truss optimization are presented in detail to illustrate the use of the proposed approach.

(Keywords: space trusses, shape optimization, mathematical programming, parametrization)

0 UVOD

Optimiranje konstrukcij se je začelo razvijati pred nekaj desetletji pri čemer so bile v ospredju predvsem palične konstrukcije. Razloga za to sta dva. Prvi je v preprostosti modeliranja in analize paličnih konstrukcij po metodi končnih elementov (KE). Drugi je v tem, da so zaradi diskretne narave paličnih konstrukcij primerni optimizacijski parametri že na dlani – velikosti prerezov elementov. Takšne spremenljivke imenujemo *dimenzijske projektne spremenljivke*.

Razvoj področja optimiranja konstrukcij je povzročil premik od paličnih k obravnavi zveznih konstrukcij. Temu razvoju je sledilo uvajanje področja

0 INTRODUCTION

Trusses are the structures that were probably most frequently addressed when the field of structural optimization began to evolve several decades ago. The reasons for this are twofold. The first reason is the simplicity of the finite-element (FE) modelling and analysis procedure; the second reason is that by the discrete nature of the truss structure very convenient optimization variables are naturally exposed – the areas of the cross-sections. We call these variables the *sizing design variables*.

As the field of structural optimization developed, emphasis was shifted from the trusses to the continuum structures, and this development was optimizacije oblike in novega tipa spremenljivk, ki jih imenujemo *oblikovne projektne spremenljivke*. Pri tem se je kmalu pojavila potreba tudi po optimizaciji topologije konstrukcij, kar je v zadnjem času pripeljalo do presenetljivega razvoja teh optimizacijskih postopkov.

Sodobne optimizacijske tehnike pri optimizaciji paličnih konstrukcij lahko razvrstimo v dve skupini. Prva skupina obravnava optimizacijo topologije in pogosto hkrati tudi optimizacijo oblike ter izmer elementov palične konstrukcije ([1], [2], [4] do [6], [12] in [17]). Druga skupina obravnava samo optimizacijo oblike konstrukcije pogosto združeno s klasično optimizacijo izmer posameznih elementov.

Optimizacijo oblike palične konstrukcije značilno izvajamo tako, da koordinate vozlišč vzamemo kot projektne spremenljivke ([3], [11], [13] do [16]). To je dokaj privlačna možnost, ker so koordinate vozlišč parametri, ki so že v običajnem mehanskem modelu. Tako ni treba uvajati novih parametrov za spremembo oblike. Ta način pa ima tudi nekaj slabih strani. Težave se pojavijo predvsem v primerih, ko imamo veliko palično konstrukcijo proste oblike in z veliko vozlišči. V takšnih primerih se lahko število projektnih spremenljivk poveča do neobvladljive vrednosti. Razen tega se pojavijo težave tudi pri izpolnjevanju estetskih zahtev ter zahtev glede gladkosti konstrukcije. Zato je za primere, ko imamo veliko palično konstrukcijo proste oblike, precej primernejša zamisel parametrizacije mreže KE in vpeljava ustreznih oblikovnih projektnih spremenljivk.

Zanimiva zamisel parametrizacije oblike ponuja kombinacija vpeljave tehnike projektnega elementa in uporaba ustreznega projektnega elementa, kakor je na primer Bézierjevo telo ([8] in [9]). Pri tem načinu je geometrijsko telo, ki ga določa lupina konstrukcije, razdeljeno v preprosta geometrijska telesa, imenovana projektni elementi (PE). Te elemente lahko parametriziramo na dokaj preprost način. Palični končni element nato določimo v definicijskem območju projektnega elementa in ne neposredno v realnem 3-D prostoru. Tako dobimo neke vrste 'konvektivno' mrežo končnih elementov, ki avtomatično sledi spremembi geometrijske oblike konstrukcije.

Povedati je treba, da sprememba geometrijske oblike mreže KE v splošnem lahko privede do popačenja oblike posameznih končnih elementov in s tem do nenatančnosti v analizi. Vendar se to ne

accompanied by the introduction of new kinds of design variables called the *shape design variable*s. As shape optimization evolved, the need for topology optimization also became increasingly evident. This caused a remarkable development in topology optimization procedures during the past decade.

The recent optimization techniques for truss structures can mostly be divided into two groups. The first group handles the truss-topology optimization and, often simultaneously, also the shape and sizing optimization of the truss ([1], [2], [4] to [6], [12] and [17]). The second group addresses only the shape optimization, usually accompanied by the conventional sizing optimization.

The shape optimization of trusses is usually performed by adopting the nodal coordinates as design variables ([3], [11], [13] to [16]). This is an appealing possibility since the nodal coordinates represent parameters already present in a conventional FE-modelled truss, and so there is no need to introduce new parameters that would act as shape variables. This approach, however, also has its drawbacks. This becomes especially evident if one considers large-scale free-form truss structures containing a myriad of nodes. In such cases the number of design variables can quickly rise to a completely unmanageable number. Apart from this problem, the requirements related to aesthetic aspects and the smoothness of the structural outline shape cannot be fulfilled easily. For these reasons a proper parameterization concept for the FE mesh and the introduction of proper shape-design variables seems to be a much more promising approach for large, free-form truss structures.

An attractive shape-parameterization concept is offered by combining the design-element technique and suitable design elements, for example, Bézier bodies ([8] and [9]). With this approach the geometrical body defined by the hull of the structure is divided into simpler geometrical objects called the design elements (DEs). These can be parameterized in a rather simple way and the truss finite elements are then defined in the domain of the design element rather than directly in real 3-D space. In this way we get some kind of a 'convective' finite-element mesh, automatically following the geometry changes of the structure.

It should be noted that in the general case the FE mesh geometry changes can lead to distortion of the finite elements and, consequently, to inaccuracies in the analysis. This, however, is not the case when dogaja, če imamo opravka s palično konstrukcijo. Pri preoblikovanju palične konstrukcije se namreč spremenita samo smer in dolžina elementov. Zato se pri paličnih konstrukcijah popačenje mreže v splošnem ne pojavlja in dodatni postopki popravljanja mreže niso potrebni. Kljub temu je dobro uporabiti primerno natančen palični element, ki upošteva kinematične nelinearnosti. To daje možnost primerne obravnave mogočega pojava konstrukcijske nestabilnosti – kot dodatek k optimizaciji ali kako drugače.

truss structures are considered. When reshaping a truss structure, only the directions and the lengths of the elements are changed. Thus, for truss structures, mesh distortion is typically not a problem, making the use of mesh-adaptation procedures unnecessary. In spite of this, it is a good idea to employ a sufficiently accurate truss element that accounts for the kinematic nonlinearities. In this way any possible structural stability problems are adequately captured and can be handled appropriately – either as an add-on to the optimization process or in some other way.

1 OBLIKOVANJE NALOGE

Obravnavajmo elastično palično konstrukcijo, modelirano s KE, ki je ustrezno podprta in obremenjena z zunanjimi statičnimi silami (sl. 1). Naj bodo lastnosti palične konstrukcije (oblika, podprtje in prerezi) odvisne od projektnih spremenljivk b_i, $i = 1,\ldots,N$, zbranih v vektorju $\mathbf{b} \in \mathsf{R}^N$. V tem primeru bo sprememba projektnih spremenljivk vplivala na spremembo odziva konstrukcije $\mathbf{u} \in \mathsf{R}^M$ (sl. 1).

Optimizacijsko nalogo lahko z besedami izrazimo tako: najdi takšne vrednosti projektnih spremenljivk, da bo konstrukcija najboljša mogoča glede na izbrane kriterije. Matematično lahko to zapišemo v obliki standardnega problema matematičnega programiranja, in sicer kot:

1 PROBLEM FORMULATION

Let us consider an elastic FE-modelled truss structure, being properly supported and loaded by external static forces, Figure 1. Let the design of the truss (shape, support locations and cross-sections) depend on the design variables b_i, $i = 1,\ldots,N$, being assembled in the vector $\mathbf{b} \in \mathsf{R}^N$. In this case a change in the design-variable values will obviously result in a change in the structural response $\mathbf{u} \in \mathsf{R}^M$ (Fig. 1).

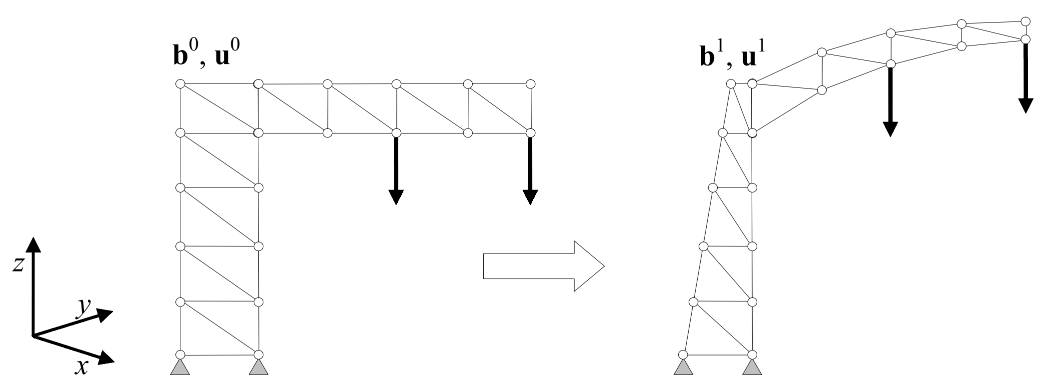
The optimal design problem can now be formulated as follows: find such values of the design variables such that the structure will be the best it can be with respect to some criteria. Mathematically, this can be formulated in the form of a nonlinear mathematical programming problem, as follows:

$$\min f_0 \tag{1}$$

ob upoštevanju pogojev:

subject to constraints:

$$f_i \leq 0, \quad i = 1,\ldots,K \tag{2}.$$



Sl. 1. *Lastnosti palične konstrukcije, to so prerezi, oblika in podprtje, vplivajo na njen odziv.*
Fig. 1. *A design change influences the cross-sections, the shape and the support locations and, consequently, the response of the truss.*

V tem zapisu $f_0 = f_0(\mathbf{b},\mathbf{u})$ pomeni namensko funkcijo, ki je pogosto definirana kot prostornina ali kot deformacijska energija konstrukcije. Omejitvene funkcije $f_i = f_i(\mathbf{b},\mathbf{u})$ pogosto pomenijo pomike vozlišč, napetosti v elementih, uklon elementov, omejitve geometrijske oblike, tehnološke omejitve in podobno. Simbol K označuje število vseh omejitvenih pogojev.

Opomniti je treba, da v nalogi (1) do (2) $\mathbf{b}$ pomeni neodvisne spremenljivke, pri čemer so odzivne spremenljivke $\mathbf{u} = \mathbf{u}(\mathbf{b})$ odvisne. Ta odvisnost je podana implicitno z enačbo odziva konstrukcije:

Here, $f_0 = f_0(\mathbf{b},\mathbf{u})$denotes the objective function that is often defined either as the volume or the strain energy of the structure. The constrained quantities $f_i = f_i(\mathbf{b},\mathbf{u})$ usually concern nodal displacements, element stresses, element buckling, geometrical constraints, technological limitations, etc. And K is the total number of imposed constraints.

Note that in (1) to (2) $\mathbf{b}$ represents the independent variables, while the response variables $\mathbf{u} = \mathbf{u}(\mathbf{b})$ are the dependent ones. This dependency is established implicitly by the structural response equation:

$$\mathbf{F} - \mathbf{R} = \mathbf{0} \tag{3}$$

kjer sta $\mathbf{F} = \mathbf{F}(\mathbf{b},\mathbf{u})$ in $\mathbf{R} = \mathbf{R}(\mathbf{b},\mathbf{u})$ vektorja notranjih in zunanjih sil. Notranje sile so očitno odvisne od $\mathbf{b}$ in od $\mathbf{u}$. Za zunanje sile pa velja, da so lahko odvisne od $\mathbf{b}$, če na primer želimo upoštevati lastno težo konstrukcije. Razen tega pa so lahko odvisne tudi od $\mathbf{u}$, če je konstrukcija na primer elastično podprta.

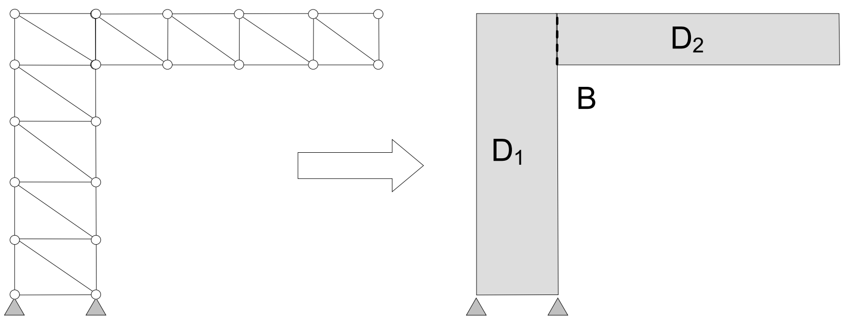
where $\mathbf{F} = \mathbf{F}(\mathbf{b},\mathbf{u})$ and $\mathbf{R} = \mathbf{R}(\mathbf{b},\mathbf{u})$ are the vectors of the internal and external forces, respectively. The internal forces obviously depend explicitly on $\mathbf{b}$ and $\mathbf{u}$. On the other hand, the external forces might become dependent on $\mathbf{b}$ if, for example, the weight of the structure is taken into account. Additionally, by employing elastic supports, the external forces will also depend on $\mathbf{u}$.

2 PARAMETRIZACIJA OBLIKE PALIČNE KONSTRUKCIJE

Obravnavali bomo 3-D palično konstrukcijo, katere lupina naj predstavlja mejno ploskev 3-D telesa $\mathcal{B}$ (sl. 2). Vzemimo, da pomeni mreža KE neke vrste konvektivno mrežo, ki avtomatično sledi spremembam oblike telesa $\mathcal{B}$. Ob teh predpostavkah lahko pričakujemo, da bomo obliko mreže KE (in palične konstrukcije) lahko spreminjali skladno in učinkovito, če nam le uspe ustrezno parametrizirati obliko $\mathcal{B}$.

2 SHAPE PARAMETERIZATION OF THE TRUSS STRUCTURE

Let us consider a 3-D truss structure, and let the hull of the truss structure represent the boundary surface of a 3-D body, $\mathcal{B}$ (Fig. 2). Let us now assume that the FE mesh represents some kind of a convective mesh, following automatically the changes of the shape of $\mathcal{B}$. Under this assumption one can expect that the shape of the FE mesh (and the truss structure) can be modified significantly in an elegant and efficient way if we only manage to conveniently parameterize the shape of $\mathcal{B}$.



Sl. 2. *Lupina palične konstrukcije predstavlja telo $\mathcal{B}$, ki je razdeljeno na projektne elemente.*
Fig. 2. *The hull of the truss defines the body, $\mathcal{B}$, which is partitioned into design elements.*

V ta namen najprej telo B razdelimo na N_D preprostejših geometrijskih objektov D_i, $i = 1,\ldots,N_D$, imenovanih projektni elementi (sl. 2). Projektni element D_i mora biti parametrizirano geometrijsko telo razmeroma preproste oblike. Na ta način lahko pričakujemo dokaj preprosto izpeljavo ustrezne parametrizacije celega telesa B.

Označimo s simbolom D poljuben projektni element (spodnji indeks, ki označuje številko projektnega elementa, bomo zaradi enostavnosti izpustili). V splošnem je D lahko vsako parametrizirano geometrijsko telo. Če želimo izbrati takšno telo, ki bo imelo najboljše splošne lastnosti, bi bilo Bézierjevo telo vsekakor eno od boljših možnosti.

Bézierjevo telo je definirano s preslikavo:

For this purpose, in the first step we partition B into N_D simpler geometrical objects D_i, $i = 1,\ldots,N_D$ termed the design elements, Figure 2. The design element D_i must be a conveniently parameterized geometrical body exhibiting a relatively simple shape. In this way, one can also expect to derive a convenient parameterization of the whole body, B.

Let us denote with the symbol D a generic design element (the subscript denoting the number of the design element was dropped for the sake of simplicity). In general D can be any parameterized geometrical body. However, if we would need to pick out the one with the best all-round qualities, a Bézier body would surely be one of the favourites.

A Bézier body is defined by the mapping:

$$\mathbf{r} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} B_i^I B_j^J B_k^K \mathbf{q}_{ijk} \quad (4),$$

kjer je $\mathbf{q}_{ijk}$ krajevni vektor nadzorne točke (ijk) telesa, medtem ko so $B_i^I = B_i^I(s_1)$, $B_j^J = B_j^J(s_2)$ in $B_k^K = B_k^K(s_3)$ i, j, k-ti Bernsteinovi polinomi [18] reda I-1, J-1 in K-1. Simboli s_1, s_2 in s_3 so neodvisni parametri, ki pomenijo koordinate točke $\mathbf{s} = [s_1\ s_2\ s_3]^T$ iz območja U = $[0,1]^3$. Zgornja preslikava torej slika točko $\mathbf{s}$ iz U v točko $\mathbf{r}$ v realnem 3-D prostoru.

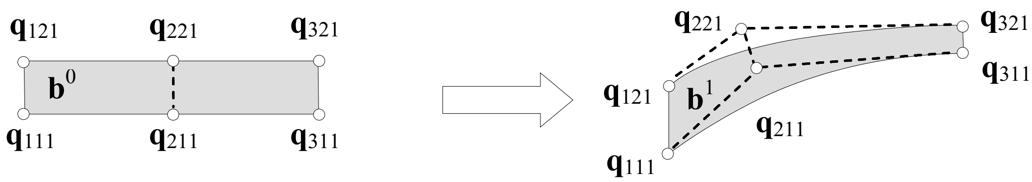
Lega in oblika D sta popolnoma določena z legami nadzornih točk (sl. 3). To pomeni, da sprememba lege $\mathbf{q}_{ijk}$ spremeni lego in obliko D. Uvedimo sedaj oblikovne projektne spremenljivke. Vzeli bomo, da so nadzorne točke telesa D odvisne od projektnih spremenljivk $\mathbf{b}$. Zapišemo lahko $\mathbf{q}_{ijk} = \mathbf{q}_{ijk}(\mathbf{b})$, kar pomeni, da bo sprememba projektnih spremenljivk povzročila spremembo oblike D.

Ko je projektni element izbran in popolnoma določen, lahko konvektivno mrežo paličnih KE dobimo preprosto tako, da vozlišča KE definiramo v domeni U namesto neposredno v realnem 3-D prostoru. S tem smo v bistvu parametrizirali obliko palične konstrukcije v odvisnosti od $\mathbf{b}$.

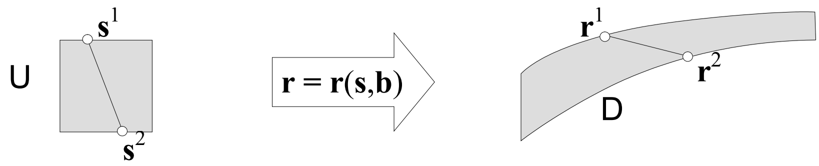
where $\mathbf{q}_{ijk}$ are the position vectors of the control points (ijk), while $B_i^I = B_i^I(s_1)$, $B_j^J = B_j^J(s_2)$ and $B_k^K = B_k^K(s_3)$ are the i-, j-, k-th univariate Bernstein polynomials [18] of the orders I-1, J-1 and K-1, respectively. The symbols s_1, s_2 and s_3 denote the independent parameters representing the coordinates of a point $\mathbf{s} = [s_1\ s_2\ s_3]^T$ from the unit cube U = $[0,1]^3$. Thus, the above relationship maps a point $\mathbf{s}$ from U into the point $\mathbf{r}$ in real 3-D space.

The position and shape of D is fully determined by the position of its control points, Figure 3. Thus, a change of the positions $\mathbf{q}_{ijk}$ changes the position and shape of D. Keeping this in mind we can see a nice opportunity to introduce our shape-design variables. We simply assume that the control points of D will depend on the design variables $\mathbf{b}$. In other words, we assume that $\mathbf{q}_{ijk} = \mathbf{q}_{ijk}(\mathbf{b})$, meaning that a variation in the values of the design variables will result in a smooth variation of the shape of D.

Once the design element is selected and fully defined, the design-dependent and convective FE mesh of a truss can simply be derived by defining the nodal positions in the domain U rather than directly in real 3-D space. By doing this the shape of the truss structure is actually parameterized in terms of $\mathbf{b}$.



Sl. 3. *Sprememba projektnih spremenljivk vpliva na spremembo oblike D.*
Fig. 3. *A design change influences the shape of D.*



Sl. 4. *Palični KE je preslikan iz domene U v realni 3-D prostor*
Fig. 4. *A truss FE is mapped from the domain U to the real 3-D space*

Obravnavajmo palični končni element, ki ima vozlišča definirana v U z legama $\mathbf{s}^j$, j = 1,2 (sl. 4). Če vzamemo, da so lege nadzornih točk $\mathbf{q}_{ijk}$ znane, lahko uporabimo enačbo (4) ter lege vozlišč $\mathbf{r}^j$, j = 1,2 paličnega končnega elementa v realnem 3-D prostoru zapišemo kot:

To be more precise, let us consider a truss finite element and let its nodes be defined in U by the positions $\mathbf{s}^j$, j = 1,2 (Fig. 4). Assuming that the positions of the control points $\mathbf{q}_{ijk}$ are known, we can make use of the relation (4) in order to get the nodal positions $\mathbf{r}^j$, j = 1,2 of the truss element in real 3-D space as follows:

$$\mathbf{r}^j = \mathbf{r}^j(\mathbf{s}^j, \mathbf{b}) \tag{5}$$

To pomeni, da smo, namesto da bi določili $\mathbf{r}^j$ neposredno v realnem 3-D prostoru, definirali njihove slike $\mathbf{s}^j$ v U. Z določitvijo vseh vozlišč mreže KE v U, namesto v realnem 3-D prostoru, dobimo palično konstrukcijo, katere oblika se lahko spreminja v skladu s preprostim premikanjem nadzornih točk $\mathbf{q}_{ijk}$.

Za palični končni element predstavljata legi vozlišč skoraj vse geometrijske podatke elementa. Edina parametra, ki ju moramo še določiti, sta ploščina A prereza paličnega elementa in najmanjši osni vztrajnostni moment I_{min}, ki ga potrebujemo, če želimo upoštevati uklon palic. Ti dve količini lahko naredimo odvisni od $\mathbf{b}$ zelo preprosto – ena ali več projektnih spremenljivk lahko določa prerez posamezne palice ali skupine palic. V vsakem primeru moramo vzeti, da velja:

This means that instead of defining $\mathbf{r}^j$ directly in the real 3-D space, we define their pre-images $\mathbf{s}^j$ in U. By defining all the nodes of the FE mesh in U rather than in real 3-D space we actually get a truss structure, the shape of which can be changed in a very elegant fashion by simply moving the control points $\mathbf{q}_{ijk}$.

For a truss finite element the positions of its nodes represent almost all the geometrical data needed. The only two parameters that still have to be determined are the area A of the cross-section and its minimal axial moment of inertia I_{min} for the case that local buckling constraints have to be taken into consideration. These two quantities can simply be made design-dependent in the conventional way – one or more design variables control the cross-sectional properties either of a single element or of a whole group of truss elements. In any case, we must assume that we have:

$$A = A(\mathbf{b}), \quad I_{min} = I_{min}(\mathbf{b}) \tag{6}$$

3 POSTOPEK REŠEVANJA

Naloga (1) do (2) je zapisana v obliki standardne naloge matematičnega programiranja in se lahko načelno reši s poljubno metodo nelinearnega optimiranja. Toda, ker so projektne spremenljivke zvezne, pomenijo gradientne metode najprimernejšo izbiro. V tem primeru je postopek reševanja iteracijski in ga lahko povzamemo kakor sledi:
- Nastavi k = 0; izberi začetne vrednosti $\mathbf{b}^{(0)}$.
- Izračunaj f_i, $i = 0,\ldots,K$ pri $\mathbf{b}^{(k)}$ (analiza odziva).
- Izračunaj $\mathrm{d}f_i/\mathrm{d}\mathbf{b}$, $i = 0,\ldots,K$ pri $\mathbf{b}^{(k)}$ (analiza občutljivosti).

3 SOLUTION PROCEDURE

The problem (1) to (2) is a standard problem of mathematical programming and can be solved virtually by any method for nonlinear optimization. But since the design variables are continuous, a gradient-based algorithm is probably the most effective choice. In that case the solution procedure is iterative and can be outlined as follows:
- Set k = 0; choose some initial $\mathbf{b}^{(0)}$.
- Calculate f_i, $i = 0,\ldots,K$ at $\mathbf{b}^{(k)}$ (response analysis).
- Calculate $\mathrm{d}f_i/\mathrm{d}\mathbf{b}$, $i = 0,\ldots,K$ at $\mathbf{b}^{(k)}$ (sensitivity analysis).

- Pošlji izračunane vrednosti optimizacijskemu algoritmu, tako da dobiš popravke $\Delta\mathbf{b}^{(k)}$ in izračunane popravljene vrednosti spremenljivk $\mathbf{b}^{(k+1)} = \mathbf{b}^{(k)} + \Delta\mathbf{b}^{(k)}$.
- Nastavi $k = k + 1$ in preveri konvergenčni kriterij, ali je izpolnjen, zaključi zanko, drugače pojdi na korak 2.

Funkcije f_i, $i = 0,\ldots,K$ so izražene v odvisnosti od $\mathbf{b}$ in $\mathbf{u}$. Tako moramo pri analizi odziva najprej izračunati $\mathbf{u}^{(k)}$ pri podanih $\mathbf{b}^{(k)}$. To naredimo z uporabo odzivnih enačb (3). Poudarimo, da moramo pri tem geometrijske parametre palic izračunati iz enačb (4), (5) in (6).

Odvodi $\mathrm{d}f_i/\mathrm{d}\mathbf{b}$, $i = 0,\ldots,K$ so odvisni od $\mathbf{b}$, $\mathbf{u}$ in $\mathrm{d}\mathbf{u}/\mathrm{d}\mathbf{b}$. Za analizo občutljivosti pri $\mathbf{b}^{(k)}$ zato potrebujemo $\mathbf{u}^{(k)}$ in $(\mathrm{d}\mathbf{u}/\mathrm{d}\mathbf{b})^{(k)}$. Odziv $\mathbf{u}^{(k)}$ je že izračunan, medtem ko moramo $(\mathrm{d}\mathbf{u}/\mathrm{d}\mathbf{b})^{(k)}$ izračunati iz občutljivostne enačbe. To enačbo lahko dobimo z odvajanjem odzivne enačbe po $\mathbf{b}$. Ko to naredimo in enačbo uredimo, dobimo:

- Submit the calculated values to the optimizer in order to get some improvement $\Delta\mathbf{b}^{(k)}$ and calculate the improved design $\mathbf{b}^{(k+1)} = \mathbf{b}^{(k)} + \Delta\mathbf{b}^{(k)}$.
- Set $k = k + 1$ and check some appropriate convergence criteria – if fulfilled exit, otherwise go to Step 2.

The functions f_i, $i = 0,\ldots,K$ are expressed in terms of $\mathbf{b}$ and $\mathbf{u}$. Thus, in order to perform the response analysis, we have to calculate $\mathbf{u}^{(k)}$ at a given $\mathbf{b}^{(k)}$. This is done by solving the response equation (3). Note that for this analysis the geometrical data for a truss element have to be retrieved from (4), (5) and (6).

The derivatives $\mathrm{d}f_i/\mathrm{d}\mathbf{b}$, $i = 0,\ldots,K$ are expressed in terms of $\mathbf{b}$, $\mathbf{u}$ and $\mathrm{d}\mathbf{u}/\mathrm{d}\mathbf{b}$. For the sensitivity analysis at $\mathbf{b}^{(k)}$ we therefore need $\mathbf{u}^{(k)}$ and $(\mathrm{d}\mathbf{u}/\mathrm{d}\mathbf{b})^{(k)}$. The response $\mathbf{u}^{(k)}$ is already known from the response analysis, while $(\mathrm{d}\mathbf{u}/\mathrm{d}\mathbf{b})^{(k)}$ has to be calculated from the sensitivity equation. This equation can be derived by differentiating the response equation with respect to $\mathbf{b}$. By doing this and rearranging the terms, we get:

$$\left(\frac{\partial\mathbf{F}}{\partial\mathbf{u}} - \frac{\partial\mathbf{R}}{\partial\mathbf{u}}\right)\frac{d\mathbf{u}}{d\mathbf{b}} = \frac{\partial\mathbf{R}}{\partial\mathbf{b}} - \frac{\partial\mathbf{F}}{\partial\mathbf{b}} \tag{7}$$

Poudariti je treba, da je lahko odzivna enačba nelinearna (kinematična nelinearnost) glede na $\mathbf{u}$, medtem ko je občutljivostna enačba vedno linearna glede na $\mathrm{d}\mathbf{u}/\mathrm{d}\mathbf{b}$. Še več, izraz v oklepajih na levi strani je tangentna togostna matrika konstrukcije. Ta matrika je znana (in že razstavljena) iz analize odziva. Tako je mogoče občutljivostne enačbe rešiti preprosto in z malo računalniškega napora. Edina stvar, ki jo potrebujemo, so parcialni odvodi notranjih in zunanjih sil po projektnih spremenljivkah – desna stran enačbe (7).

Za izračun $\partial\mathbf{R}/\partial\mathbf{b}$ in $\partial\mathbf{F}/\partial\mathbf{b}$ potrebujemo odvode $\mathrm{d}\mathbf{u}^j/\mathrm{d}\mathbf{b}$, $\mathrm{d}A/\mathrm{d}\mathbf{b}$ in $\mathrm{d}l_{\min}/\mathrm{d}\mathbf{b}$. Iz (4) izhaja:

It should be noted that while the response equation can be nonlinear (kinematic nonlinearities) with respect to $\mathbf{u}$, the sensitivity equation is always linear with respect to $\mathrm{d}\mathbf{u}/\mathrm{d}\mathbf{b}$. Furthermore, the term in the parentheses on the left is the tangential stiffness matrix of the structure. This matrix is known (and already decomposed) from the response analysis. Thus, the sensitivity equation can be quite easily solved with a relatively small computational effort. The only things we need are the partial design derivatives of the internal and external forces – the terms on the right of equation (7).

For the calculation of $\partial\mathbf{R}/\partial\mathbf{b}$ and $\partial\mathbf{F}/\partial\mathbf{b}$ we need the derivatives $\mathrm{d}\mathbf{u}^j/\mathrm{d}\mathbf{b}$, $\mathrm{d}A/\mathrm{d}\mathbf{b}$ and $\mathrm{d}l_{\min}/\mathrm{d}\mathbf{b}$, where from (4) it follows that:

$$\frac{d\mathbf{r}^j}{d\mathbf{b}} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} B_i^I B_j^J B_k^K \frac{d\mathbf{q}_{ijk}}{d\mathbf{b}} \tag{8}$$

Torej dejansko potrebujemo le odvode $\mathrm{d}\mathbf{q}_{ijk}/\mathrm{d}\mathbf{b}$, $\mathrm{d}A/\mathrm{d}\mathbf{b}$ in $\mathrm{d}l_{\min}/\mathrm{d}\mathbf{b}$. Da bi bile te količine preprosto dosegljive, je morda najprimerneje, da v kodo za analizo vgradimo razločevalnik aritmetičnih izrazov. Tako lahko $\mathbf{q}_{ijk}$, A in $l_{\min}$ v vhodni datoteki definiramo kot poljubne izraze v odvisnosti od projektnih spremenljivk. Ko so ti izrazi znani, lahko razločevalnik preprosto izračuna tudi odvode $\mathrm{d}\mathbf{q}_{ijk}/\mathrm{d}\mathbf{b}$, $\mathrm{d}A/\mathrm{d}\mathbf{b}$ in $\mathrm{d}l_{\min}/\mathrm{d}\mathbf{b}$.

Thus, the actual data needed are $\mathrm{d}\mathbf{q}_{ijk}/\mathrm{d}\mathbf{b}$, $\mathrm{d}A/\mathrm{d}\mathbf{b}$ and $\mathrm{d}l_{\min}/\mathrm{d}\mathbf{b}$. To make these quantities easily available, perhaps the most practical way is to implement into the FE code a functional expression parser. In this way $\mathbf{q}_{ijk}$, A and $l_{\min}$ can be defined in the input file by any expressions in terms of the design variables. With these expressions at hand the parser can also easily evaluate the derivatives $\mathrm{d}\mathbf{q}_{ijk}/\mathrm{d}\mathbf{b}$, $\mathrm{d}A/\mathrm{d}\mathbf{b}$, and $\mathrm{d}l_{\min}/\mathrm{d}\mathbf{b}$.

4 NUMERIČNA ZGLEDA

Vsi optimizacijski primeri bodo rešeni z aproksimacijsko metodo, opisano v [7] in [10]. Elastični modul uporabljenega materiala je $E = 210$ GPa.

4.1 Podporni lok

Obravnavajmo problem optimizacije izmer in oblike konstrukcije podpornega loka, kakor prikazuje slika 5. Izmere prerezov palic ter oblika konstrukcije so odvisni od 8 projektnih spremenljivk b_1 do b_8.

Začetne mere in podprtje palične konstrukcije so prikazani na sliki 6.

Celotna konstrukcija je modelirana s paličnimi elementi, ki imajo votel krožni prerez (sl. 7). Prerez elementa je odvisen od projektnih spremenljivk, kakor je prikazano v preglednici 1.

Oblika palične konstrukcije je bila parametrizirana z enim projektnim elementom, ki je

4 NUMERICAL EXAMPLES

All the optimization problems were solved by the approximation method described in [7] and [10]. The Young's modulus of the employed material is $E = 210$ GPa.

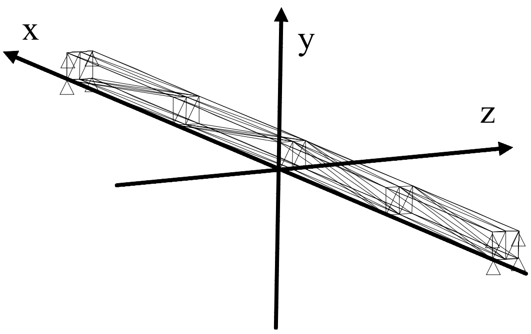
4.1 A Supporting Arch

Let us consider the shape and sizing optimization problem of the supporting arch structure shown in Figure 5. The cross-sectional properties of the truss elements as well as the shape of the whole structure depend on 8 design variables b_1 to b_8.

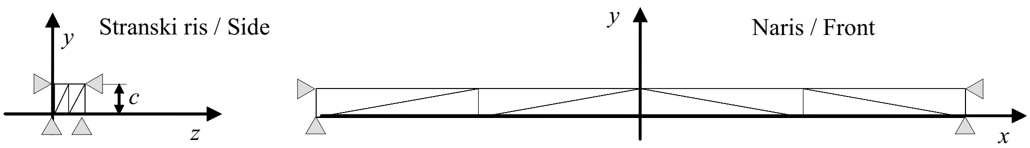
The initial dimensions of the structure and the supported ends are shown in Figure 6.

A hollow, circular, cross-sectional profile is used for all the truss elements (Fig. 7). The cross-section is considered to be design dependent, as given in Table 1.

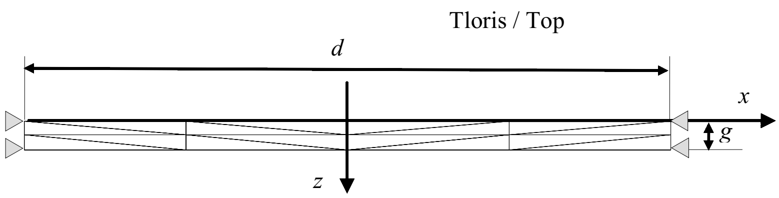
The shape of the truss was parameterized using 1 design element with 3 × 3 × 2 = 12 control



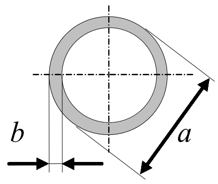
Sl. 5. *3-D konstrukcija podpornega loka*
Fig. 5. *The 3D supporting arch structure*



	Izmere [mm] Dimensions [mm]
c	500
d	10000
g	500



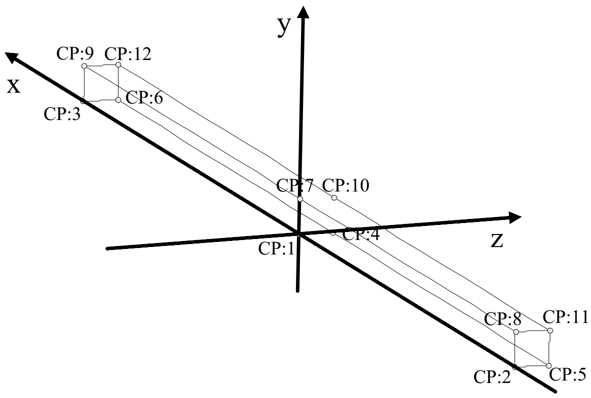
Sl. 6. *Začetna oblika konstrukcije – naris, tloris in stranski ris*
Fig. 6. *Initial design of the truss – side, front and top views*



Sl. 7. *Prerez paličnega elementa*
Fig. 7. *Cross-section of the truss elements*

Preglednica 1. *Izmeri prereza palice, podani v odvisnosti od projektnih spremenljivk*
Table 1. *Design dependencies of the cross-section*

Profil / Profile	Izmeri [mm] / Dimensions [mm]
Krožni, votel Circular, hollow	$a = 60 + 60b_7$, $b = 4 + 4b_8$



Sl. 8. *Začetna oblika projektnega elementa in lege nadzornih točk*
Fig. 8. *Initial shape of the design element and the positions of the control points*

Preglednica 2. *Nadzorne točke, podane v odvisnosti od oblikovnih projektnih spremenljivk*
Table 2. *Design-dependent coordinates of the control points*

Nadzorne točke Control point	*y* [mm]	*z* [mm]
CP:1	$500b_1$	$500b_2$
CP:4	$500b_1$	$500 - 500b_2$
CP:7	$500 + 500b_1 + 500b_3$	$500b_4$
CP:8	$500 + 500b_5$	$500 + 500b_6$
CP:9	$500 + 500b_5$	$500 + 500b_6$
CP:10	$500 + 500b_1 + 500b_3$	$500 - 500b_4$
CP:11	$500 + 500b_5$	$500 - 500b_6$
CP:12	$500 + 500b_5$	$500 - 500b_6$

vseboval 3 × 3 × 2 = 12 nadzornih točk. Lege nadzornih točk (sl. 8) so odvisne od 6 oblikovnih projektnih spremenljivk, kakor je prikazano v preglednici 2. Koordinata x nadzornih točk je nespremenljiva, spreminjata se samo koordinati y in z.

Vpeljali smo 8 projektnih spremenljivk. Zahtevam glede simetrije konstrukcije smo zadostili avtomatično s simetričnimi definicijami koordinat nadzornih točk v odvisnosti od projektnih spremenljivk.

Konstrukcija je obremenjena z dvema različnima in sočasno delujočima obremenitvama (neodvisnima od oblike paličja), ki delujeta na vsako vozlišče:

points. The positions of these control points, Figure 8, depend on 6 shape-design variables, as given in Table 2. The coordinate x of all the control points is constant, only the coordinates y and z are changing.

So far we have introduced 8 design variables. It should be noted that the structural symmetry requirements are taken into account automatically by the symmetric definition of the control point coordinates in terms of the design variables.

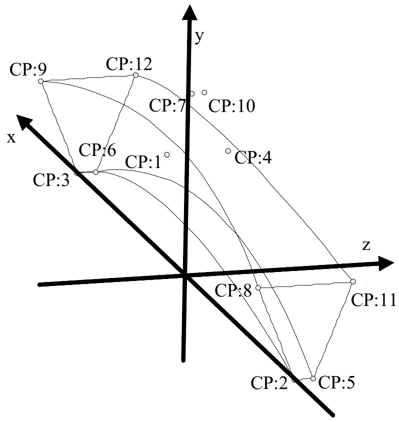
The structure is loaded by two different (design-dependent) loads acting simultaneously on all the nodes:

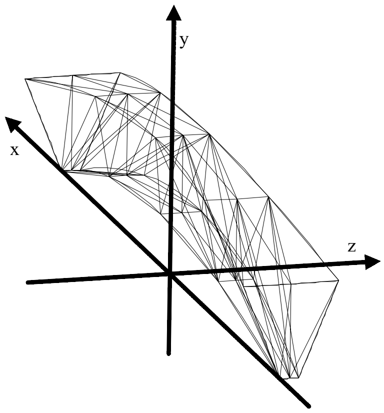
Preglednica 3. *Primerjava začetnih in optimalnih vrednosti namenske funkcije*
Table 3. *Comparison of initial and optimal design*

	Začetek / Initial	Optimum / Optimal
Normirana deformacijska energija Normalized strain energy	1	0,057

Preglednica 4. *Spodnje in zgornje meje, začetne in končne vrednosti projektnih spremenljivk*
Table 4. *The limits, the initial and the final values of the design variables*

i	b_{min}	b_{max}	b_{start}	$b_{optim.}$
1	-2	10	0	6,5253
2	-2	10	0	-1,1425
3	-2	10	0	2,1244
4	-2	10	0	0,1725
5	-2	10	0	3,9795
6	-2	10	0	-2
7	-0,5	10	0	-0,1016
8	-0,5	10	0	-0,0945





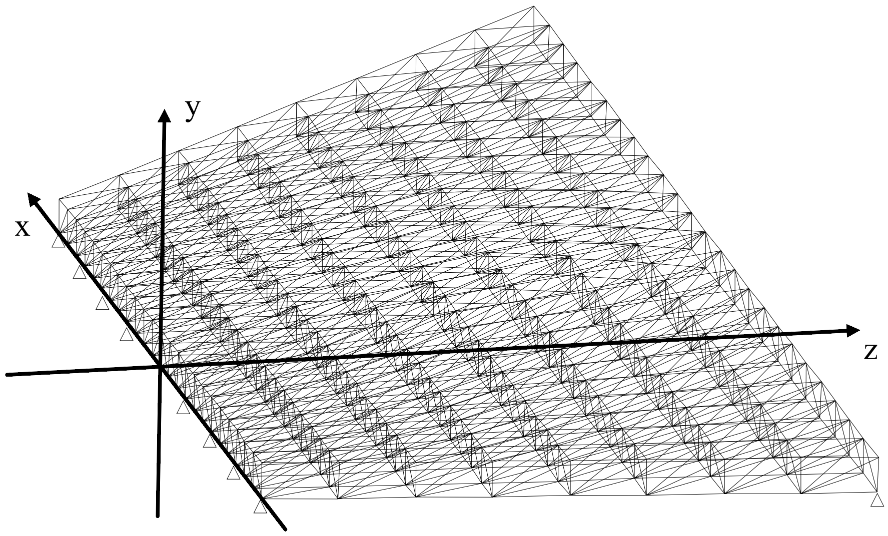
Sl. 9. *Optimalni projekt*
Fig. 9. *Optimal design*

1. zunanja sila v nasprotni smeri osi y 5000 N,
2. zunanja sila v nasprotni smeri osi z 2000 N.

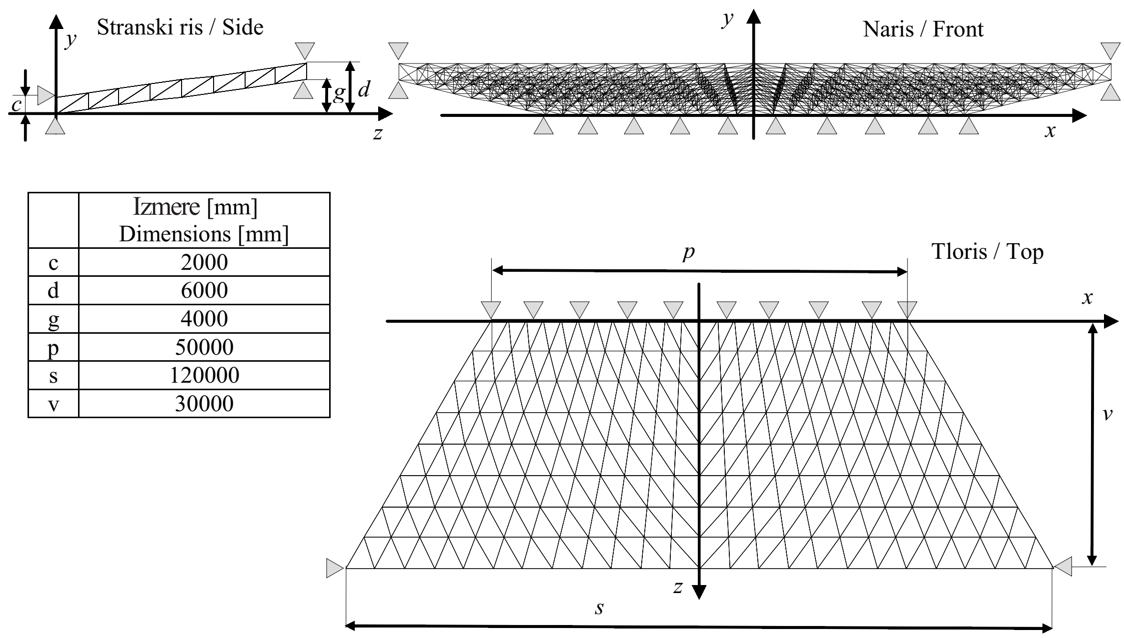
Cilj optimizacijske naloge je bil zmanjšati deformacijsko energijo konstrukcije, pri tem pa smo želeli obdržati prostornino (težo) nespremenjeno. Rezultati so prikazani v preglednicah 3 in 4 ter sliki 9.

1. force in opposite direction to the y 5000 N,
2. force in opposite direction to the z 2000 N.

The objective was to minimize the strain energy of the structure while keeping the volume (weight) of the structure constant. The obtained results are given in Tables 3 and 4 and Figure 9.



Sl. 10. *3-D strešna konstrukcija*
Fig. 10. *The 3D roof structure*



	Izmere [mm] Dimensions [mm]
c	2000
d	6000
g	4000
p	50000
s	120000
v	30000

Sl. 11. *Začetna oblika konstrukcije – naris, tloris in stranski ris*
Fig. 11. *Initial design of the truss – side, front and top views*

Na sliki 9 sta prikazana optimalna oblika projektnega elementa in palične konstrukcije podpornega loka.

The optimal design of the design element and of the structure are shown in Figure 9.

4.2. Dvoslojna palična konstrukcija

4.2. A Double-Layer Truss

Obravnavajmo problem optimizacije dvoslojnega paličja strešne konstrukcije (sl. 10). Izmere prerezov palic ter oblika konstrukcije so odvisni od 18 projektnih spremenljivk b_1 do b_{18}.

Začetne izmere in podprtje palične konstrukcije so prikazani na sliki 11.

Celotna konstrukcija je modelirana s paličnimi elementi, ki imajo votel krožni prerez (sl. 7). Prerez elementa je odvisen od projektnih spremenljivk, kakor je prikazano v preglednici 5.

Oblika palične konstrukcije je bila parametrizirana z enim projektnim elementom, ki je vseboval 3 × 5 × 2 = 30 nadzornih točk. Lege nadzornih točk (sl. 12) so odvisne od 16 oblikovnih projektnih spremenljivk, kar je prikazano v preglednici 6. Koordinati x in z nadzornih točk sta nespremenljivi, spreminja se samo y.

Vpeljali smo 18 projektnih spremenljivk. Zahtevam glede simetrije konstrukcije smo zadostili avtomatično s simetričnimi definicijami koordinat nadzornih točk v odvisnosti od projektnih spremenljivk.

Let us consider the optimization problem of the double-layer truss of a roof structure (Fig. 10). The cross-sectional properties of the truss elements as well as the shape of the whole structure depend on 18 design variables, b_1 to b_{18}.

The initial dimensions of the structure and the supported ends are shown in Figure 11.

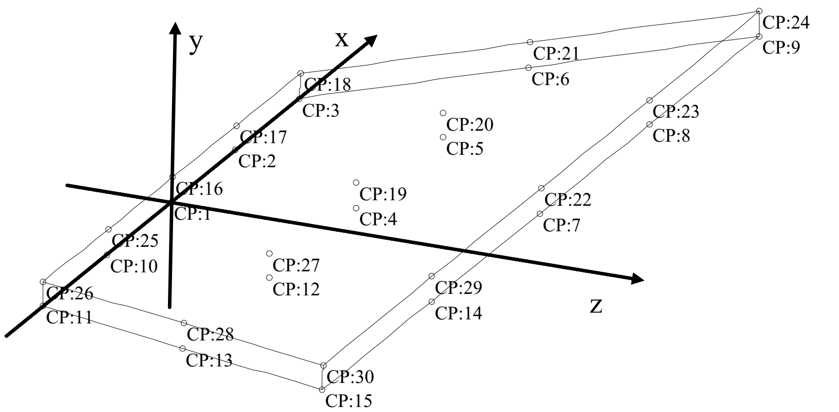
A hollow, circular, cross-sectional profile is used for all the truss elements, Figure 7. The cross-section is considered to be design dependent, as given in Table 5.

The shape of the truss was parameterized using 1 design element with 3 × 5 × 2 = 30 control points. The positions of these control points, Figure 12, depend on 16 shape-design variables, as given in Table 6. The coordinates x and z of all the control points are constant, only y is changing.

We introduced 18 design variables. It should be noted that the structural symmetry requirements are taken into account automatically by the symmetric definition of the control point coordinates in terms of the design variables.

Preglednica 5. *Izmeri prereza palice podani v odvisnosti od projektnih spremenljivk*
Table 5. *Design dependencies of the cross-section*

Profil / Profile	Izmeri [mm] / Dimensions [mm]
Krožni, votel Circular, hollow	$a = 216 + 108b_{15}$, $b = 5 + 5b_{16}$



Sl. 12. *Začetna oblika projektnega elementa in lege nadzornih točk*
Fig. 12. *Initial shape of the design element and the positions of the control points*

Preglednica 6. *Nadzorne točke, podane v odvisnosti od oblikovnih projektnih spremenljivk*
Table 6. *Design-dependent coordinates of the control points*

Nadzorne točke / Control point	y [mm]
CP:1	$1000b_{17}$
CP:2, CP:10	$1000b_{18}$
CP:4	$2000+1000b_1$
CP:5, CP:12	$2000+1000b_2$
CP:6, CP:13	$2000+1000b_3$
CP:7	$4000+1000b_4$
CP:7, CP:14	$4000+1000b_5$
CP:16	$2000+200b_6$
CP:17, CP:25	$2000+200b_7$
CP:18, CP:26	$2000+200b_8$
CP:19	$3000+1000b_1+1000b_9$
CP:20, CP:27	$3000+1000b_2+1000b_{10}$
CP:21, CP:28	$3000+1000b_3+1000b_{11}$
CP:22	$5000+1000b_4+1000b_{12}$
CP:23, CP:29	$5000+1000b_5+1000b_{13}$
CP:24, CP:30	$5000+1000b_{14}$

Konstrukcija je obremenjena z dvema različnima in sočasno delujočima obremenitvama:

3. lastna teža konstrukcije,
4. zunanja navpična sila 500 N, ki deluje na vsako vozlišče zgornjega sloja (neodvisna od oblike paličja).

Cilj optimizacijske naloge je bil zmanjšati deformacijsko energijo konstrukcije, pri tem pa smo želeli obdržati prostornino (težo) nespremenjeno. V nalogo matematičnega programiranja so bili vključeni še pogoji, ki so se nanašali na geometrijsko obliko konstrukcije, napetosti elementov ter lokalni uklon elementov.

Natančneje lahko optimizacijsko nalogo definiramo tako: najdi takšne vrednosti projektnih spremenljivk, da bo deformacijska energija konstrukcije najmanjša ob hkratni zadostitvi naslednjih pogojev:

1. prostornina konstrukcije: se ne sme povečati,
2. absolutna napetost v palici: $\leq$ 120 MPa,
3. koordinata y nadzorne točke 4: $\geq$ 8000 mm,
4. koordinata y nadzorne točke 6 in 13: $\geq$ 2000 mm,
5. koordinata y nadzorne točke 7: $\geq$ 9000 mm,
6. koordinata y nadzorne točke 19: $\geq$ 10000 mm,
7. koordinata y nadzorne točke 21 in 28: $\geq$ 4000 mm,

The structure is loaded by two different loads acting simultaneously:

3. structural own weight,
4. vertical force of 500 N per each node of the upper layer (independent of the shape of the structure).

The objective was to minimize the strain energy of the structure, while keeping the volume (weight) of the structure constant. Additionally, the constraints related to structural geometry, element stresses and local element buckling were imposed.

More precisely, the design problem was formulated as follows: find such values of the design variables that the strain energy will be minimal, and at the same time the following constraints will be fulfilled:

1. volume of the structure: must not increase,
2. absolute element stress: $\leq$ 120 MPa,
3. y-coordinate of control point 4: $\geq$ 8000 mm,
4. y-coordinate of control points 6 and 13: $\geq$ 2000 mm,
5. y-coordinate of control point 7: $\geq$ 9000 mm,
6. y-coordinate of control point 19: $\geq$ 10000 mm,
7. y-coordinate of control points 21 and 28: $\geq$ 4000 mm,

8. koordinata *y* nadzorne točke 22: ≥ 12000 mm,
9. napetost v palici deljena z Eulerjevo uklonsko napetostjo: ≤ 0,5.

Za ponazoritev pomembnosti različnih pogojev, vključenih v optimizacijsko nalogo

8. *y*-coordinate of control point 22: ≥ 12000 mm,
9. element stress divided by Euler buckling stress: ≤ 0,5.

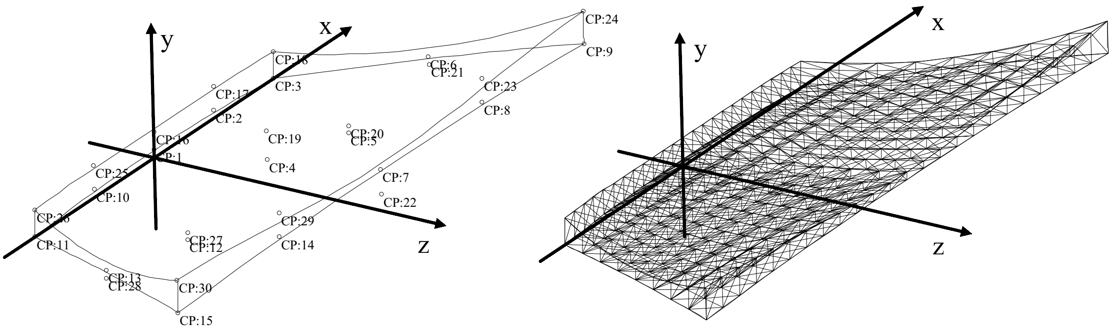
To illustrate the importance of different constraints imposed in an optimization task (objective

Preglednica 7. *Primerjava začetnih in optimalnih vrednosti namenske funkcije*
Table 7. *Comparison of initial and optimal designs*

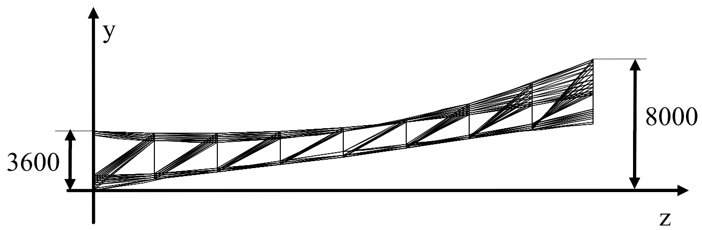
	Začetek Initial	Optim. A Optimal A	Optim. B-1 Optimal B-1	Optim. B-2 Optimal B-2	Optim. C Optimal C
Normirana deformacijska en. Normalized strain energy	1	0,633	0,657	0,129	0,409
Najv. prekoračitev pog. [%] Max constraint violation [%]	0,33	< 0,01	< 0,01	< 0,01	< 0,01

Preglednica 8. *Spodnje in zgornje meje, začetne in končne vrednosti projektnih spremenljivk*
Table 8. *The limits, the initial and the final values of the design variables*

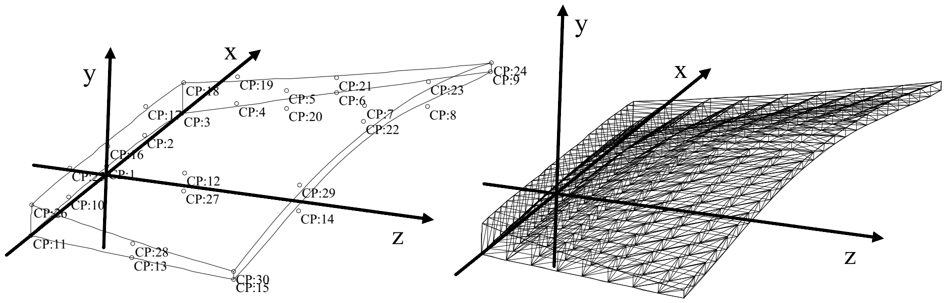
i	b_{min}	b_{max}	b_{start}	$b_{optim.A}$	$b_{optim.B-1}$	$b_{optim.B-2}$	$b_{optim.C}$
1	1	20	0	1	8,3366	15,8311	10,1462
2	-5	20	0	-2,2309	5,1148	13,1452	16,8198
3	-5	20	0	0,5618	0	1,3984	4,1225
4	1	20	0	1	8,2273	19,6642	20
5	1	20	0	1	1,9661	1,1754	4,6804
6	1	20	0	5,7514	6,3781	5,4663	6,0998
7	-5	20	0	9,7385	11,9870	5,9173	7,0945
8	-5	20	0	6,5004	7,8854	-1,0671	-0,7597
9	1	20	0	1,5017	1,2318	4,8182	1
10	-5	20	0	-1,1399	-4,1456	-2,8699	-5
11	-5	20	0	-3	-0,2885	0,0265	-1,8245
12	-5	20	0	-5	-3,8488	-3,9597	-5
13	1	20	0	1	1	5,6628	1,9260
14	-1	20	0	1,9238	-1	-1	-1
15	-5	20	0	0	0	-0,6990	0
16	-5	20	0	0	0	-0,6504	0
17	1	20	0	1	1	1	1,0566
18	1	20	0	1	1	1	1,1429



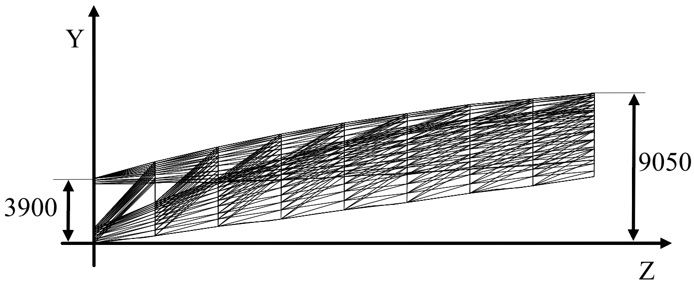
Sl. 13. *Optimalni projekt A*
Fig. 13. *Optimal design A*



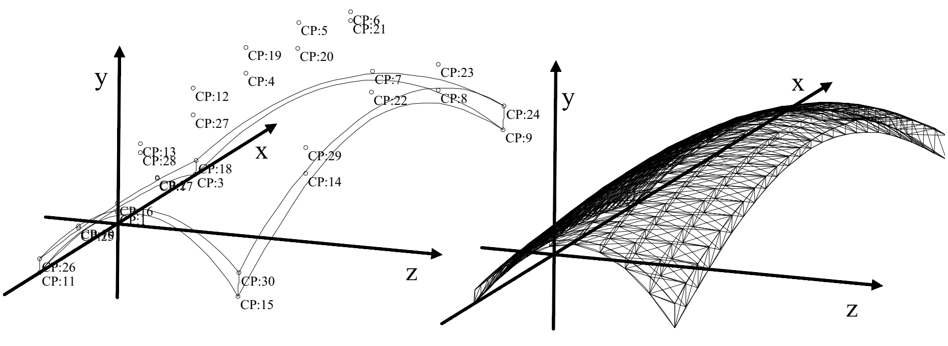
Sl. 14. *Optimalna projekt A – oblika in nekatere izmere strehe*
Fig. 14. *Optimal design A – the shape and some dimensions of the roof*



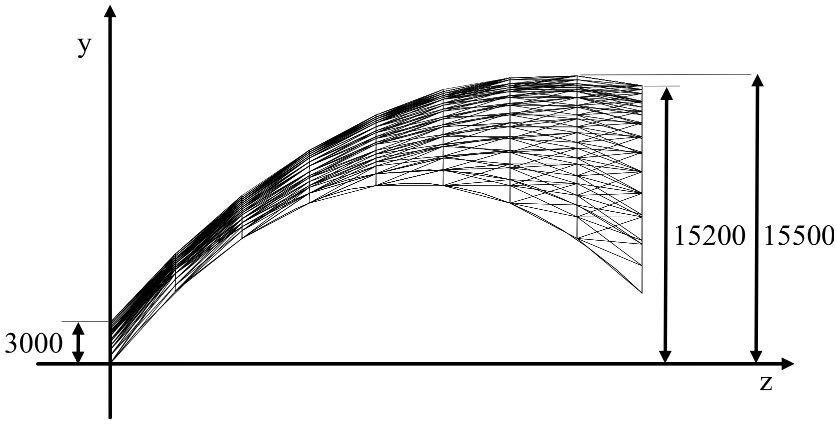
Sl.15. *Optimalni projekt B-1*
Fig. 15. *Optimal design B-1*



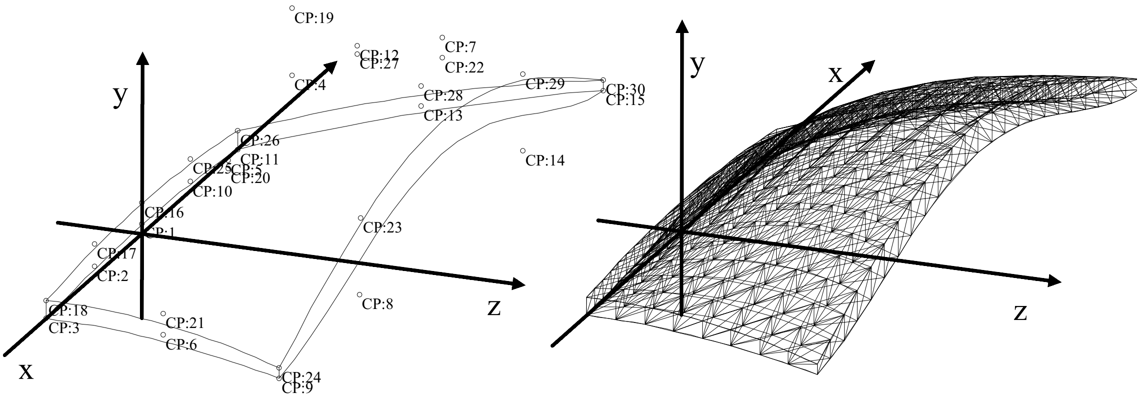
Sl. 16. *Optimalna projekt B-1 – oblika in nekatere izmere strehe*
Fig. 16. *Optimal design B-1 – the shape and some dimensions of the roof*



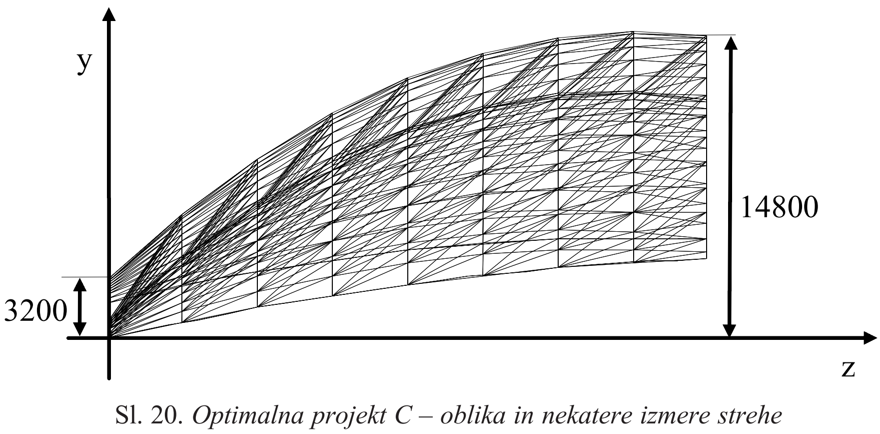
Sl. 17. *Optimalni projekt B-2*
Fig. 17. *Optimal design B-2*



Sl. 18. *Optimalna projekt B-2 – oblika in nekatere izmere strehe*
Fig. 18. *Optimal design B-2 – the shape and some dimensions of the roof*



Sl. 19. *Optimalni projekt C*
Fig. 19. *Optimal design C*



Sl. 20. *Optimalna projekt C – oblika in nekatere izmere strehe*
Fig. 20. *Optimal design C – the shape and some dimensions of the roof*

(namenska funkcija je bila vedno enaka), smo oblikovali tri optimizacijske primere:

A. pogoji 1 do 2,

function was always the same), three optimizations cases were formulated:

A. constraints 1 to 2,

B. pogoji 1 do 8,
C. pogoji 1 do 9.

Za primer A so rezultati prikazani v preglednicah 7 in 8. Pripadajoča oblika konstrukcije je prikazana na slikah 13 in 14. Nato smo zagnali primer B in kakor je bilo pričakovati, smo dobili nekoliko večje vrednosti namenske funkcije. Ta rezultat je označen kot B-1 in je podan v preglednicah ter na slikah 15 in 16. Ker smo posumili, da sta oba dobljena rezultata (A in B-1) lokalna optimuma, smo vzeli rezultat B-1 in ročno povečali vrednosti projektnih spremenljivk b_1 in b_2. Po ponovnem zagonu optimizacije smo dobili novo obliko konstrukcije (B-2, sl. 17 in 18) z občutno nižjo vrednostjo namenske funkcije. To potrjuje, da sta A in B-1 dejansko le lokalna optimuma.

V primeru C smo želeli upoštevati še uklon palic. Kot začetne vrednosti optimizacijske naloge so bile uporabljene vrednosti primera B-2. Rezultati za primer C so podani v preglednicah in na slikah 19 in 20.

V vseh optimizacijskih primerih, za podporni lok in dvoslojno palično konstrukcijo, je bil postopek dokaj stabilen. Kakor je bilo prikazano, lahko z gradientnim algoritmom učinkovito rešujemo optimizacijske probleme. Vendar pa se pri optimizaciji oblike pogosto pojavlja veliko lokalnih optimumov, kar otežuje položaj. V našem primeru nam je uspelo kar hitro priti do rezultata, ki bi lahko bil (vsaj blizu) skupni optimum. Na žalost to vedno ni tako in v splošnem je projektantova intuicija lahko zelo pomembna, da pridemo vsaj blizu celotnega optimuma.

5 SKLEP

Tehnika projektnega elementa in Bézierjevo telo kot projektni element nam ponujata zanimiv postopek pri optimizaciji oblike paličnih konstrukcij. Geometrijski pogoji, kakor so simetrija in zahteve glede estetike konstrukcije, so upoštevani avtomatično s postavitvijo primernih odvisnost med nadzornimi točkami in projektnimi spremenljivkami. Prav tako lahko v optimizacijski problem preprosto vključimo tudi poljubne druge omejitvene pogoje. Za reševanje takšnih problemov lahko uspešno uporabimo splošne gradientne optimizacijske postopke. Vendar je treba povedati, da gradientni postopki po navadi konvergirajo k najbližjemu lokalnemu optimumu. Pri optimizaciji oblike imamo lahko hitro opravka z mnogimi lokalnimi optimumi, ki so lahko zelo daleč narazen v projektnem prostoru.

B. constraints 1 to 8,
C. constraints 1 to 9.

The first case, A, was run, and the obtained results are given in Tables 7 and 8. The corresponding structure is shown in Figures 13 and 14. Then case B was run and, as expected, a result with a somewhat greater objective function value was obtained. This result is denoted as B-1 and is given in the tables and in Figures 15 and 16. Since we suspected that both the obtained results (A and B-1) are local optima, we took the result B-1 and manually enlarged the values of b_1 and b_2. After an optimization restart a new design (B-2, Figures 17 and 18) was obtained with a significantly lower objective function value. This proves that A and B-1 are actually only local optima.

Finally, the result B-2 was used as the initial design for case C, where the local buckling is also taken into account. The result for case C is given in the tables as well as in Figures 19 and 20.

In all the cases, for the supporting arch and the double-layer truss, the solution procedure was stable. As shown, a gradient-based algorithm can perform the optimization very efficiently. However, in shape-design problems the presence of many local optima can complicate the situation. In this example, we managed rather quickly to get a result that might be (at least close to) the global optimum. Unfortunately, this might not always be so, and in general the designing engineer's intuition may be critical when it comes to getting a near-global-optimum result.

5 CONCLUSION

The design-element technique and the Bézier body, acting as the design element, offer an attractive option for the shape-optimised design of truss structures. Geometrical constraints like symmetry or aesthetic requirements can be taken into account automatically by prescribing proper dependencies between the control points and the design variables. Behavioural constraints of any type can easily be included into the design problem. General-purpose gradient-based optimizers can be employed to solve the problem efficiently. However, care should be taken because gradient-based optimizers typically converge to the nearest local optimum. In a shape-design problem there can exist many such local optima, and they might be very far away in the design space.

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Analiza merilnih sistemov za zagotavljanje kakovosti v procesu šest sigm

Measuring-System Analysis for Quality Assurance in a Six-Sigma Process

Mirko Soković - Duško Pavletić - Romeo Matković

Danes na trgu avtomobilske industrije obstaja velika konkurenca zato morajo podjetja stalno izboljševati kakovost izdelkov/storitev če želijo obdržati svoj položaj. Zagotoviti je treba brezhibno delovanje poslovnega sistema ter nenehno izboljšanje vseh procesov v podjetju. Pri tem si pomagajo z različnimi metodami in orodji, tako že znanimi kakor tudi novejšimi, kakršna je metodologija Šest sigm - 6σ. V prispevku je razložena študija merilnih sistemov, ki so zelo pomemben element v metodologiji šest sigm.

(Ključne besede: sistemi merilni, variacije, metodologija šest sigm, študije ponovljivosti in primerljivosti)

To maintain market share, suppliers to the automotive industry must be involved in the continuous improvement of their processes. They have to strive to perfect their processes as well as their overall business. Therefore, the search for appropriate improvement methods is ongoing, whether these methods are well known or completely new, e.g., six-sigma (6σ) methods. This paper explains the analysis of measuring systems as a part of a six-sigma methodology.

(Keywords: measurement systems, variance, six sigma methodology, gauge repeatability and reproducibility (R&R) study)

0 UVOD

Dandanes je znano pravilo, da kupci postavljajo zahteve po 0 ppm slabih izdelkov, kar pomeni raven kakovosti 6σ. Takšne zahteve se postavljajo predvsem podjetjem, ki so zmožna zagotoviti raven kakovosti med 3σ in 4σ, in to tudi obvladovati ([1] do [3]). Pri ravni kakovosti 4σ je verjetnost dobave izdelkov ustrezne kakovosti okoli 99,9937 % ali 63 ppm. Teoretično se ta verjetnost lahko sprejme kot trenutno zadostna raven kakovosti, vendar če upoštevamo dopusten premik procesa za ± 1,5 σ (kar je v praksi najbolj pogosto), prihajamo do podatka, da je verjetnost pojave neustreznih izdelkov 99,379 % ali 6210 ppm. To dejstvo je, z vidika poslovanja podjetja in obstanka na zahtevnem avtomobilskem trgu, nesprejemljivo.

V celotnem sistemu uvajanja filozofije 6σ je pomemben element obvladovanje in analiza merilnih sistemov. Analiza merilnih sistemov se v osnovi omeji na statistične analize merilnih sistemov, ki se uporabljajo v izdelovalnem procesu. V metodologiji

0 INTRODUCTION

In the modern automotive industry, suppliers are expected to achieve a quality level as high as 0 ppm, which means a 6σ quality level. At present, many suppliers are capable of providing a quality level of 3σ to 4σ ([1] to [3]). At a 4σ quality level, the probability of delivering defective products is 0.000063 or 63 ppm. Such a level of quality is theoretically acceptable if we suppose that the process is without shifts. With shifts taken into account (based on experience, the process shifts that can usually be expected equal ± 1.5σ) the probability of delivering defective products is as high as 0.006210 or 6210 ppm. Such a level of delivered quality in the modern automotive industry is unacceptable.

An important element in 6σ methodology is measurement system analysis. Measurement system analysis deals with a statistical analysis of measurement systems used in production processes. In the context of 6σ methodology, measurement

6σ so znane bolj podrobne analize in statistične metode za obvladovanje merilne in preskusne opreme, to so: analiza ponovljivosti in primerljivosti (znana kot R&R), stabilnost, linearnost, razlikovanje itn. [4].

V prispevku bo prikazan vpliv merilnih sistemov na kakovost izdelkov ter celotno raven kakovosti. Če imamo ustrezen proces in ga želimo obvladovati na ravni procesa 6σ, ne bo ta nič boljši, če ga merimo z neustrezno merilno opremo ali merilno opremo, za katero ne vemo, kaj se z njo dogaja, oz. v kakšnem tehničnem stanju je. Merilni odstopek, ki iz tega izhaja, je zelo pomemben dejavnik pri merjenju, ker meritev z neustreznim merilom lahko zavaja in vodi k napačnem sklepu o samem procesu ali izdelku.

system analysis consists of the following: a detailed statistical analysis of a measurement and experimentation equipment or gauge R&R analysis, an analysis of stability, linearity and discrimination [4].

This paper deals with the effect of a measurement system on the quality of products and the overall quality of manufacturing. For processes that are at the 6σ quality level, the measurement equipment should also be at a high quality level; otherwise, the measurement error could be high, causing the wrong decision to be made.

1 ANALIZA MERILNIH SISTEMOV

Matematično analize merilnih sistemov vključujejo razumevanje variacij v procesu merjenja, kakor je prikazano v enačbi:

1 MEASUREMENT SYSTEM ANALYSIS

Measurement system analysis involves understanding measurement process variations, presented by the following equation:

$$\sigma_T^2 = \sigma_p^2 + \sigma_m^2$$

pri čemer pomenijo: σ_T^2 - skupna varianca, σ_p^2 - varianca procesa in σ_m^2 - varianca merjenja.

To je edini pravi način razumevanja variacij v procesu. Pri analizi merilnih sistemov se določajo statistične značilnosti: ponovljivost, primerljivost, linearnost, natančnost.

Ponovljivost določamo kot spremenljivost zaporednih meritev enega merilca, ki večkrat meri z istim merilnikom isto lastnost na istem merjencu. **Primerljivost** je mera za spremenljivost zaporednih meritev različnih merilcev, ki merijo isti merjenec ali iste lastnosti z istim merilnikom.

Linearnost je je mera zanesljivosti merilnika na celotnem merilnem območju merilnika.

Odmik je razlika med povprečjem izmerkov in imensko vrednostjo. Odmik predstavlja tudi mero točnosti.

Študija ponovljivosti in primerljivosti (PP) merilnih sistemov se uporablja tako za začetno oceno merilnih sistemov kakor tudi za določanje velikosti vpliva merilnega sistema na vrednost indeksa sposobnosti procesa.

where: σ_T^2 - total variance, σ_p^2 - process variance, σ_m^2 - measurement variance.

Measurement system analysis deals with several statistical characteristics: repeatability, reproducibility, linearity and bias.

Repeatability is a measure of the variability of successive measurements of the same part, or the same characteristic, by the same operator, using the same measuring instrument. And **reproducibility** is a measurement of the variability of successive measurements of the same part, or the same characteristic, by different operators, using the same measuring instrument.

Linearity is a measure of an instrument's accuracy over the range of the instrument's capability.

Bias is the difference between the average of the measurements and the nominal value.Bias also represents a measure of precision.

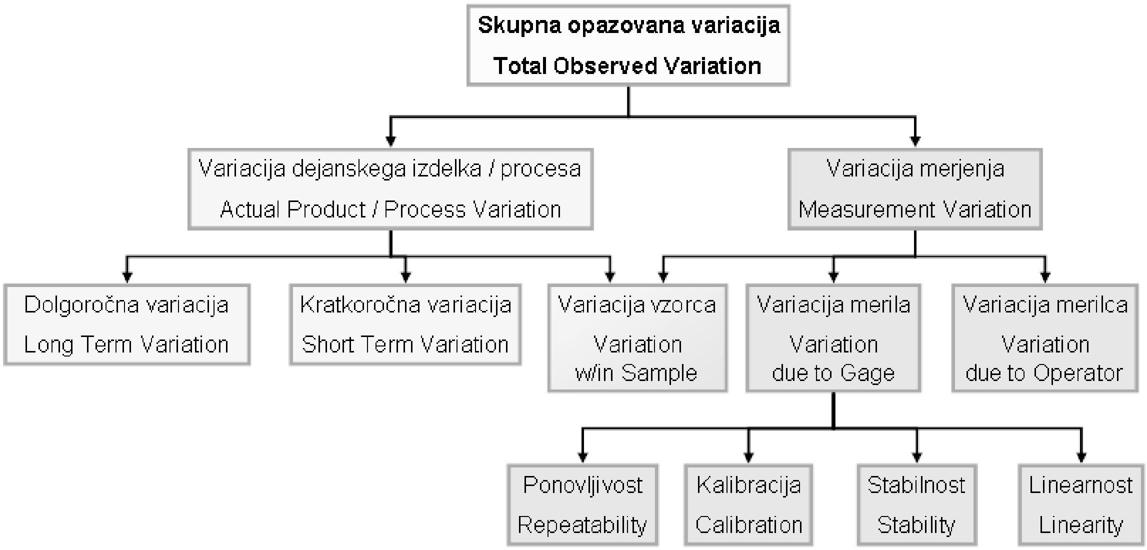
A gauge R&R analysis can be used for a first evaluation of measurement systems, as well as for finding the magnitude of a measurement system's effect on the process capability index.

1.1 Viri merilnih odklonov

Analiza merilnih sistemov izmeri in razpozna različne vire odklonov, ki lahko vplivajo na merilni sistem. Merilni odklon je skupna variacija

1.1 Sources of measurement variation

Measurement system analysis quantifies and identifies different sources of variation that might affect the measurement system. Measurement variation is the



Sl. 1. *Blokovni diagram skupne opazovane variance*
Fig. 1. *Total-observed-variation flow chart*

pri merjenju, ki je lahko posledica variacije na vzorcu merjenja ali variacije merilnega sistema. Na sliki 1 je nazorno prikazano, kako določimo skupno variacijo: ta je setavljena iz variacije meritve in variacije izdelka. Pomembna pri analizi merilnih sistemov je variacija meritve, ki izhaja iz variacije merilnega sistema (merilni instrument ali naprava, merilec, okolje itn.)

1.2 Vpliv merilnega odstopka na indeks sposobnosti procesa Cp

Merilni odstopek je prikazan na sliki 2 kot skupni seštevek odstopka izdelka in odstopka merilnega sistema. V prvem izrazu je definirana natančnost skozi srednjo vrednost meritve. V drugem izrazu izhaja natančnost kot mera variacije merilnega sistema.

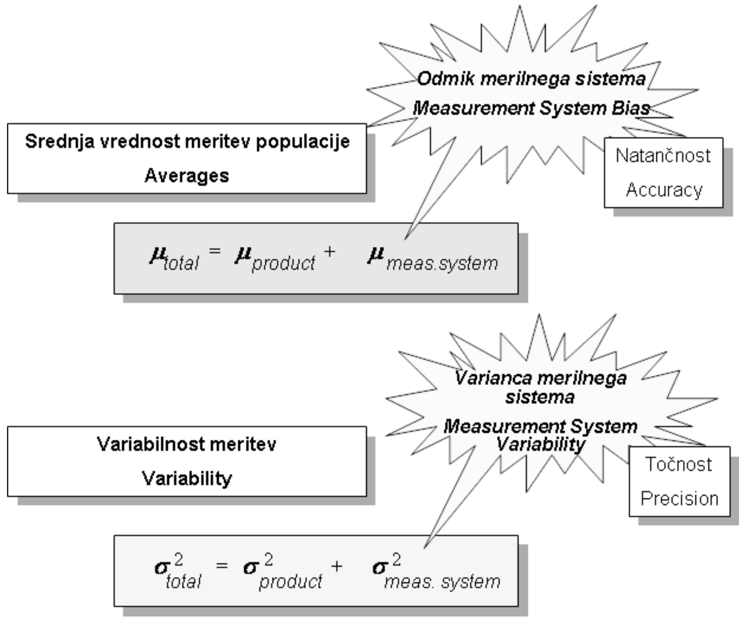
Na podlagi preizkusov in analiz proizvodnega procesa smo dobili rezultate, ki pokažejo, kako vpliva odstotek odmika merilnega sistema na indeks sposobnosti procesa Cp ([5] in [6]). S slike 3 je razvidno, da 10 % napake merilnega sistema skoraj ne vpliva na dejanski Cp izdelka. Izkaže se tudi, če pri izračunu sposobnosti za določen proces dobimo vrednost Cp = 1,3 in upoštevamo 10 % odmik merilnega sistema, bo tudi dejanski Cp približno enak. Vendar, ker je večja napaka merilnega sistema, je dejanski Cp boljši od opazovanega. To pove, da moramo zelo dobro poznati merilni sistem, preden

total observed variation in measurements, which can be attributed to the variation in the item being measured or to the measurement system itself. Components of the total observed variation are shown in Figure 1. The total observed variation includes the actual product/process variation and a measurement variation, which consists of the variation due to the operator, the variation due to the gauge and the variation within the sample.

1.2 Measurement error effect on the process capability index Cp

Measurement error as a result of actual product variation and measurement system variation is shown in Figure 2. The first equation defines the accuracy, taking into account the average of the measurements. The second equation defines precision as a measure of the measurement system.

A measurement error's effect on the process capability index Cp is determined through experiments and the process analysis, Figure 3. For example, 10% of the measurement system error has a negligible effect on the actual process capability index Cp ([5] and [6]). On the other hand, with an observed process capability index of Cp = 1.3 and a measurement system error equal to 10%, the value of the actual Cp will be approximately 1.3. If the measurement system error is bigger, the actual process capability is then better observed. This means that the measurement system error has to be



Sl. 2. *Skupna varianca in srednja vrednost*
Fig. 2. *Accuracy and precision of the measurement system*

ugotavljamo izhod določene meritve z ustrezno negotovostjo.

V primeru, ko smo analizo Cp delali z merilno napravo, ki ima odstotek merilnega odstopka do 30 %, je iz diagrama razvidno, da ta nima tako pomembnega vpliva na dejanski Cp. Vendar, če uporabljamo merilno napravo z več ko 30 odstotki merilnega odstopka, je zelo pomemben vpliv na dejanski Cp; pri 70 odstotkih merilnega odstopka je opazovani Cp = 1,3, dejanski pa Cp = 3,0.

Na podlagi tega bi lahko napačno sklepali, kaj se v resnici dogaja s procesom. Da bi se temu izognili, je treba vedeti, kaj se dogaja z merilnim instrumentom ter kako določiti odstotek merilnega odstopka, da bi lahko ustrezno ukrepali.

1.3 Kakovost merilnih sistemov

Merilni sistemi imajo določene karakteristike, po katerih jih razlikujemo glede na kakovost. Kakovost merilnih sistemov lahko delimo na:

- razlikovanje,
- natančnost, točnost, odmik,
- ponovljivost ali test-retest,
- učinek odmika vključno s primerljivostjo,
- stabilnost (skladnost),
- linearnost.

Vsaka od naštetih komponent merilnega odstopka vpliva na variacijo rezultatov meritev in

known in order to be certain of the measurements results.

In general, measurement system errors up to 30% will have little or no effect on the capability index, so the values of the observed and actual capability indices will be almost the same.

A measurement system error greater than 30% will have a significant effect on the capability index, e.g., with a measurement system error as high as 70% the observed process capability equals Cp = 1.3, while the actual Cp = 3.0.

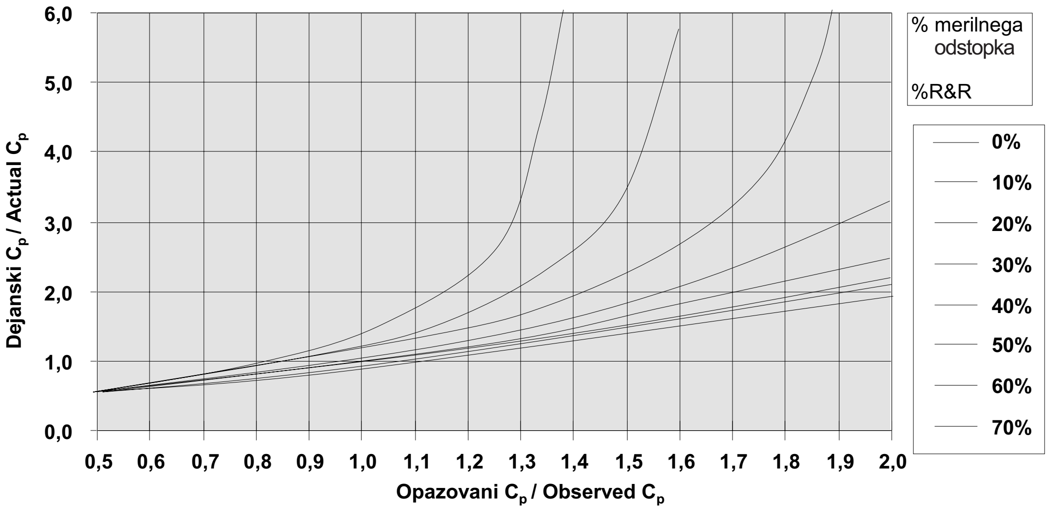
So, to make a sound decision about process capability, a measurement system should be evaluated and the magnitude of its variability should be taken into account.

1.3 Quality of measurement systems

Measurement systems have certain characteristics that define their level of quality. These characteristics are:

- discrimination,
- accuracy, precision,
- repeatability, or test-retest,
- bias effect with reproducibility,
- stability (consistency),
- linearity.

Each of the various components of measurement error can contribute to a variation in



Sl. 3. *Vpliv odstotka merilnega odstopka na indeks sposobnosti procesa Cp*
Fig. 3. *Measurement error effect on the process capability index Cp*

provzroča napačno sklepanje o kakovosti merjenca.

2 ŠTUDIJA PP ZA MERILNE SISTEME Z ODČITAVANJEM VREDNOSTI

Skozi predhodno razlago smo prišli do analize merilnih sistemov, ki podaja sklepno ugotovitev, kaj se dogaja z merilnim sistemom kot celoto, vključno z merilcem.

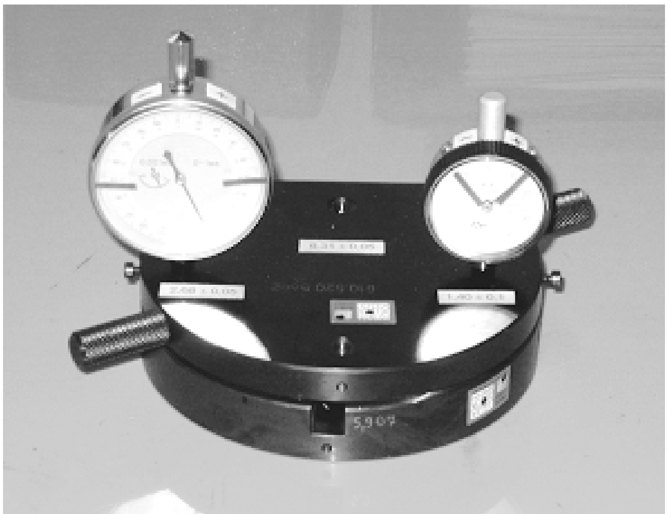
Merilni sistemi z odčitavanjem vrednosti so merilne naprave, ki imajo možnost merjenja z odčitavanjem določene mere (sl. 4) [7].

the given value causing the wrong decision to be made.

2 GAUGE R&R OF A MEASUREMENT SYSTEM FOR QUANTITATIVE DATA

So far we have a measurement system analysis that takes into account all the elements of a measurement system, including operators.

Measurement systems for quantitative data enable readings of a measured characteristic numerical value, Figure 4 [7].



Sl. 4. *Merilna naprava za merjenje višine*
Fig. 4. *Hight measurement gauge*

Pri šudiji posameznega merilnega sistema izhajamo iz naslednjih postavk [8]:
- merita dva ali trije merilci,
- običajno se meri 10 vzorcev,
- vsak vzorec se izmeri 2 ali 3 krat.

Študijo PP (ponovljivosti in primerljivosti) merilnega sistema uporabljamo, ko želimo ugotoviti ([6] in [9]):
- ali ima merilni sistem ustrezno razlikovanje;
- izvore variacij v merilnem sistemu;
- relativno velikost za vsak izvor variacije;
- ali je potrebno kakršnokoli ukrepanje, če je, kaj bi priporočili;
- kako bo skupina razumela ali bo merilni sistem ustrezen tudi v prihodnosti? Vključno s ponovljivostjo teh rezultatov v prihodnosti in potrebami raziskovanja.

Razume se, da smo v našo analizo vključili naslednje izvore variacij:
- meritev,
- vzorec nasproti vzorcu,
- merilec nasproti merilcu.

In general, gauge R&R is conducted in the following conditions [8]:
- the measurement is conducted by two or three operators,
- there are 10 units to measure,
- each unit is measured two or three times by each operator.

R&R analysis is used when the following are of special interest ([6] and [9]):
- Does the measurement system have adequate discrimination?
- What are the sources of variation in the measurement system?
- What is the relative magnitude of each of the sources of variation?
- Is there any action required, and what can be recommended?
- How will the team understand whether the measurement system will be adequate in the future, including the repeatability of these results in the future and developing needs?

The following sources of variation should be included in the analysis:
- measurement,
- part-to-part,
- operator-to-operator.

2.1 Postopek za izvajanje študije PP

1) Umeri merilo ali zagotovi, da je še umerjeno.
2) Zagotovi, da prvi merilec izvaja meritve skozi vse vzorce z naključnim izborom.
3) Zagotovi, da tudi drugi merilec izvaja meritve skozi vse vzorce z naključnim izborom.
4) Nadaljuj, dokler se ne zvrstijo vsi merilci, ki sodelujejo v raziskavi.
5) Ponavljaj korake 2 do 4 za vsa potrebna števila meritev.
6) Uporabi obrazec za ugotavljanje statističnih podatkov študij PP:
   a) ponovljivost,
   b) primerljivost,
   c) standardno odstopanje za obe prej omenjeni karakteristiki,
   d) odstotek PP,
   e) odstotek tolerančne analize,
7) Analiziraj rezultate in ukrepaj, če je potrebno.

2.1 Procedure for performing an R&R study

1) Calibrate the gauge, or ensure that it has already been calibrated.
2) Ensure that the first operator measures all the units once in a random order.
3) Ensure that the second operator measures all the units once in random order.
4) Continue until all the operators have measured all the units once.
5) Repeat steps from 2 to 4 for the required number of trials.
6) Use the form provided to determine the statistics of the R&R study:
   a) repeatability,
   b) reproducibility,
   c) standard deviation for each of the above,
   d) %R&R,
   e) % tolerance analysis.
7) Analyze the results and determine follow-up action, if any.

Število merilcev:
- Če so v postopku prisotni različni merilci oz. operaterji, izberi od 2 do 4 merilca z metodo naključne izbire.

Number of operators:
- If the process uses multiple operators, chose 2–4 at random.

- Če je v postopku samo en operater oz. merilec ali pa nobeden, opravi študijo brez učinka merilca (zanemari primerljivost).

Število vzorcev:
- Izberi zadostno število vzorcev, in to tako, da je: (število vzorcev) × (število merilcev) > 15.

2.2 Primer študije PP za merilni trn Marposs ϕ35,31 mm z metodo ANOVA

Poznani sta dve metodi analize PP, in sicer analiza PP po metodi ANOVA (analiza variance) ter po metodi $\overline{X}$ - R. Razlika med njimi je ta, da se metoda $\overline{X}$ - R več uporablja, ker kalkulacija izhaja iz kontrolnih kart in je bolj preprosta. Vendar je metoda ANOVA bolj natančna, ker:
- metoda ANOVA računa mogoče povezave med merilci in vzorci, metoda $\overline{X}$ - R pa ne;
- komponente variacije, uporabljene pri metodi ANOVA, so bolje ocenjene od razpona uporabljenega pri metodi $\overline{X}$ - R.

V nadaljevanju prispevka bomo podali primer študije PP, ki je bila narejena za proces izdelave okrova turbo kompresorja. Analizo smo naredili s programom MINITAB™, ki je prirejen za metodo ANOVA.

V proizvodnem procesu se za merjenje premerov okrova turbo kompresorja uporablja merilni trn Marposs, ki je sestavni del naprave Marposs E9066 in je prikazan na sliki 5. V danem primeru bo podana analiza PP za merjenje premera ϕ35,31 ± 0,08 mm (sl. 6) ([6] in [9]).

- If the process uses only one operator, or no operators, perform study without operator effects (ignore reproducibility effect).

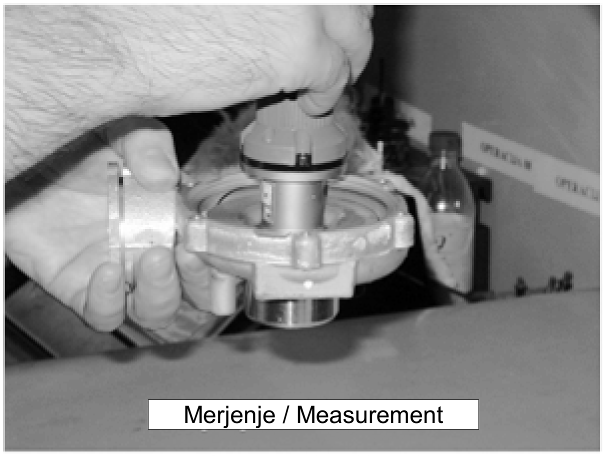
Number of samples:
- Select enough samples so that: (number of samples) × (number of operators) > 15.

2.2 Example of gauge R&R with ANOVA method for a Marposs ϕ35.31 mm measurement gauge

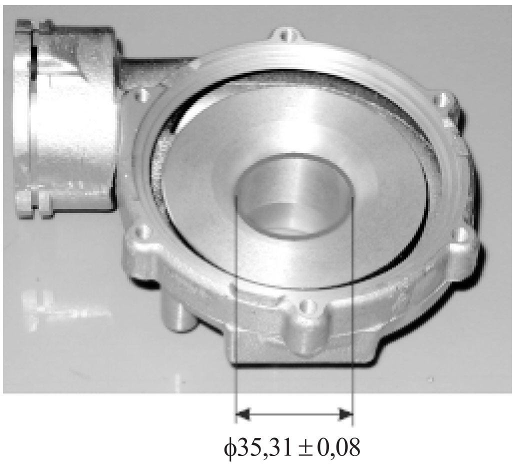
Two gauge R&R methods are known, the ANOVA and the $\overline{X}$ - R method. The $\overline{X}$ - R method is simpler and is used when the gauge R&R analysis is based on control charts. The ANOVA method is more precise because:
- The ANOVA calculates possible interactions between operators and samples, while the $\overline{X}$ - R method does not.
- Components of variation used by the ANOVA are better evaluated in comparison with the range used by the $\overline{X}$ - R method.

Later in the paper there will be an example of a gauge R&R analysis in the production of a turbo-charger housing. An analysis will be made with the ANOVA method using the MINITAB™ statistical analysis package.

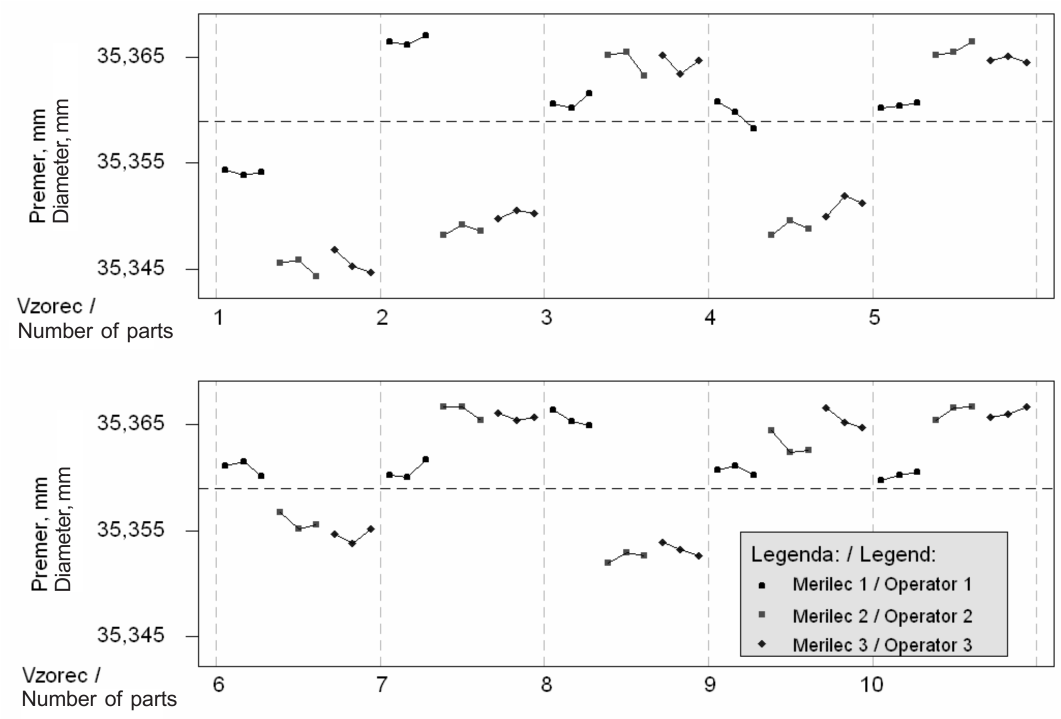
The Marposs measurement gauge, which is part of the Marposs E9066 measurement system, is used to measure the diameter of the turbo-charger housing, Figure 5. In the presented example, a gauge R&R analysis for a ϕ35.31 ± 0.08 mm measurement will be shown (Fig. 6) ([6] and [9]).



Sl. 5. *Merilna naprava Marposs in merjenje premera 35,31±0,08 mm*
Fig. 5. *Marposs measurement gauge and measurement of diamater 35.31 ± 0.08 mm*



Sl. 6. *Pomembna kota na okrovu turbo kompresorja (tip 716108-2-20)*
Fig. 6. *Important dimension on the housing of turbocharger 716108-2-20*



Sl. 7. *Diagram poteka za meritve karakterističnega premera po merilcih in po vzorcih*
Fig. 7. *Flow chart of diameter measurement for operators and number of parts*

V analizi smo upoštevali vsa prej omenjena pravila. Na temelju dobljenih rezultatov smo naredili diagram poteka po merilcih in po vzorcih, kar prikazuje slika 7, ter kontrolno karto $\overline{X}$ - R za premer ϕ35,31 ± 0,08 okrova turbo kompresorja (sl. 8).

S slike 7 je razvidno, da je nekaj narobe z merilcem 1, ker se na nekaterih vzorcih meritev merilca 1 rezultati precej razlikujejo od preostalih.

S slike 8 je tudi razvidno, da se meritve merilca 1 razlikujejo od meritev drugih dveh merilcev. Na karti R je tudi razvidno, da je merilec 1 imel največji razpon pri meritvah in se njegove meritve ne ujemajo s preostalima dvema merilcema. To lahko pomeni, da merilec 1 ni zadostno usposobljen za izvajanje meritev.

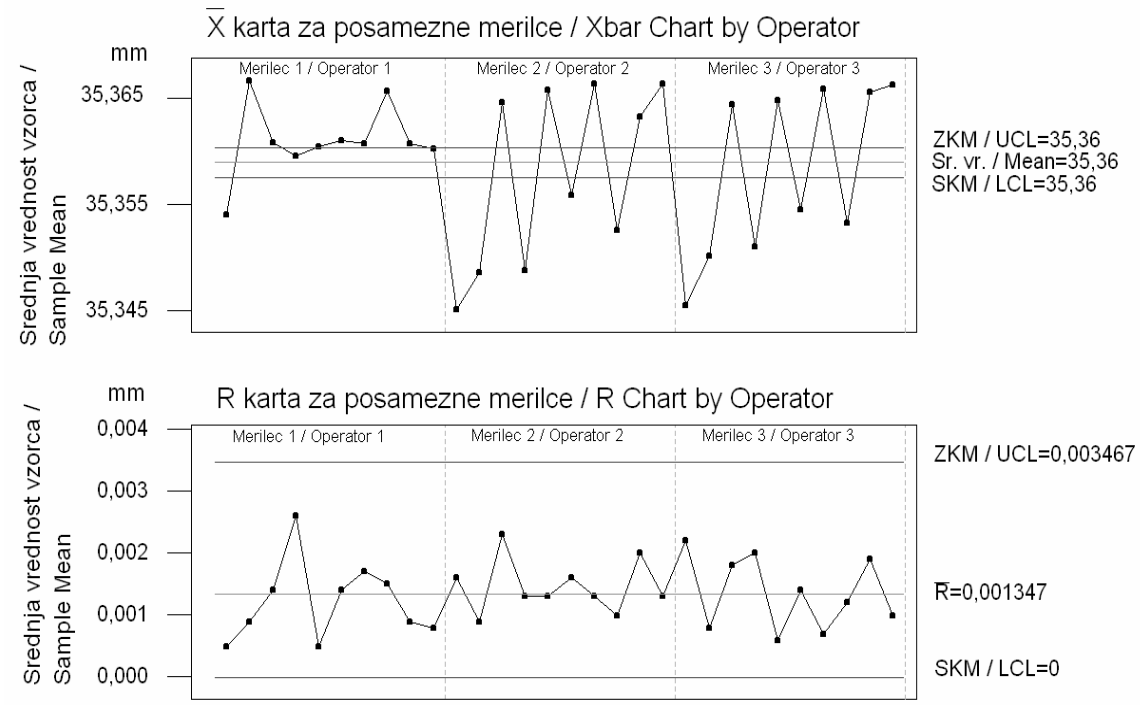
Na sliki 9 je podana celotna analiza PP v grafični obliki. Iz diagrama *Merilec*Vzorec medsebojno* je tudi razvidno, da merilec 1 ne ustreza; prav tem daje slabe rezultate ponovitve. Vendar ponovljivost meritev ni problematična, zato lahko sklepamo, da je treba bolj usposobiti merilca 1 za merjenje; po tem ponoviti meritve ter primerjati rezultate analize PP. Lahko že sedaj sklepamo, da bo merilna naprava ustrezna za merjenje, če se le bodo uskladili merilci.

In the example, the procedure for performing an R&R study is followed. Based on the measurements of the turbocharger-housing diameter 35.31±0.08 mm, a flow chart and an $\overline{X}$ - R control chart have been drawn, shown in Figure 7 and Figure 8, respectively.

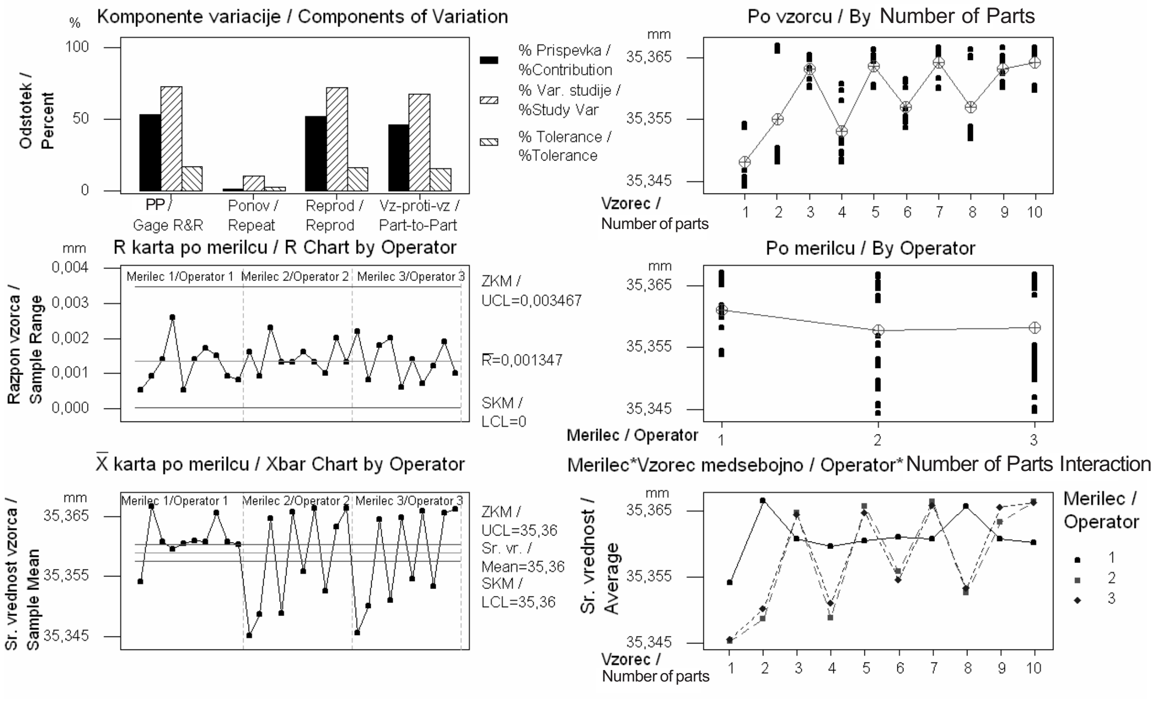
As can be seen in the flow chart in Figure 7, operator 1 measurements for several parts are significantly different from operator 2 and operator 3 measurements for the same parts.

The same conclusion can be drawn from Figure 8. As is show both on the $\overline{X}$ and R control charts, the measurements of operator 1 are quite different from the other two operators. This could mean that operator 1 is not adequately instructed for carrying out the planned measurements.

The gauge R&R analysis is shown in Figure 9. On the *Operator*Part numbers Interaction* diagram it is clear that the operator 1 measurements are significantly different from the other two operators and, consequently, the reproducibility is poor. At the same time, the repeatability is quite good, which leads to the conclusion that operator 1 should be better instructed in the measurement procedure. Furthermore, based on the gauge R&R analysis results, the measurement gauge appears to be appropriate for the planned measurements.



Sl. 8. *Kontrolna karta $\overline{X}$ - R za premer ϕ35,31±0,08 mm okrova turbo kompresorja*
Fig. 8. *$\overline{X}$ - R control chart for turbo-charger housing ϕ35.31 ± 0.08 mm*



Sl. 9. *Analiza PP*
Fig. 9. *Gauge R&R analysis*

3 SKLEPI

Merilni sistemi so v postopku zagotavljanja kakovosti zelo pomemben dejavnik. Če želimo izboljšati sistem kakovosti in dosegati zelo visoko raven zaupanja kupca v naše izdelke/storitve, moramo zelo resno jemati merilne sisteme kot komponente procesa, ki vplivajo neposredno na kakovost izdelka/storitve.

Če ne vemo zagotovo, kaj se dogaja z merilno opremo in v kakšni meri ji lahko zaupamo, tudi ne vemo zanesljivo, kaj se dogaja s kakovostjo procesa.

Probleme v proizvodnem procesu moramo reševati sistematično in zagotavljati najboljši mogoči način reševanja z ustrezno analizo merilnih sistemov.

Obstajajo različne metode v različnih primerih: od analize ponovljivosti, primerljivosti do zelo zapletene analize PP, ki skozi celotno analizo variacij sistema pokaže, kaj se s sistemom dogaja in kako moramo ukrepati, če je z njim kaj narobe.

Merilni sistem je kompleksen sistem, ki vključuje množico elementov, od merilnih naprav, človeka do vplivov okolja in podobno. Zato je zelo pomembno imeti pod nadzorom vse elemente, ki jih je mogoče obvladovati.

3 CONCLUSIONS

Measurement systems are a very important element in the quality-assurance process. To improve process quality and achieve a high level of customer confidence in products and services, measurement systems, which directly influence the products' quality, should become important components in the production processes.

If the measurement system error is unknown, the exact process quality level cannot be determined for sure.

Problems in the production process should be solved systematically using the best available process-improvement methods and an adequate measurement system analysis.

For a measurement system evaluation several methods are used, from simple repeatability and reproducibility analyses to complex gauge R&R analysis, which, through an in-depth analysis of measurement system variation, shows what is wrong with the measurement system and what action should be taken to correct existing problems.

A measurement system is a complex system that includes measurement gauges, but also the operators, the environment, etc. To ensure sound measurements and confidence in the measurement results, all the elements of the measurement system should be under control.

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Statistična analiza gospodarsko enakovrednih nalivov

Statistical Analysis of the Equivalent Design Rainfall

Jože Panjan - Marija Bogataj - Boris Kompare

Statistično analizo padavinskih podatkov uporabljamo za oblikovanje kanalizacijskega omrežja in črpališč, ugotovitev trajanja in pogostosti prelivanja razbremenilnikov in zadrževalnikov oziroma za določitev kritičnega dotoka na komunalno čistilno napravo ali izpust v vodotok (npr. iz avtocest). Pri tem sta osnovna podatka jakost in trajanje naliva pri izbrani povratni dobi.

Opisani so postopki, ki se uporabljajo za analizo gospodarsko enakovrednih nalivov (GEN) pri nas in v tujini. Natančneje je prikazana metoda stohastičnega modeliranja, ki je uporabna predvsem za ugotovitev verjetnosti pojava delnih nalivov višjih pogostosti in za določitev spodnje meje vrednotenja nalivov. Prikazani so rezultati izračunov za vrednotenje padavin na podlagi statistične analize opazovanih nalivov na območju Ljubljane.

(Ključne besede: statistika nalivov, jakost nalivov, pogostost nalivov, trajanje nalivov, analize regresijske)

Statistical analyses of rainfall data are used for the design of sewerage systems and pump-stations, for the evaluation of the duration and the frequency of overflow in runoff detention facilities, for the determination of the critical influence on a municipal wastewater-treatment plant or for the protection of watercourses from storm-water runoff (e.g., from highways). The basic data in this calculation are the intensity and the duration of a rainstorm.

Different procedures used in the analysis of Equivalent Design Rainfall (EDR) in Slovenia and abroad are described. The stochastic model used is presented in more detail because of its applicability for the determination of the probability of the occurrence of partial rainfalls of higher frequencies and the determination of the lower limit of rainfall evaluation. Computation procedures and the results of the evaluation of rainfall data according to the stochastic model are presented for Ljubljana.

(Keywords: rainfall statistics, rainfall intensity, rainfall frequency, rainfall duration, regression analysis)

0 UVOD

Pri dimenzioniranju odvodnje so osnovni podatki za določitev količin odtoka padavinske vode s površin v naseljih in odvodnji avtocest, posamezni, statistično ovrednoteni nalivi ali deževja določenega časovnega trajanja t_r (npr. t_r = 5, 10, 15, 30 min …) in pogostosti n, ki pove, kolikokrat se naliv pojavi v enem letu (n = 1 pomeni, da se pojavi enkrat na leto, n = 0,5 pa enkrat v dveh letih itn.), oziroma kakšna je njegova povprečna povratna doba T=1/n. Za njihovo vrednotenje se uporabljajo različne statistične metode. Z ovrednotenjem padavinskih podatkov za oblikovanje kanalizacijskih sistemov se je v Sloveniji

0 INTRODUCTION

The basic data for the design of rainfall-runoff drainage from urban areas and highways are individual, statistically evaluated storms and rainfalls of a certain duration, t_r, (e.g., t_r = 5, 10, 15, 30 min …) and their frequency, n, which tells us how many times the rainfall phenomena occurs in one year (n = 1 means that it appears once per year, n = 0.5 once in two years etc.), or what is its average return period, T=1/n. Different statistical methods are used for their evaluation. In Slovenia, Sketelj [1] from the University of Ljubljana, Faculty of Civil and Geodetic Engineering, Institute of Sanitary Engineering, was največ ukvarjal Sketelj [1] na UL, Fakulteta za gradbeništvo in geodezijo, Inštitut za zdravstveno hidrotehniko, pred več ko 40 leti. Vse analize so potekale "peš". Temeljni problemi, ki se pri tem pojavijo, so, kako natančni naj bodo padavinski podatki (mm/h), kakšen naj bo najmanjši časovni korak opazovanja nalivov iz zapisanih časov merjenja in v kakšnem časovnem koraku naj bodo podani preprosti in sestavljeni nalivi. Zato smo preverili, kako se lotevajo teh problemov v tujini.

V zadnjih 36 letih (od 1964 do 2000) v Sloveniji padavine niso bile statistično vrednotene za oblikovanje sistemov odvodnje. Pridobili smo podatke z Ministrstva za okolje, prostor in energijo (MOPE), Agencije za okolje (ARSO), Urada za meteorologijo (prej Hidrometeorološki zavod Republike Slovenije - HMZ). Podatki so shranjeni v digitalni obliki za Ljubljano od leta 1965 do vključno 1996, skupaj 32 let.

Posredovali so lahko digitalne meritve za nalive v časovnem koraku Δt = 5 minut. Intenzivnost padavin je bila zajeta z natančnostjo 0,1 mm/h, kar so, tako za naše vrednotenje kakor tudi v primerjavi z mednarodnimi dosežki, dobri podatki.

Svetovna meteorološka organizacija (WMO) priporoča, naj analize vremenskih pojavov temeljijo na časovni vrsti vsaj za 30 let teh pojavov, za potrebe načrtovanja kanalskih sistemov pa zadoščajo tudi časovne vrste iz 10 do 15 letnih opazovanj, če ni drugih podatkov.

Zelo podrobno se s to problematiko ukvarjajo na Danskem [2], kjer so potekale celovite raziskave o osnovah oblikovanja in analize sistemov urbane odvodnje glede na lokalne in regionalne točkovne padavinske podatke. Pri tem so uporabili enominutni osnovni časovni korak.

Švicarska meteorološka služba [3] zajema podatke z ločljivostjo 10 minut. Zato je švicarski Zvezni inštitut za okoljske znanosti in tehnologijo razvil metodo (1998), s katero je 10-minutne padavinske podatke mogoče razdeliti v podatke z enominutno ločljivostjo in natačnostjo 0,1 mm/h.

Meteorološka služba nemške dežele Vestfalije je za celotno območje uvedla standardno metodo za simulacijo padavinskega dogajanja in odtoka. V delu Maul-Koetterja in Einfalta [4] so uporabljeni različni matematični modeli za simulacijo razmer padavine – odtok.

V Franciji s podatki za območje Seine Saint Denise [5] preučujejo izvedljivost izgradnje

involved in the processing and evaluation of rainfall data for the design of sewerage systems more than 40 years ago. All the calculations had to be carried out by hand in those times. The basic problems that emerged in such an analysis are how accurate the precipitation data (mm/h) should be, what should be the minimum time interval for the observation of rainstorms, and at what intervals should elementary and composed rainfalls be given. For this reason we explored how these problems are tackled abroad.

In Slovenia, the recorded precipitation data have not been statistically evaluated for the design of runoff drainage systems in the last 36 years (from 1964 to 2000). The digitally processed data saved for Ljubljana since 1965 to 1996 have been provided by the Ministry of the Environment, Spatial Planning and Energy, the Nature Protection Authority, the Office for Meteorology (formerly the Hydrometeorological Institute). Therefore, our evaluation extends over the years 1965 to 1996 inclusive, which means a total of 32 years.

We received the measurements for rainfalls with a time step Δt = 5 min as digital data. The intensity of rainfalls is accurate to 0.1 mm/h, which is high-quality data for our application, and, as will be seen, also in the world-wide comparison.

The World Meteorological Organisation (WMO) recommends that analyses of meteorological phenomena should be carried out on data extending over at least 30 years, but for the purpose of the sewage-system designs, data extending over 10 to 15 years suffices if no other data is available.

In Denmark [2] researchers have studied this question in depth, where comprehensive research on the fundamentals of the design and analyses of urban drainage systems with respect to local and regional point precipitation data has been performed. The basic time step is one minute.

The Swiss Meteorological Service [3] measures data with a resolution of 10 minutes. Therefore, The Swiss Federal Institute of Environmental Sciences and Technology developed a method in 1998 that makes it possible to divide 10-minute precipitation data into data with 1-minute resolution and 0.1 mm/h accuracy.

The meteorological service in the German federal land of Westphalia introduced a standard method for the simulation of precipitation events and drainage for the whole region. In the work of Maul-Koetter and Einfalt [4] different mathematical models are used for the simulation of precipitation-drainage conditions.

In France, using data for the region Seine Saint Denis [5], the feasibility to construct a naključnostnega modela, združljivega s potrebami urbane odvodnje, kjer so podatki nanizani po 5-minutnih korakih. Ločnica med suhim in deževnim obdobjem je na robu koraka, na katerem je skupna količina padavin 2 mm, ali kjer je mejna jakost 0,2 mm/h.

V Kanadi [6] so določili jakosti in ustrezne povratne dobe na podlagi mesečnih skrajnosti (največjih nalivov) za obdobje 35 oz. 50 let.

1 NAKLJUČNOSTNO MODELIRANJE NALIVOV

Temeljne značilnosti obnašanja padavin lahko opišemo in analiziramo s stohastičnim modeliranjem.

Jakost padavin lahko razumemo kot naključno spremenljivko Q, ki lahko zavzame eno od diskretnih vrednosti $q_1, q_2, \ldots, q_m$ oziroma poljubno vrednost na nekem koraku pozitivne realne osi $0 < q < q_{max}$. Porazdelitev naključne spremenljivke opišemo s porazdelitveno funkcijo $F(q) = P(Q \leq q)$ in v njej podamo njene parametre. Ker nas pri oblikovanju zanimajo predvsem porazdelitve skrajnih vrednosti jakosti nalivov, te opišemo z logaritmično normalno porazdelitvijo, za katero velja, da se njihov logaritem Y:

stochastic model with a time step compatible with the needs of urban drainage (5 minutes time step) is explored. The dividing line between the dry and the rainy periods is a total amount of precipitation of 2 mm or the limit intensity of 0.2 mm/h.

In Canada [6] the intensities and corresponding return periods were determined on the basis of the monthly maxima (maximum rainfall) for periods of 35 and 50 years respectively.

1 STOCHASTIC MODELLING OF RAINFALL

The fundamental characteristics of rainfall behaviour can be described and analysed with stochastic models.

The precipitation intensity can be described with a random variable Q, which can take over one of the discrete values $q_1, q_2, \ldots, q_m$, or an arbitrary value in the interval $0 < q < q_{max}$. The distribution of random variables are described by their cumulative distribution function, defined by $F(q) = P(Q \leq q)$, where its parameters have to be given. As we are analysing the extreme values of the rainfall intensities, the variable Q is most suitably described by a lognormal distribution. The probability density function Y of the lognormal distribution:

$$Y = \ln Q \qquad (1)$$

porazdeljuje standardizirano normalno. Splošna formula za logaritmično normalno porazdelitev je:

is normally distributed. The general formula for the probability density function of the lognormal distribution is:

$$f_Q(q) = \begin{cases} \dfrac{1}{q\sigma(\ln q)\sqrt{2\pi}} e^{\frac{-1}{2}(\ln(q/Me(Q))/\sigma(\ln q))^2} & \Leftarrow q > 0 \\ 0 & \Leftarrow q \leq 0 \end{cases} \qquad (2).$$

Z vstavitvijo standardizirane normalno porazdeljene spremenljivke z, ki je dobro poznana in tabelirana:

Let us introduce a standardized normally distributed variable Z, which is widely tabulated:

$$z = (\ln(q \,/\, Me(Q)) \,/\, \sigma(\ln q)) \qquad (3),$$

dobimo preprostejši izraz za porazdelitveno funkcijo jakosti nalivov, ki omogoča brati iskane vrednosti porazdelitvene funkcije prek preglednic za standardizirano normalno porazdelitev:

in this case one gets a simpler equation for the density function of the rainfall intensities, which can be easily evaluated using tables of the standardized normal distribution, since:

$$F_Q(q) = P(Q \geq q) = F_Z(\ln(q / Me(Q)) / \sigma(\ln q)) \qquad (4),$$

kjer je $Me(Q)$ povprečje porazdelitve Q. Za aritmetično povprečje $M_y = \ln q'$ smo v (4) namreč upoštevali zvezo (5):

Here, $Me(Q)$ is the median of the distribution of Q. For the asymmetric mean $M_y = \ln q'$ we used in Eq. (4) the equality (5):

$$\ln q - M_Y = \ln q - \ln MeQ = \ln \frac{q}{MeQ} \qquad (5).$$

V enačbi (4) zapis $F_z(.)$ označuje porazdelitveno funkcijo standardizirane normalne porazdelitve, za katero imamo preglednice vrednosti želene natančnosti.

Pri tem zapisu je varianca jakosti padavin pri matematičnem upanju jakosti:

In (4) $F_z(.)$ is the CDF of the standardised normally distributed variable, and is also widely tabulated and given with the desired precision.

Following this description the variance of the rainfall intensities by mathematical expectation of a certain intensity:

$$M_Q = q' = q'(t, T_p) \quad (6),$$

naslednja:

is as follows:

$$\sigma^2(Q) = (q')^2 (e^{\sigma^2(\ln q)} - 1) \quad (7).$$

Varianco lahko ocenimo iz eksperimentalnih podatkov. Od tod izhaja koeficient variacije:

The variance can be estimated from the experimental data. Subsequently, the coefficient of variation follows:

$$C_v = \sqrt{(e^{\sigma^2(\ln q)} - 1)} \quad (8).$$

Vrednotenje opravimo za vsako enoto opazovalnega časovnega območja, za korak vnaprej določene dolžine, v vsem obravnavanem obdobju (N let). Izračunati moramo vse statistike empirične porazdelitve: aritmetično povprečje *q'*, standardni odmik *S*(*Q*), koeficient asimetrije *Cs*(*Q*), koeficient variacije *Cv*(*Q*).

Rezultati postopkov vrednotenja so nizi GEN (Gospodarsko Enakovrednih Nalivov) določene pogostosti (*n*), jakosti odtoka (*q*) in trajanja (*t*), ki jih v koordinatnem sistemu predstavimo kot točke *q* = *q* (*t, n*) razpršene okrog ploskve *q'* = *q'* (*t, n*), ki ji pravimo ploskev JTP (jakost, trajanje, pogostost). Točke z enako pogostostjo določajo v linearnem merilu regresijsko krivuljo hiperbolične oblike $q' = C / t^{\alpha}$ (v logaritmičnem merilu pa točke enake pogostosti določajo regresijsko premico) oziroma črtni grafikon, dokler se ne lotimo obdelave podtakov analitično in dokler ostajamo na opisni ravni. Na ravni opisne statistike imamo opravka s t.i. neizravnanimi točkami. Za nadaljnjo analizo je treba uporabiti metodo, s katero krivuljo "izravnamo" in dobimo t.i. izravnane krivulje. Obstaja kar nekaj metod, s katerimi je mogoče analitično izraziti izravnane krivulje GEN.

Do sedaj izvedene enačbe v tuji literaturi imajo praktični pomen le na območjih, od koder izhajajo podatkovne zbirke, zato so za Slovenijo praktično neuporabne (uporabna je struktura enačbe, ne pa tudi parametri). Zato je treba za padavine v naši državi ali natančneje na posameznih območjih Slovenije (za vsako posebej) z regresijsko analizo

The evaluation for each unit of the observed time interval for the whole data set (N years) was performed. All the statistical parameters of the empirical distribution: arithmetic mean *q'*, standard deviation *S*(*Q*), coefficient of asymmetry *Cs*(*Q*), coefficient of variation *Cv*(*Q*) have been calculated.

The results of the evaluation procedures are sets of EDR (Equivalent Design Rainfall) of a certain frequency (*n*), runoff intensity (*q*) and duration (*t*), which are presented in the coordinate system as points *q* = *q* (*t, n*) scattered around the surface *q'* = *q'*(*t, n*) or the IDF plane (Intensity, Duration, Frequency). The points with equal frequency, represented on a linear scale, constitute a regression curve with a hyperbolic shape, $q' = C / t^{\alpha}$ (the same points constitute a regression line on the logarithmic scale) or line graph, as long as the data are analytically treated and as long as one stays on a descriptive level. On the level of descriptive statistics one speaks about non-straightened data and curves. For a further analysis it is necessary to use a method by which the data or the curve is straightened to obtain a straightened curve. There exist several equations with which it is possible to express analytically the straightened EDR curves.

Equations, derived till now in other countries, have practical meaning only for the region where they come from. Therefore, they are more or less useless for Slovenia (the structure can be used, but not the specific parameter values). That is why it is necessary in our country, or even for smaller areas of Slovenia, to find the values of parameters *C* and poiskati parametra C in α regresijske krivulje (hiperbole) oziroma njene linearizacije:

α of the regression curve (of hyperbole) and of its linearization:

$$\log q' = \log C - \alpha \cdot \log t \qquad (9).$$

Vrednosti parametrov določimo z metodo najmanjših kvadratov napake (MNK) ([8] in [10]). Zaradi popačenega merila je treba pri uporabi logaritemskega koordinatnega sistema upoštevati v vsaki točki tudi njeno utež, ki je sorazmerna vrednosti ordinate y. Tako dobimo regresijsko premico $\log q' = \log q'$ ($\log t$, n = konst) v logaritmičnem koordinatnem sistemu. Če v zgornji logaritmični enačbi izrazimo: $y' = \log q'$, $B = \log C$, $-A = \alpha$ in $x = \log t$, preide enačba v splošen izraz za premico. Vrednosti y_k pri posameznih meritvah (k = 1, 2, …) odstopajo od pričakovane vrednosti na premici za napako v_k. Zato pri danih parih vrednosti (x_k,y_k) iščemo parametra A in B tako, da bo vsota kvadratov odmikov posameznih točk od premice, ki jo neznana parametra A in B določata, najmanjša.

Tako dobimo sistem linearnih enačb, za katere pa moramo zaradi loma premice v (T_k) upoštevati napako z $b_k = (B - f_k)$. Zaradi popačenega merila pa upoštevamo še utež (p) premice, ki je sorazmerna vrednosti njene ordinate.

Z dobljenimi rezultati iz splošne enačbe za izenačevalno premico izračunamo še vrednost konstante C za obravnavani odsek: $\log C = B - A \log t(T_k)$. Postopek ponovimo za vse odseke GEN.

Parameter values are determined with the Least Square Error (LSE) method ([8] and [10]). Due to the distorted scale, it is necessary in an application of the logarithmic coordinate system to take into account, for each point, also its weight, which is proportional to the ordinate value. The result is a straight line, $\log q' = \log q'$ ($\log t$, n = const), in the logarithmic coordinate system. When we set in the above logarithmic equation: $y' = \log q'$, $B = \log C$, $-A = \alpha$ and $x = \log t$, we obtain a general expression for a straight line. The values of y_k of the distinct measurements (k = 1, 2, …) deviate from the expected value on the straight line for the error v_k. Thus, our task is to find parameters A and B in such a way as to minimise the sum of the squared errors for all pairs of (x_k, y_k).

So, we get a system of linear equations. Still, we have to take into account breaks of the straight line in T_k, i.e., to account for the correction of $b_k = (B - f_k)$. Owing to the distorted scale of the logarithmic coordinate system used for straightening, a weight (p) proportional to the ordinate value must be applied, too.

Then, the value of the constant C can be obtained from the general equation for the regression line at the investigated section: $\log C = B - A \log t(T_k)$. This procedure is repeated for all sections of the EDR.

2 RAČUNALNIŠKI MODELI ZA NAPOVEDOVANJE GEN

Iz časovne vrste za 32 let za padavine na območju Ljubljane je bilo treba pregledati okoli 3,4 milijona podatkov. Za branje in vrednotenje podatkov smo izdelali več programov v C^{++} in Excelu. Po ovrednotenju smo poiskali analitični izraz (parametra 10^A in 10^B) za krivulje konstantne pogostosti, ki se jim dobljene točke (t_k, q_k), k = 1, 2, … $m(n)$ kar se da dobro prilegajo.

Osnovna oblika arhiviranih digitalnih padavinskih podatkov je podana v preglednici 1. Vsaka vrstica je sestavljena iz 50 mest (znakov); vsebuje (1) - šifro opazovalne postaje (5 mest), (2) - leto (3 mesta), (3) - mesec (2 mesti), (4) - dan (2 mesti) in (5) - uro (2 mesti) pojava padavin ter (6) – (17) - 12 podatkov za 5-minutno količino padavin (12×3 mesta).

2 COMPUTER MODELS FOR THE PREDICTION THE EDR

From the precipitation time series for 32 years for Ljubljana it was necessary to manipulate about 3.4 million data points. Several programs in C^{++} and Excel were written for data preparation and evaluation. After that, an analytical expression was sought for the parameters (10^A and 10^B) of the lines (curves) for the given frequencies, which the points (t_k, q_k), k = 1, 2, … $m(n)$ should fit as well as possible.

The basic form of archived digital precipitation data is given in table 1. Every row consists of 50 places (characters). It contains (1) - the code of the measuring station (5 places), (2) - the year (3 places), (3) - the month (2 places), (4) - the day (2 places) and (5) - the hour of beginning of precipitation and (6) – (17) - 12 data points for 5-minute rainfalls (12×3 places).

Preglednica 1. *Prikaz podatkov za 28.12. do 30.12.1979, kakor so zapisani v elektronskem arhivu [9]*
Table 1. *Presentation of the data for 28.12. to 30.12.1979 as they are written in electronic form [9]*

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]
192	979	12	28	19	0	0	0	0	1	1	2	5	5	1	1	0
192	979	12	28	20	0	1	0	0	1	0	1	1	1	1	1	0
192	979	12	28	21	0	1	0	1	0	0	1	0	0	1	0	0
192	979	12	28	22	1	0	1	1	1	0	1	1	1	1	1	1
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
192	979	12	29	11	0	0	0	0	1	0	0	0	0	0	0	0
192	979	12	30	8	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88

Pomen šifer: -88 sneg; Meaning of codes: -88 snow

Zaradi nepreglednosti tako zapisanih podatkov bi bilo pri vrednotenju trajanja in poteka posameznega deževja zelo težko izhajati iz podane osnovne oblike zapisa.

Zato sta bila v Excelu izdelana algoritem in računalniški program SURED. Kot primer rezultatov programa so v preglednici 2 prikazani obdelani podatki za isto obdobje kakor v preglednici 1.

Za določitev največjih mesečnih vrednosti smo izdelali program SORTMAX. Z vpeljavo sestavljenih deževij, ki imajo prekinitev dežja krajšo od 5 minut, dobimo deževja, ki trajajo dlje in zato zmanjšamo njihovo skupno število. Za primer: v letu 1996 dobimo namesto 2 396 enostavnih deževij le 1 476 sestavljenih deževij, za celotno obdobje pa se povprečno število 1 589 deževij zmanjša na 1 011 sestavljenih deževij na leto.

Za časovne korake naliva, ki so daljši od 5 minut, lahko dobimo tudi informacijo o povečani

Because of the lack of clarity of such coded data in view of the duration and evolution of rainfall it would have been a very difficult task to start the evaluation from the given basic form of the data.

Thus, an algorithm *SURED* was derived and programmed in Excel. An example of the result using this program is shown in Table 2 for the same period as in the previous Table 1.

The SORTMAX program was developed to determine the maximum monthly values. With the introduction of composite rains, which have a break in rainfall shorter than 5 minutes, one can obtain longer rainfalls and thus reduce their total number. As an example, 1 476 composite rainfalls instead of 2 396 elementary rainfalls were obtained for the year 1996, while an average of 1 589 rainfalls per year for the whole period is reduced to 1 011 composite rainfalls per year.

A higher intensity of runoff for the time intervals higher than 5 minutes can also be obtained.

Preglednica 2. *Primer preureditve podatkov s programom SURED*
Table 2. *An example of the data rearrangement with the program SURED*

Zap. št. deževja Consec. no. of rainfall	Začetek Beginning		Konec End		Skupni čas trajanja Total duration of rainfall	Skupna višina padavin Total rainfall depth	Intenzivnost padavin po 5 minut Intensity of 5 minute rain
	datum date	ura hour	datum date	ura hour	[min]	[mm]	[mm]
1777/79	28.12.	18:20	28.12.	18:55	35	1,6	0,1 0,1 0,2 0,5 0,5 0,1 0,1
1778/79	28.12.	19:05	28.12.	19:10	5	0,1	0,1
1779/79	28.12.	19:20	28.12.	19:25	5	0,1	0,1
1780/79	28.12.	19:30	28.12.	19:55	25	0,5	0,1 0,1 0,1 0,1 0,1
…	…	…	…	…	…	…	…
1786/79	28.12.	21:10	28.12.	21:25	15	0,3	0,1 0,1 0,1
1787/79	28.12.	21:30	28.12.	22:40	70	1,7	0,1 0,1 0,1 0,1 0,1 0,1 0,2 0,1 0,1 0,2 0,1 0,1 0,2 0,1

potrebni jakosti odtoka. Višine padavin v mm zapišemo v enorazsežno matriko. Za vsako določeno trajanje izberemo samo en delni naliv, in sicer tistega, ki od vseh z enakim trajanjem izkazuje največjo jakost (q_{max}).

Dobljenim rezultatom mesečnih skrajnosti (največjih jakosti odtoka q_{max}) za posamezne časovne korake nalivov je treba poiskati ustrezne verjetnosti pojava oz. njihovo relativno pogostost, kar smo storili z uporabo Hazenove empirične in teoretične porazdelitvene funkcije. Pri izračunu upoštevamo vse rezultate (nalivov po jakosti navzdol ne omejimo) za vsa možna trajanja, to je do 1 080 minut (18 ur). Izračun poteka po celicah preglednice za vsak časovni korak posebej (t = 5, 10, 15, 20, 30, ..., 1 080 minut). Delne nalive enakega trajanja razvrstimo od največje vrednosti q_{max} proti najmanjši in po empirični enačbi [7] za vsako razmerje q_{max}/q'_p (q'_p…srednja vrednost podatkov) posebej. Iščemo, kakšna je verjetnost P_e, da se bo pojavila večja ali enaka vrednost od m-te v nizu, če je m rang podatka v ranžirni vrsti. P_e je dejansko kvantilni rang pojava in ga v odstotkih zapišemo:

Rainfall depths [mm] are recorded in a one-dimensional matrix. For each fixed duration of observation only one partial rainfall is chosen, namely that which shows the maximum intensity (q_{max}) from all the rainfalls with the same duration.

Then it is necessary to find out the probability of the occurrence or the frequencies corresponding to the obtained results of the monthly maximal intensities of runoff (q_{max}), which can be done by means of Hazen‘s empirical and theoretical distribution function. In this computation all the results (there is no lower limit for rainfall intensities) for all possible duration times with the same time intervals up to 1080 minutes (18 hours) were taken into account. The computation runs in the cells of the table for each time interval separately (t = 5, 10, 15, 20, 30, ..., 1 080 minutes). The partial rainfalls of the same duration are arranged from the highest q_{max} to the lowest value, and by means of the empirical equation [7] it is sought for each ratio q'_{max}/q'_p (q'_p… mean value of data). It is sought the probability of the occurrence P_e of a higher or equal value than the m-th in a set, provided that m is the rank of the datum in the ranking list, while P_e is indeed the quantile rank of the event and is written as:

$$P_e[\%] = \frac{m-0{,}5}{n} \cdot 100 \qquad (10).$$

Iz urejenega niza podatkov izračunamo empirične statistike. Ker je koeficient asimetrije bistveno odvisen od števila statističnih podatkov, so lahko zaradi majhnega števila podatkov ocene povprečja netočne. Da bi se izognili podcenjevanju asimetrije zaradi majhnega števila istovrstnih podatkov (n), smo upoštevali popravni faktor:

Experimental values of the parameters are computed from the ordered set of data. The coefficient of asymmetry is very dependent on the number of data, i.e., a low number of data can result in inaccurate estimations of the median or other quantiles. To avoid underestimations of the asymmetry due to a small number of data (n) of the same rank we used the correction factor:

$$F = 1 + \frac{8{,}5}{n} \qquad (11).$$

Tako dobimo prirejeni koeficient asimetrije, ki je definiran kot:

In this way, we obtain an adjusted asymmetry coefficient which is defined as:

$$C_{s(prir)} = C_s \cdot F \qquad (12).$$

Na podlagi empirično dobljenih parametrov porazdelitve poiščemo tako teoretično porazdelitev, ki najbolj ustreza našim empiričnim podatkom. Uporabili smo zopet Hazenovo porazdelitev. Ta temelji na predpostavki, da se ekstremni pojavi porazdeljujejo zelo asimetrično, zato normalna aproksimacija nikakor ni primerna, pač pa logaritmična normalna krivulja verjetnostne gostote ustrezneje opiše pojav. Izhajamo iz splošne enačbe za hidrološko frekvenčno analizo:

On the basis of the empirically obtained distribution parameters, a theoretical distribution that best fits the empirical data is sought. Hazen‘s distribution was applied here. It is based on the assumption that extreme events, which usually form an asymmetric curve, better fit to the log-normal curve, which is a result of the logarithmic distribution, than to the normal distribution function. We are starting from the general equation for the hydrologic frequency analysis:

$$x = \mu + \Delta x \quad (13),$$

kjer je $\Delta x = \sigma \cdot K_H$ (σ je standardni odklon in K_H je frekvenčni faktor po Hazen-u), ter dobimo:

where $\Delta x = \sigma \cdot K_H$ (σ is the standard deviation, and K_H is the frequency factor according to Hazen), we obtain:

$$x = \mu + \sigma \cdot K_H \quad (14).$$

Po deljenju s povprečno vrednostjo preide enačba v obliko:

After division with the mean value this equation has the following form:

$$\frac{x}{\mu} = 1 + C_v \cdot K_H \quad (15),$$

kjer je $C_V = \sigma / \mu$ ustrezni koeficient variacije pojava. S statistikami empirične porazdelitve zapišemo pričakovano razmerje med največjo in srednjo jakostjo nalivov nespremenljive frekvence:

where $C_V = \sigma / \mu$ corresponds to the coefficient of variation. Using the statistics of an empirical distribution, the expected ratio between the maximum and mean rainfall intensity by selected frequency is:

$$\frac{x}{\overline{x}} = \frac{q'_{\max}}{q'_p} = 1 + C_v \cdot K_H \quad (16)$$

$$C_v = \frac{S}{\overline{x}} \quad (17).$$

Pri vrednotenju nalivov na ljubljanskem območju smo si delo poenostavili z računalniškim programom STEVP, ki določi odločujoče delne nalive in njihove jakosti ter nalive še prešteje. Pri pisanju programa se je izkazalo, da je zagotavljanje pogojev, da se zaporedja enojnih nalivov, ki jih upoštevamo v eni kombinaciji, ne smejo prekrivati, zelo težavno. Na sliki 1 je prikazan alogaritem iskanja in zapisa delnih nalivov iz sestavljenega naliva.

Further work on the evaluation of rainfall data has been simplified with the computer program *STEVP,* which determines the relevant partial rainfalls, their intensities and counts their number. At the time of writing the program it turned out that it is difficult to satisfy the condition that groups of single rainfalls, considered in one combination, should not overlap. In Figure 1 is the algorithm for searching and recording partial rainfalls from combined rainfalls.

3 REZULTATI IN RAZPRAVA

3 RESULTS AND DISCUSSION

Končno vrednotenje je opravljeno s programom KONPAD v C++, ki je rezultate predhodnih treh programov uporabil kot vhodne podatke.

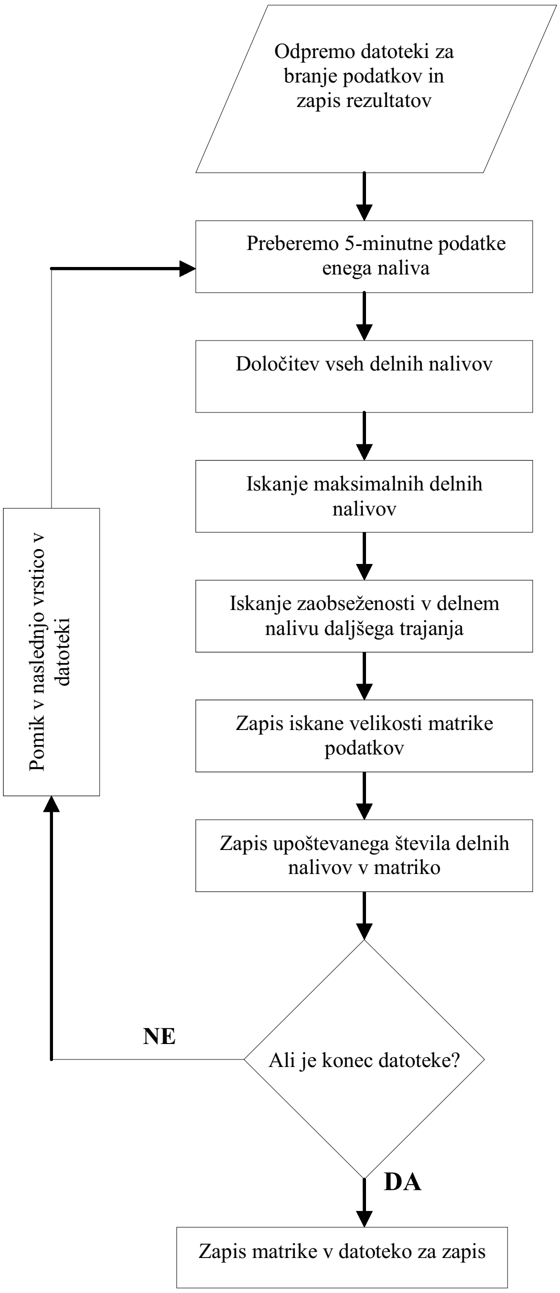
Program rezultate izpiše v tri datoteke, in sicer v prvo preglednico prikaze ovrednotenih nalivov, v drugo preglednico preštete delne nalive po času trajanja in velikosti jakosti odtoka in v preglednico 3 vsa deževja.

Na sliki 2 je prikazana primerjava našega (IZH2) stohastičnega modeliranja za obdobje (1965 do 1996) s predhodno analizo Sketlja [1] (IZH1) za obdobje (1921 do 1946) ter dveh izračunih Agencije RS za okolje, Urada za meteorologijo (HMZ) za Bežigrad (HMZ1: 1948 do 1998) in Kleče (HMZ2: 1979 do 1989), ki ne upošteva delnih nalivov znotraj sestavljenega naliva. Vidimo, da so njihove vrednosti jakosti nalivov nižje, kar je bilo seveda treba pričakovati.

The final evaluation was carried out with the program KONPAD in C++ , which used results of the former three programs as input data.

This program writes the results in three files, namely, in the first table is a presentation of the individual evaluated rainfalls, in the second table are counted partial rainfalls according to their duration and intensity of runoffs, and in Table 3 are all the rainfalls.

Figure 2 shows a comparison of our stochastic model (IZH2) for the period (1965 to 1996) with previous computations of Sketelj [1] (IZH1) period (1921 to 1946) and two analyses of the Environmental Agency of Slovenia, (HMZ) for station Bežigrad (HMZ1: 1948 to 1998) and Kleče (HMZ2: 1979 to 1989), which does not consider elementary rainfalls inside the composite rainfalls. Their values of intensity are lower, which is to be expected.



Sl. 1. *Algoritem za določanje delnih nalivov iz sestavljenih nalivov*

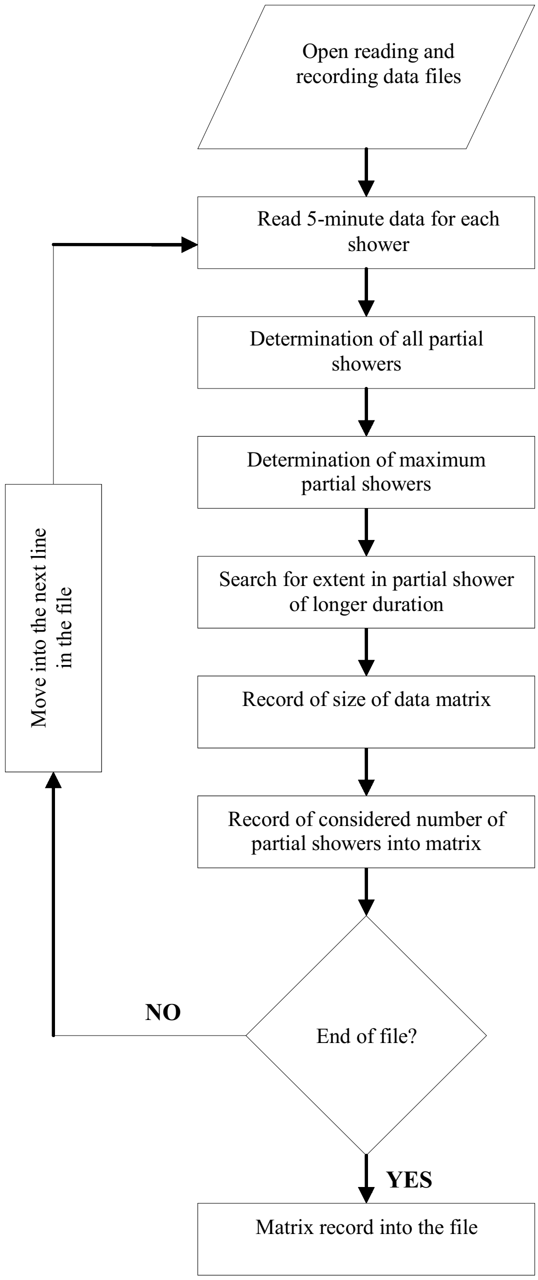


Fig. 1. *Algorithm for establishing partial rainfalls from combined rainfalls*

4 SKLEPI

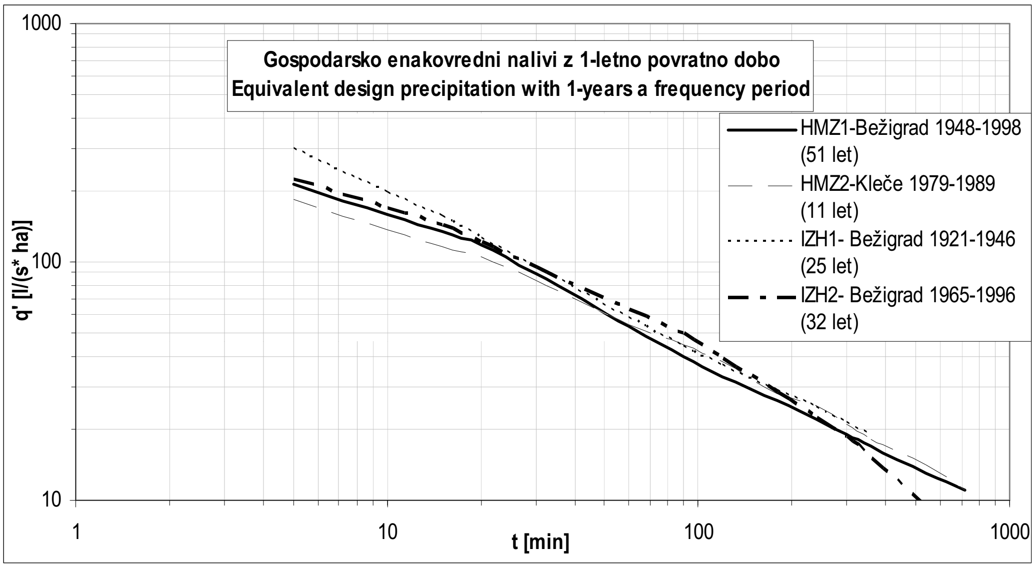
Izdelali smo računalniško ovrednotenje padavinskih podatkov in ga uporabili na primeru Ljubljane za obdobje let 1965 do 1996. Z računalniškimi programi v C^{++} in Excelu (SURED, SORT-MAX, STEVP in KONPAD), smo ugotavljali

4 CONCLUSIONS

A computer evaluation of precipitation data was developed and applied in the case of Ljubljana for the period 1965 to 1996. Using computer programs in C^{++}and Excel (SURED, SORTMAX, STEVP, and KONPAD) the maximum intensities of all rainfalls,

Preglednica 3. *Prikaz jakosti padavin po naključnostnem modelu*
Table 3. *Presentation of the intensities of rainfalls according to the stochastic models*

IZH2- naključnostni model IZH2-stochastic analysis		Jakost padavin [l/(s.ha)] Intensity of rainfall [l/(s.ha)]											
1965-1996 (32 let/years)		Trajanje naliva / Rainfall duration Minute/Minutes											
Povratna doba Return period	Pogostost Frequency	**5**	**10**	**15**	**20**	**30**	**60**	**90**	**120**	**180**	**240**	**300**	**360**
100 let/ years	**0,01**	633,3	486,5	416,9	373,7	320,3	213,3	168,2	142,1	112,0	67,3	45,3	32,8
25 let/ years	**0,04**	504,5	381,9	324,5	289,1	245,6	168,2	134,7	115,1	78,3	51,6	37,4	28,7
20 let/ years	**0,05**	484,1	365,3	309,9	275,7	233,8	158,9	126,8	108,0	73,7	49,2	35,9	27,8
10 let/ years	**0,1**	420,6	313,8	264,4	234,1	197,3	130,1	101,9	85,7	59,6	41,6	31,4	25,0
5 let/ years	**0,2**	361,8	267,7	224,5	198,1	166,1	107,8	83,8	70,0	49,4	35,5	27,4	22,2
2 leti/ years	**0,5**	280,3	211,1	178,8	151,9	120,6	81,3	64,6	50,5	35,8	28,0	23,1	18,8
1,5 let/ years	**0,67**	256,5	193,3	163,9	138,8	109,8	73,6	58,2	45,8	32,7	25,7	21,3	16,9
1 leto/ year	**1**	223,9	168,9	143,3	121,1	95,5	63,6	50,1	39,6	28,4	22,4	18,7	15,1
8 mes./ months	**1,5**	192,8	143,2	120,4	106,4	81,2	51,1	38,9	32,1	24,5	20,2	17,4	13,3
6 mes./ months	**2**	169,5	126,0	105,9	93,7	71,2	44,6	33,9	27,9	21,2	17,5	15,0	11,3
4 mes./ months	**3**	135,3	100,8	84,9	75,1	57,3	36,1	27,5	22,7	17,3	14,3	12,3	8,6
3 mes./ months	**4**	110,6	82,7	69,7	61,8	47,1	29,7	22,6	18,7	14,2	11,7	10,1	8,9
2 mes./ months	**6**	74,6	56,1	47,5	42,2	32,7	21,1	16,4	13,6	10,6	8,8	7,7	



Sl. 2. *Grafična primerjava različnih obdelav GEN za Ljubljano z enoletno povratno dobo (IZH2 je rezultat te študije)*
Fig. 2. *Graphical comparison of different EDR evaluations for Ljubljana for a frequency of 1 year (IZH2 is result of present study)*

največje jakosti vseh nalivov, vključno z delnimi nalivi znotraj sestavljenih nalivov do trajanja 18 ur. Kot rezultat so podani gospodarsko enakovredni nalivi - GEN $q' = q'(t, n)$ v preglednični in grafični obliki (diskretne vrednosti na ploskvi enakovrednih nalivov). Poiskali smo parametre splošne hiperbole

including partial rainfalls within composite rainfalls up to 18 hours, were determined. Equivalent Design Rainfalls (EDRs) $q' = q'(t, n)$ are given as results in tabular and graphical forms (discrete values on the plain of equivalent rainfalls). The parameters of the general hyperbola were sought for each frequency za vsako frekvenco *n* prek lineariziranega zapisa odnosov med obravnavanimi kazalci, ki opisujejo naliv. Parametre smo določili po metodi najmanjših kvadratov z upoštevanjem uteži zaradi logaritemskega merila. Rezultati statističnega vrednotenja tega stohastičnega obnašanja padavin IZH2 so primerjani s prejšnjimi izračuni IZH1 in HMZ1 ter HMZ2 (sl. 2).

V povprečju so rezultati le malo nižji od prejšnjih izsledkov IZH1. Za celoten niz GEN smo povzeli, da so ujemanja naših rezultatov zelo dobra, predvsem še v časovnem odseku 30 do 60 minut. Rezultati jakosti nalivov so za te časovne korake celo višji, in to pri nižjih pogostostih (od $n = 1$ do $n = 0,1$), kar se ujema z izkušnjami zadnjih let (manj povprečnih letnih padavin in več močnejših nalivov kratkega trajanja). Tako so npr. nalivi na območju Ljubljane, ki so trajali 60 minut pogostosti $n = 1$ po IZH2 jakosti 63,6 l/(s.ha), po IZH1 62,5 l/(s.ha) in po HMZ1 54 l/(s.ha). Vidimo, da se razlikujejo le malo. Za naliv $t = 15$ min, $n = 1$, ki se najpogosteje uporablja za oblikovanje, pa je po IZH2 143,3 l/(s.ha), po IZH1 160,6 l/(s.ha) in po HMZ1 135 l/(s.ha). Spodnja meja vrednotenja, ki za mejne vrednosti upošteva jakosti odtoka pogostosti več ko $n = 6$, pa se ujema na 1 l/(s.ha) natančno.

Z manjšimi popravki so programi uporabni tudi za obdelavo podatkov za katerekoli druge postaje v Sloveniji ali druga obdobja.

n, using linearized relationships among the functions that describe a rainfall. Parameters values were determined by the least square error method taking into account weights due to a logarithmic scale. The results of our evaluation IZH2 by means of the stochastic models are compared with previous calculations IZH1 and HMZ1, HMZ2 (Fig. 2).

On average the results are only slightly lower than previous computations IZH1. For the complete set of EDRs it was concluded that the agreement is good, especially for the time interval of 30–60 minutes. The results of the rainfall intensities are even higher for these time intervals at lower frequencies (from $n = 1$ to $n = 0,1$), which is in agreement with experiences over the last few years (lower average annual rainfall and more rainfalls of higher intensities and short duration). The rainfalls of 15 minutes duration and frequency $n = 1$ by IZH2 are 63.6 l/(s. ha), by IZH1 62.5 l/(s.ha) and by HMZ 1 54 l/(s.ha). The differences are minimal. For the rainfall of $t = 15$ min. and $n = 1$, which is frequently used in drainage design the intensity by IZH2 is 143.3 l/(s.ha), by IZH1 160.6 l/(s.ha) and by HMZ1 135 l/(s.ha). The lower limit of evaluation, which takes into account runoff intensities with a frequency greater than $n = 6$, is in accordance within 1 l/(s·ha) precision.

With minor changes, the computer programs are also applicable for data processing for other stations in Slovenia or for other periods.

5 OZNAKE
5 NOMENCLATURE

konstanta	C		constant
porazdelitvena funkcija	CDF		Cumulative Distribution Function
Gospodarsko Enakovredni Nalivi	GEN/EDR		Equivalent Design Rainfall
višina padavin	h	mm	depth of rainfall
intenziteta padavin	i	mm/h	rainfall intensity
JTP ploskev (jakost, trajanje, pogostost)	IDF		plane (Intensity, Duration, Frequency)
zaporedna številka podatka q'_{max}	m		consecutive number of data q'_{max}
pogostost	n		frequency
število let	N		number of years
verjetnost pojava višje ali enake vrednosti	P		probability of occurrence of a higher or equal value
izmerjena vrednost padavin	q	mm/h	measured unit intensity of a runoff
vrednost spremenljivke za pojav, ki ima v hidrološki seriji povratno dobo T	q_i		value of the variable for the event having a return period T in a hydrological series
enotska jakost padavin	q'	l/(s.ha)	expected unit intensity of a runoff at f(n,t)
opazovani pojav	Q		an observed event
povratna doba	T		return period
trajanje naliva	t, t_r	min	duration of a rainfall
smerni koeficient premice	α		slope of the line
pričakovana vrednost (matematično upanje)	μ		mean value (mathematical expectation)

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Osebne vesti - Personal Events

Prof.dr. Peter Leš
1937 - 2005

Prof. dr. Peter Leš se je rodil 18. julija 1937 leta v Novem Sadu. Od leta 1943 do 1945 je bil v nemških taboriščih. Leta 1950 je končal OŠ Ivana Cankarja v Mariboru. V šolskem letu 1951/52 se je vpisal v pomorsko srednjo šolo v Piranu in jo leta 1956 končal. Po srednješolki maturi se je zaposlil v ladjedelnici Piran, kjer je v treh mesecih kot vodja skupine za remont in montažo opravil generalno popravilo zapuščenega diselskega motorja z močjo 600 KM za prvo slovensko ribiško ladjo za novo ustanovljeno ribiško podjetje v Izoli. Leta 1956 se je zaposlil pri Splošni plovbi v Piranu, kjer je služboval kot asistent stroja na različnih prekooceanskih parnih in motornih ladjah in pri tem opravljal remontna in vzdrževalna pripadajoča dela na parnih kotlih, pogonskih in pomožnih strojih oziroma motorjih. Leta 1959 je pred komisijo uprave pomorske oblasti za južni Jadran v Boki Kotorski opravil izpit za naziv pomorskega strojnega oficirja. Leta 1959/60 se je vpisal na Fakulteto za strojništvo v Ljubljani in diplomiral leta 1964 pri prof. F. Lobetu iz področja obdelovalnih strojev. V jeseni leta 1964 se je zaposlil v tovarni avtomobilov TAM v Mariboru v Odd. za vzdrževanje obdelovalnih strojev. Zaposlitev je prekinil zaradi odsluženja rednega vojaškega roka. Po odslužitvi vojaškega roka se je ponovno zaposlil v TAM-u in sicer najprej v karosernici kot obratni inženir, kasneje pa je prevzel v tehnološki pripravi oddelek za preizkušanje tehnologije, ki je obsegala preizkuševalna dela tehnologičnosti in osvajanje novih proizvodov v mehanski obdelavi, karosernici, kovačnici, toplotni obdelavi in montaži. Hkrati je kot vodja oddelka sodeloval pri večjih projektih osvajanja proizvodnje, razvoja in novih ter izpopolnjenih vozil kot tudi na projektih uvajanja mrežnega planiranja in uvajanja avtomatske obdelave podatkov. S svojim delom je neposredno sodeloval pri preizkušanju novih orodij in naprav, namenjenih predvsem preoblikovalnim postopkom.

Leta 1967 je bil prvič na VTŠ-u izvoljen v naziv »asistent« ter nato v isti naziv še leta 1970 in 1973.

Magistriral je leta 1975 v Zagrebu na Fakulteti za strojništvo in ladjedelništvo (FSB). Doktoriral je leta 1980 prav tako na FSB v Zagrebu z naslovom »Hladno oblikovanje sinterovanih metala«.

Leta 1975 je bil izvoljen v naziv »predavatelja« v. š., 1976 »profesor« v. š. in 1981 v naziv »izredni profesor«. V naziv »redni profesor« je bil izvoljen leta 1987.

Veliko truda in znanja je vložil v svojo akademsko kariero. Znanje iz stroke je poglabljal z delom na priznanih inštitutih v tujini, posebej bi omenil uspešno sodelovanje s profesorjem Langejem iz TU Stuttgart. Prav tako bi omenil njegove povezave z domačimi univerzami in predvsem tudi z industrijo. Povedati moram, da je znal svoje praktične izkušnje koristno prenašati na študente in strokovnjake iz prakse.

Znanstveno raziskovalna dejavnost prof. dr. Petra Leša je dokumentirano tako z rezultati raziskav, posebnih nalog, kakor tudi s prenosom rezultatov v prakso. Kot član vodstva strokovnega združenja Zajednica naučno-istraživačkih institucija proizvodnog mašinstva Jugoslavije in uredniškega odbora časopisa »Obrada metala deformisanjem« ter programskega sveta za usposabljanje tehnično-tehnoloških delavcev pri GZS je intenzivno skrbel za prenos novih dosežkov v prakso, za uveljavljanje novih spoznanj in usposabljanje kadrov. Posebno zavzeto je sodeloval na domačih in mednarodnih seminarjih in simpozijih, kjer je predstavljal domače raziskovalne dosežke. Uveljavljanje novih tehnologij je bila njegova pomembna naloga, ki jo je tudi z uspehom izvajal in ob tem uporabljal sodobne metode reševanja tehnoloških problemov.

Na Fakulteti za strojništvo Univerze v Mariboru (FS) je bil predstojnik Katedre za materiale in preoblikovanje, predstojnik Inštituta za tehnologijo materialov, vodja Laboratorija za preoblikovanje gradiv, član Senata in član Upravnega odbora FS. Več let je bil tudi član Uredniškega odbora Strojniškega vestnika.

Prof. dr. Peter Leš je vzgojil preko 200 inženirjev in diplomantov, ki so danes uspešni strokovnjaki in manegerji v naših podjetjih. Prav tako je bil tudi uspešen mentor in komentor na podiplomskem študiju.

Njegova pedagoška dejavnost je bila vedno ocenjena kot zelo uspešna. Zaradi tega mu je bilo tudi poverjeno predavanje na podiplomskem študiju in izbran je bil za člana evalvacijske skupine za tehnologijo Zavoda SRS za šolstvo. Posebej je potrebno omeniti njegove učbenike, skripta in študijske pripomočke, ki so bili vedno vzorno in temeljito pripravljeni.

Dekan, prof.dr. Andrej Polajnar

Doktorati, magisteriji in diplome - Doctor's, Master's and Diploma Degrees

DOKTORATI

Na Fakulteti za strojništvo Univerze v Ljubljani so z uspehom zagovarjali svoje doktorske disertacije:

dne *7. junija 2005*: **mag. Martin Zupančič**, z naslovom: "Izločevalno utrjevanje in lastnosti maraging jekla";

dne *16. junija 2005*: **mag. Ferdinand Deželak**, z naslovom: "Vplivi prehodnih pojavov pri impulznem hrupu na energijski ekvivalent";

dne *29. junija 2005*: **mag. Robert Cvelbar**, z naslovom: "Interkonverzija materialnih funkcij viskoelastičnih materialov";

dne *25. julija 2005*: **mag. Primož Čermelj**, z naslovom: "Karakterizacija dinamičnega obnašanja kompleksnih struktur z lokaliziranimi nelinearnostmi".

Na Fakulteti za strojništvo Univerze v Mariboru sta z uspehom zagovarjala svoji doktorski disertaciji:

dne *1. junija 2005*: **mag. Tone Lehrer**, z naslovom: "Model načrtovanja regalnih skladiščnih sistemov";

dne *18. julija 2005*: **mag. Zvonko Kremljak**, z naslovom: "Hevristični model za upravljanje razvoja sposobnosti, podprt s teorijo stvarnih opcij".

S tem so navedeni kandidati dosegli akademsko stopnjo doktorja znanosti.

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S tem so navedeni kandidati dosegli akademsko stopnjo magistra znanosti.

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Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:

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dne *26. junija 2005*: Boštjan JEVNIK, Andraž KOSI, Samo MLAKAR, Rok OGRIN;

dne *27. junija 2005*: Denis PORENTA, Matej PUŠLAR, Sven BOŽIČ;

dne *28. junija 2005*: Simon MUSTAR, Janez KOŠIR, Matjaž BUTALA;

dne *29. junija 2005*: Klemen HUDOKLIN, Tadej ISKRA, Ivan KLANČIŠAR, Janko KOCJAN, Dragan MLADENOVIČ.

Na Fakulteti za strojništvo Univerze v Mariboru so pridobili naziv diplomirani inženir strojništva:

dne *23. junija 2005*: Edvard BOKAN;

dne *28. junija 2005*: Danilo FRAS, Rafko GRUDEN, Miran MILFELNER, Bogdan PERNEK, Dušan VRHOVNIK;

dne *30. junija 2005*: Damijan HUNJADI, Boros LOPERT, Peter MIKULJAN, Borut MOHORIČ, Tomaž PERMANŠEK, Milan RAJH, Miro RAKUŠA, Jasna ŠVAGAN, Anton TURINEK, Jožef VOGRINČIČ.

Navodila avtorjem - Instructions for Authors

Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

Strojniški vestnik izhaja od leta 1992 v dveh jezikih, tj. v slovenščini in angleščini, zato je obvezen prevod v angleščino. Obe besedili morata biti strokovno in jezikovno med seboj usklajeni. Članki naj bodo kratki in naj obsegajo približno 8 strani. Izjemoma so strokovni članki, na željo avtorja, lahko tudi samo v slovenščini, vsebovati pa morajo angleški povzetek.

Za članke iz tujine (v primeru, da so vsi avtorji tujci) morajo prevod v slovenščino priskrbeti avtorji. Prevajanje lahko proti plačilu organizira uredništvo. Če je članek ocenjen kot znanstveni, je lahko objavljen tudi samo v angleščini s slovenskim povzetkom, ki ga pripravi uredništvo.

Papers submitted for publication should comprise:
- Title, Abstract, Main Body of Text and Figure Captions in Slovene and English,
- Bilingual Tables and Figures (graphs, drawings or photographs),
- List of references and
- Information about the authors.

Since 1992, the Journal of Mechanical Engineering has been published bilingually, in Slovenian and English. The two texts must be compatible both in terms of technical content and language. Papers should be as short as possible and should on average comprise 8 pages. In exceptional cases, at the request of the authors, speciality papers may be written only in Slovene, but must include an English abstract.

For papers from abroad (in case that none of authors is Slovene) authors should provide Slovenian translation. Translation could be organised by editorial, but the authors have to pay for it. If the paper is reviewed as scientific, it can be published only in English language with Slovenian abstract, that is prepared by the editorial board.

VSEBINA ČLANKA

Članek naj bo napisan v naslednji obliki:
- Naslov, ki primerno opisuje vsebino članka.
- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
- Uvod, v katerem naj bo pregled novejšega stanja in zadostne informacije za razumevanje ter pregled rezultatov dela, predstavljenih v članku.
- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

THE FORMAT OF THE PAPER

The paper should be written in the following format:
- A Title, which adequately describes the content of the paper.
- An Abstract, which should be viewed as a mini version of the paper and should not exceed 250 words. The Abstract should state the principal objectives and the scope of the investigation, the methodology employed, summarize the results and state the principal conclusions.
- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

OBLIKA ČLANKA

Besedilo članka naj bo pripravljeno v urejevalnilku Microsoft Word. Članek nam dostavite v elektronski obliki.

Ne uporabljajte urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata.

Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

THE LAYOUT OF THE TEXT

Texts should be written in Microsoft Word format. Paper must be submitted in electronic version.

Do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering.

Equations should be on a separate line in the main body of the text and marked on the right-hand side of the page with numbers in round brackets.

Enote in okrajšave

V besedilu, preglednicah in slikah uporabljajte le standardne označbe in okrajšave SI. Simbole fizikalnih veličin v besedilu pišite poševno (kurzivno), (npr. *v, T, n* itn.). Simbole enot, ki sestojijo iz črk, pa pokončno (npr. ms^{-1}, K, min, mm itn.).

Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti v **slovenskem jeziku**, npr. časovno spremenljiva geometrija (ČSG).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v ločljivosti, primerni za tisk, v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Diagrami in risbe morajo biti pripravljeni v vektorskem formatu.

Pri označevanju osi v diagramih, kadar je le mogoče, uporabite označbe veličin (npr. *t, v, m* itn.), da ni potrebno dvojezično označevanje. V diagramih z več krivuljami, mora biti vsaka krivulja označena. Pomen oznake mora biti pojasnjen v podnapisu slike.

Vse označbe na slikah morajo biti dvojezične.

Preglednice

Preglednice morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot preglednica 1, preglednica 2 itn. V preglednicah ne uporabljajte izpisanih imen veličin, ampak samo ustrezne simbole, da se izognemo dvojezični podvojitvi imen. K fizikalnim veličinam, npr. *t* (pisano poševno), pripišite enote (pisano pokončno) v novo vrsto brez oklepajev.

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

Vsa literatura mora biti navedena v seznamu na koncu članka v prikazani obliki po vrsti za revije, zbornike in knjige:

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controller for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.
[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.
[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

Podatki o avtorjih

Članku priložite tudi podatke o avtorjih: imena, nazive, popolne poštne naslove in naslove elektronske pošte.

SPREJEM ČLANKOV IN AVTORSKE PRAVICE

Uredništvo Strojniškega vestnika si pridržuje pravico do odločanja o sprejemu članka za objavo, strokovno oceno recenzentov in morebitnem predlogu za krajšanje ali izpopolnitev ter terminološke in jezikovne korekture.

Avtor mora predložiti pisno izjavo, da je besedilo njegovo izvirno delo in ni bilo v dani obliki še nikjer objavljeno. Z objavo preidejo avtorske pravice na Strojniški vestnik. Pri morebitnih kasnejših objavah mora biti SV naveden kot vir.

Units and abbreviations

Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

All abbreviations should be spelt out in full on first appearance, e.g., variable time geometry (VTG).

Figures

Figures must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Fig. 1, Fig. 2, etc. Pictures may be saved in resolution good enough for printing in any common format, e.g. BMP, GIF, JPG. However, graphs and line drawings sholud be prepared as vector images.

When labelling axes, physical quantities, e.g. *t, v, m,* etc. should be used whenever possible to minimise the need to label the axes in two languages. Multi-curve graphs should have individual curves marked with a symbol, the meaning of the symbol should be explained in the figure caption.

All figure captions must be bilingual.

Tables

Tables must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Table 1, Table 2, etc. The use of names for quantities in tables should be avoided if possible: corresponding symbols are preferred to minimise the need to use both Slovenian and English names. In addition to the physical quantity, e.g. *t* (in italics), units (normal text), should be added in new line without brackets.

All table captions must be bilingual.

The list of references

References should be collected at the end of the paper in the following styles for journals, proceedings and books, respectively:

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controller for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.
[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.
[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

Author information

The information about the authors should be enclosed with the paper: names, complete postal and e-mail addresses.

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