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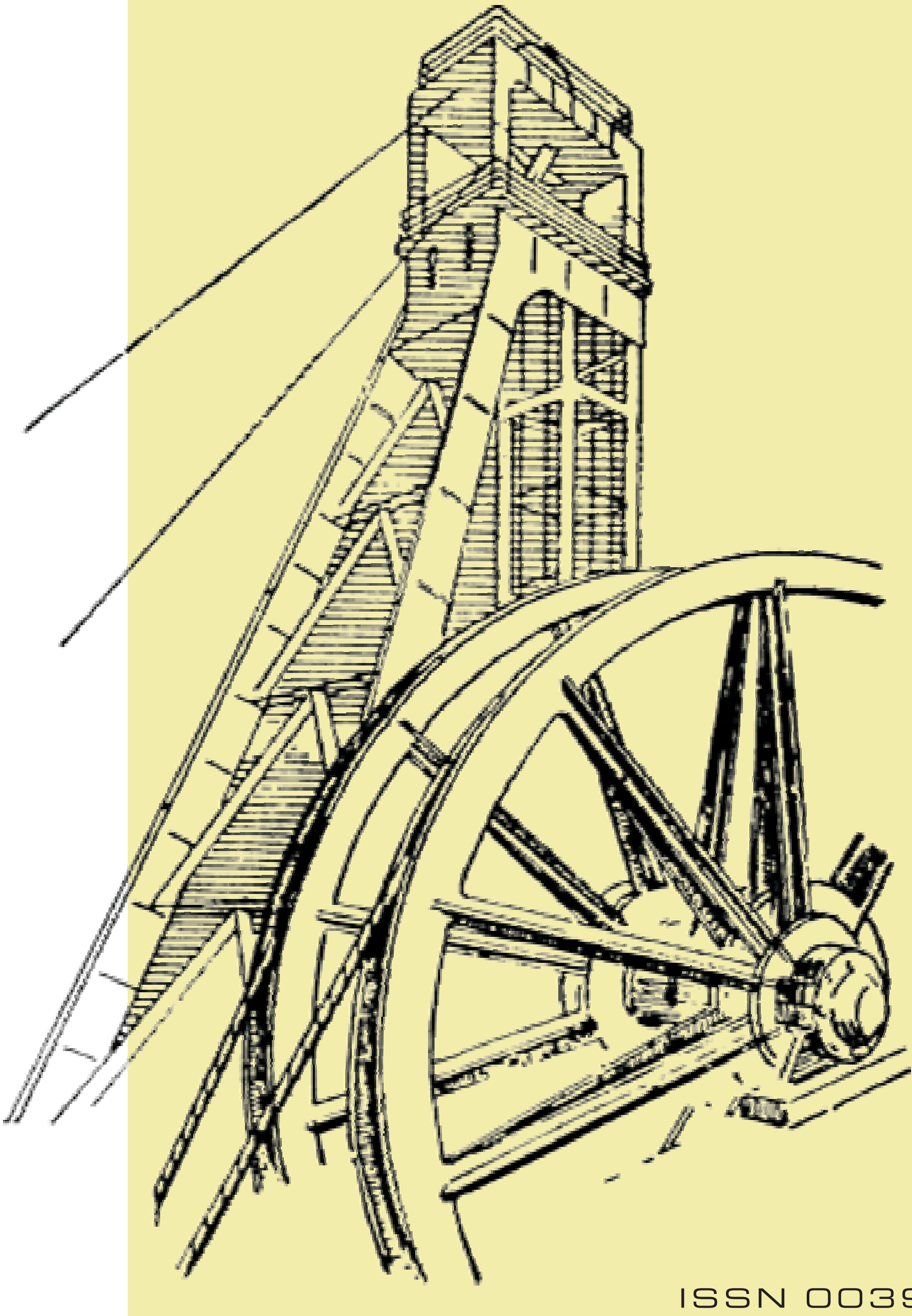

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Hevristični model razvoja proizvodnih zmogljivosti

A Heuristic Model for the Development of Production Capabilities

Zvonko Kremljak - Andrej Polajnar - Borut Buchmeister

Menedžerji v proizvodnih okoljih se pri odločanju srečujejo z visoko stopnjo nezanesljivosti, zaradi hitrih in velikih sprememb, ki opredeljujejo okolja, v katerih delujejo njihove organizacije. Ta pomeni, da menedžerji pri odločanju nimajo popolnih informacij o prihodnjih dogodkih, ne poznajo vseh mogočih alternativ in ne poznajo posledic vseh mogočih odločitev.

Spoprijeti se z negotovostjo pomeni razvijati hevristična orodja, ki lahko ponudijo zadovoljive rešitve, ne pa tudi optimalne. Metode simulacij, ki temeljijo na ekstrapoliranju merljivih podatkov iz preteklosti, niso ustrezne kot pomoč pri odločitvah v okoliščinah negotovosti. V zadnjem času se kot prevladujoča hevristika za reševanje odločitvenih problemov pri visoki stopnji negotovosti pojavlja teorija stvarnih možnosti. Zato se postopki stvarnih možnosti danes uporabljajo za vrednotenje investicij v raziskave in razvoj, v razvoj novih izdelkov, v proizvodno tehnologijo in preostale proizvodne vire. Na inženirskem področju smo priča intenzivnemu razvoju metod, orodij in tehnik, ki sicer po svojem poreklu spadajo na področje uporabne matematike, informacijskih znanosti, operacijskih raziskav in ekonomske teorije (genetski algoritmi, evolucijsko programiranje, genetsko programiranje, mehka logika, nevronske mreže, teorija stvarnih možnosti itn.), se pa zelo uspešno uporabljajo pri reševanju različnih tehničnih optimizacijskih problemov. Teorija stvarnih možnosti se uporablja tudi pri obravnavanju tehnologije, razvoja in raziskav ter proizvodnje. Razmišljanja o uporabnosti teorije stvarnih možnosti so se razširila tudi na področje strateškega menedžmenta.

(Ključne besede: sistemi proizvodni, upravljanje tveganja, teorija stvarnih možnosti, modeliranje negotovosti, mehka logika)

Managers in production environments face a high level of uncertainty in their decision making due to the major, rapidly developing changes defining the environments in which their organisations operate. This means that managers do not possess complete information about future events, do not know all the possible alternatives or the consequences of all their possible decisions.

Overcoming this uncertainty requires the development of heuristic tools, which can offer satisfactory, if not optimal, solutions. Simulation methods based on the extrapolation of available data from the past are unsuitable for help in decision-making processes in uncertain conditions. Lately, the dominant heuristics used for solving decision-making problems during a high level of uncertainty is the theory of real options. For this reason the real-options approach is currently used for an evaluation of the investments in research and development, the development of new products, production technologies and other production sources. As regards engineering, we are witnessing the intensive development of new methods, tools and techniques, which by their origin belong to the field of applied mathematics, information sciences, operational research and economic theory (genetic algorithms, evolution programming, genetic programming, soft logic, neuron networks, the theory of real options, etc.), and are very successfully applied in the solving of various technical optimisation problems. The theory of real options is also used in issues related to technology, research and development, and production. The thoughts on the use of the theory of real options have also spread to the area of strategic management.

(Keywords: production systems, risk management, real option theory, uncertainty modelling, fuzzy logic)

0 UVOD

Odločanje v okoliščinah velike negotovosti postaja eden najbolj raziskovanih pojavov na področjih strateškega menedžmenta, organizacijske teorije, industrijskega inženiringa in menedžmenta razvoja in raziskav. Negotovost je definirana kot značilnost pojava, ki se upira merljivosti in ga je zaradi tega nemogoče učinkovito omejiti na pripadajoče stopnje verjetnosti. V nasprotju z nezanesljivostjo je tveganje merljivo s stopnjami verjetnosti in ga je mogoče upravljati. Nobelovec Arrow [2] predlaga definicijo nezanesljivosti, po kateri ta pomeni, da nikoli nimamo popolnega opisa sveta ali stanja, za katerega verjamemo, da je resničen. Ta definicija pomeni, da verjetnosti, da se kot posledica dejavnosti zgodi dogodek, ni mogoče objektivno določiti, ampak je zgolj rezultat subjektivnih domnev. Neobvladljivost negotovosti še povečujejo človekove spoznavne omejitve. Spoznavna baza človeka sestoji iz predvidevanj o prihodnosti, poznavanja mogočih alternativ in znanja, ki omogoča poznavanje posledic odločitev. Ta spoznavna baza je izrazito omejena in jo opisuje pojav omejene racionalnosti [6].

Ta izhaja iz teorije finančnih možnosti, katere temelje sta postavila nobelovca Black in Scholes [3]. Naključnostna diferencialna enačba, ki sta jo razvila, omogoča vrednotenje finančnih možnosti v okoliščinah negotovosti. Logika finančnih možnosti se je hitro razširila na stvarne možnosti, ki jih obravnava zajeten kup znanstvene literature ([1], [5] in [10]). Finančna možnost predstavlja možnost za nakup ali prodajo finančnega premoženja, ki že obstaja in se prodaja na finančnih trgih v obliki delnic in obveznic. V nasprotju z njo pomeni stvarna možnost možnost za spremembo stvarnega premoženja, virov ali intelektualnih dejavnosti, na primer: postaviti novo tovarno, osvojiti nov trg, razviti novo tehnologijo ali izdelek.

Teorija stvarnih možnosti se je uveljavila kot vodilna hevristika za obravnavanje pojavov, povezanih z negotovostjo. Na prej naštetih znanstvenih področjih se potreba po obvladovanju nezanesljivosti kaže pri razvojno-raziskovalnih projektih, razvoju novih proizvodnih tehnologij, projektih razvoja novega izdelka, investicijah v napredno proizvodno tehnologijo, odločitvah o selitvi proizvodnje in razvoju proizvodnih zmogljivosti, kakor so prilagodljivost v proizvodnji ter obvladovanje kakovosti.

0 INTRODUCTION

Decision-making in high-risk conditions is becoming a common area for research within strategic management organizational theory, research and development management, and industrial engineering. Risk is measurable with probability levels and can thus be managed; however, this cannot be applied to uncertainty. The Nobel Prize winner Arrow [2] proposed an uncertainty theory that suggests that there can never be a perfect definition of the world or conditions for which we believe are real. This definition can be interpreted as such: the probability that an event will occur as a result of our activity cannot be defined objectively, but can only be an outcome of our subjective assumptions. The inability to master uncertainty only enhances human cognitive limitations. The human cognitive base comprises future predictions, potential alternative options and the ability to foresee the consequences of a decision. This cognitive base is very limited and can be described by the phenomenon called Bounded Rationality [6]. It outlines that in decision-making, managers do not have complete data on future-event occurrences and therefore cannot predict all the possible alternatives or forecast all the consequences of their decisions.

It is derived from the Financial Options Theory, which was developed by the Nobel Prize winners [3] Black and Scholes. The stochastic differential equation they developed enables the assessment of financial options in uncertain conditions. Financial Options logic rapidly developed into Real Options, which is outlined in a sizable amount of scientific literature ([1], [5] and [10]). The Financial Option presents a purchase or a sales option for financial assets, which already exist and are being sold in financial markets in the form of stock and bonds. The Real Option, on the other hand, represents an option for real asset change, source and intellectual activity change, for example, building a new factory, conquering new markets and developing new products or technologies.

The Real Options theory has become the leading heuristic for dealing with uncertainty phenomena. The need to manage uncertainty in the above-mentioned scientific fields is most apparent with research and development projects, new production technology development, new product development projects, advanced production technology investments, production migration decisions and production capabilities development, such as production flexibility and quality management.

1 TEORETIČNO OZADJE

Pomembna literatura obravnava problematiko odločanja v pogojih negotovosti le delno. Trenutno potekajo najbolj izrazite raziskave na področju večkriterijskega odločanja, podprtega z izvedenskimi sistemi. Ne glede na pomemben razvoj so problemi, povezani z izbiro ustreznih metod za zapletene in mehko strukturirane odločitvene probleme, z merskimi lestvicami, statistično interpretacijo, sistemsko optimizacijo ter ciljnimi funkcijami pri večkriterijskih problemih nezadostno obravnavani in hkrati ne rešeni.

Različni avtorji ([4], [11], [12] in [15]) trdijo, da pomeni teorija stvarnih možnosti pravšnjo hevristiko za upravljanje postopka razvoja zmogljivosti. Zmogljivost je definirana kot organizacijsko znanje podjetja, ki omogoča izvajaje poslovnih postopkov [8]. Strateška šola dinamičnih zmogljivosti trdi, da zmogljivosti zaradi svojih značilnosti, kakor so sistemska zapletenost in zgodovinska odvisnost, pomenijo temelje za doseganje trajnih konkurenčnih prednosti ([7], [9], [13] in [16]). Iste značilnosti, ki delajo zmogljivosti težko posnemljive in težko prenosljive in zato strateško vredne, omejujejo možnosti uspešnega upravljanja postopka razvoja zmogljivosti. Ta je opredeljen z visoko stopnjo negotovosti in zato se teorija stvarnih možnosti pojavlja kot hevristika, s potencialom pomagati menedžerjem pri upravljanju postopka razvoja zmogljivosti.

1.1 Opredelitev termina negotovost

O gotovosti v organizacijskem sistemu govorimo, kadar usposobljen posameznik sprejema odločitve, povezane z delovanjem organizacijskega sistema, pri čemer ima popolno znanje o mogočih stanjih v prihodnosti in so ta stanja popolnoma neodvisna od dejavnosti, ki jih tak sistem izvaja. Takšen organizacijski sistem je popolnoma prilagodljiv, saj se je mogoče pripraviti na vsa možna stanja.

Osnutek tveganja v organizacijskem sistemu pomeni, da je možno objektivno določiti stopnje verjetnosti nekega stanja ali dogodka. Pomeni, da usposobljen posameznik pozna vsa mogoča stanja v prihodnosti in verjetnosti, da se ta stanja uresničijo.

Stvarnost v organizacijskem sistemu je običajno težko opisati z osnutkoma gotovosti in tveganja. Avtor Kylaheiko [12] navaja podroben

1 THEORETICAL BACKGROUND

The problem of decision-making in uncertain conditions is only partially presented in the relevant literature. Intensive research in the area of multi-level decision-making, supported by expert systems, is currently under way. Despite the immense importance of development, problems associated with choosing the appropriate methods for complex and soft-structured decision-making problems, measuring scales, statistical interpretation, systems optimization and multifaceted problems are inadequately handled and consequently not solved.

Various authors ([4], [11], [12] and [15]) claim that the Real Options theory presents the right heuristic approach to capability-development process management. Capability is defined as the organizational know-how that enables business-process implementation [8]. The strategic school of dynamic capabilities claims that due to their characteristics, such as complexity and historical dependency, capabilities are the foundation for achieving a sustainable competitive advantage ([7], [9], [13] and [16]). The very characteristics that make it difficult to imitate and transfer capabilities, consequently adding to their strategic value, also limit the possibility of successful capability-development process management. This process is also defined by a high level of uncertainty, which makes the Real Options theory only appear as a heuristic, potentially helping managers handle the capability-development process.

1.1 Definition of the uncertainty term

The term certainty in an organizational system is used when a competent individual makes decisions associated with organizational system operations based on perfect knowledge of all possible future situations, and these situations are completely independent of the activities performed by such a system. Such an organizational system is totally adaptable, as one can prepare for any possible future situations.

The concept of risk in an organizational system means that an objective assessment of probability levels for an event or a situation to occur is possible. This means that a competent individual is aware of all possible future situations and of the probability that these situations will actually occur.

Reality in an organizational system is difficult to describe with the concepts of certainty and

pregled različnih tipov negotovosti. Osnutek negotovosti je dosti bolj primeren za opisovanje stanja v organizacijskih sistemih:
- *Parametrična negotovost* predstavlja tip negotovosti, ki ga je še mogoče matematično obvladovati. Negotovost se tiče samo subjektivnih parametrov verjetnosti.
- *Strukturna negotovost* pomeni, da ima oseba, ki odloča, nepopolno znanje o strukturi problema. Za strukturno negotovost je značilno, da je nemogoče imeti znanje o vseh mogočih posledicah. Pomembno je poudariti, da strukturna negotovost pomeni, da stanja v prihodnosti niso neodvisna od dejavnosti.

1.2 Izzivi proučevanja negotovosti

Tip strukturne negotovosti je najmanj raziskan v znanstveni literaturi [14]. Nenapovedljiva negotovost pomeni nezmožnost prepoznati ustrezne vplivne veličine in njihove funkcijske povezave.

Tsoukas [18] govori o *radikalni negotovosti*, ko poudarja, da je v organizacijskih sistemih nemogoče vnaprej vedeti, katero znanje se bo razvilo in katere kombinacije razpršenega znanja bodo pomembne za določene okoliščine.

Obsežne zamiselne razprave in izkustvene raziskave dokazujejo, da je razumevanje osnutka negotovosti ključno za razumevanje delovanja organizacijskega sistema. Kljub zavedanju o pomembnosti upravljanja organizacijskih sistemov v razmerah negotovosti, je na voljo presenetljivo malo sistemskih postopkov in hevristik, ki bi podpirale postopek sprejemanja odločitev v negotovih okoliščinah.

V zadnjem času se je kot vodilna hevristika za obvladovanje postopka odločanja v okoliščinah negotovosti uveljavila teorija stvarnih možnosti. Stvarne možnosti so pomembne v različnih situacijah:
- ko je projekt mogoče ustaviti;
- ko je investicija prilagodljiva, npr. ko je mogoče zamenjati proizvodno tehnologijo;
- ko priložnosti v prihodnosti temeljijo na odločitvah, ki so sprejete danes, npr. razvoj in raziskave.

1.3 Stvarne možnosti in razvoj zmogljivosti

Postopek razvoja zmogljivosti je negotov zaradi zapletene strukture zmogljivosti in zaradi njenega dolgotrajnega razvoja. Bowman in Hurry [4]

risk. The uncertainty concept is far more suitable for describing the actual state that an organizational system is in [12]:
- *Parametric uncertainty* is a type of uncertainty that can still be mathematically mastered. Uncertainty can only be related to subjective probability parameters.
- *Structured uncertainty* means that the decision-maker has limited knowledge of the problem structure. In structured uncertainty it is impossible to possess knowledge of all possible consequences. It should be emphasized that structured uncertainty means that future situations are not independent of the activity.

1.2 Uncertainty research challenges

The structured uncertainty type is the least researched theme in scientific literature [14]. U*nforeseeable uncertainty* means the inability to recognize the relevant influence variables and their functional connections.

Tsoukas [18], who talks about *radical uncertainty,* emphasizes that it is impossible to predict which proficiency will be developed and which scattered knowledge combinations will be important for the specific conditions in organizational systems.

Extensive conceptual discussions and empirical research studies prove that in order to comprehend organizational system operations, it is imperative to understand the uncertainty concept. Despite the fact that there is awareness of the importance of organizational systems management in uncertain conditions, there are surprisingly few systematic approaches and heuristics in place that support the process of decision-making in uncertain environments.

Recently, the Real Options theory has become the leading heuristic for decision-making process management in uncertain conditions. Real options are important in different situations:
- When a project can be terminated.
- When the investment is flexible. For example, when it is possible to modify the production technology.
- When future opportunities are based on decisions made today. For example, research and development.

1.3 Real Options and Capability Development

The capability-development process is uncertain due to the complex nature of capabilities and its lengthy development procedure. Bowman and sta ugotavljala, da menedžerji v poslovnih sistemih pravzaprav intuitivno uporabljajo logiko stvarnih možnosti, ko sprejemajo odločitve v zvezi z razvojem zmogljivosti.

Uporabnost stvarnih možnosti ne bodo povečala matematična orodja, ki bodo zapleteno stvarnost omejila v nekaj spremenljivk, ampak razvoj hevristik, ki bodo upoštevale zapletenost stvarnih razmer in obenem omogočale odločitve na podlagi merljivih pokazateljev.

1.4 Sistemski postopek za obravnavanje razvoja zmogljivosti

V analitičnem delu je treba podrobno analizirati vire in zmogljivosti. Ugotoviti je treba, kateri viri in zmogljivosti so že na voljo in v katerih povezavah jih je mogoče uporabiti. Ugotoviti je treba primanjkljaj virov in zmogljivosti. Strokovna literatura ponuja nekaj sistemskih postopkov, ki podpirajo analiziranje virov in zmogljivosti. Preden se izvedenska skupina loti razčlenitve razvoja zmogljivosti na kategorije in dejavnike, je treba opredeliti tipe negotovosti. Milikenova delitev na negotovost stanja, učinka in odziva je koristna, saj poenoti razumevanje pojma med različnimi člani izvedenske skupine.

Razčlenjevanje obravnavanega postopka na kategorije in dejavnike negotovosti pomeni del, ki se vsebinsko razlikuje v različnih sistemskih okoljih. Izvedenska skupina, ki obravnava negotovost seljenja proizvodnje na geografsko oddaljeno lego, bo identificirala drugačne dejavnike in kategorije kakor izvedenska skupina obrambnega sistema, ki obravnava izvajanje mirovnega opravila na geografsko oddaljenem kraju. Razčlenitev na kategorije in dejavnike negotovosti pomeni razstavitev zapletenega problema in omogoča začetek izvajanja postopkovnega dela.

2 METODOLOGIJA

Za pričujoč prispevek je bil uporabljen dvojni metodološki postopek zaradi potrebe po usklajevanju med celostnim obvladovanjem znanstvenega problema in analitično-numerično natančnostjo oblikovanega hevrističnega postopka. Običajno razviti numerični modeli predstavljajo zgolj abstrakten model stvarnega sistema in so razviti brez izkustvenih kakovostnih temeljev, ki določajo zapleteno

Hurry [4] have found that managers, when making capability-development decisions in business systems, actually use the logic of real options intuitively.

The applicability of real options will not be enhanced by mathematical tools, which reduce the complex reality to a few variables, but by the development of heuristics that take into account the complexity of real conditions and simultaneously enable decisions to be based on measurable indicators.

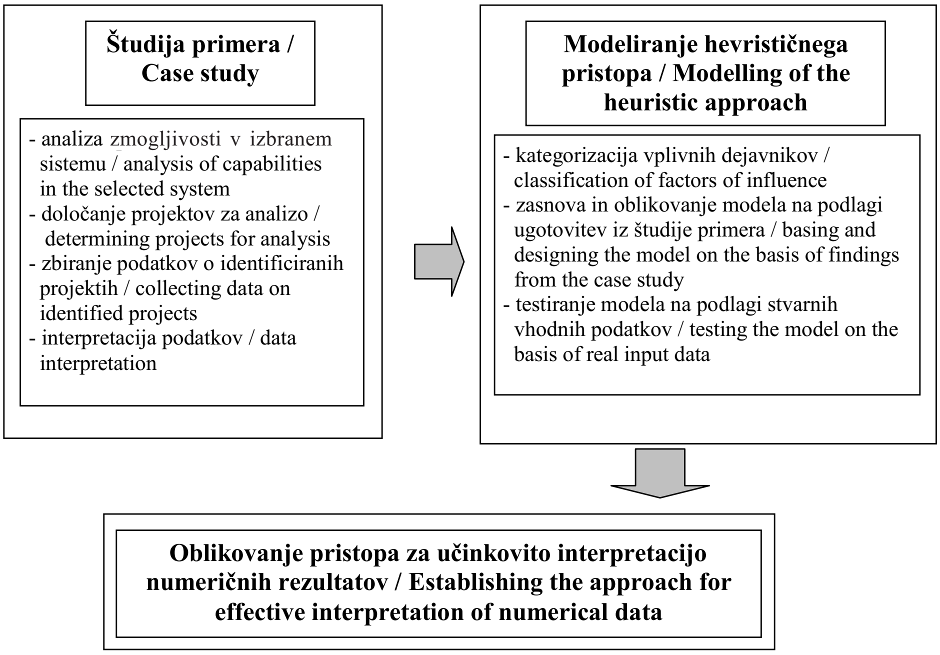
1.4 A systematic approach to handling capability development

In the analytical part of the work, the sources and abilities should be analyzed in detail. It is necessary to find out which sources and abilities have already been at disposal, and in which contextual applications they might be used. It is necessary to find out the deficiency of sources and abilities. Professional literature offers some system approaches, the application of which serves as support for analyzing sources and abilities. Before the expert team starts with ability development, broken down into categories and factors, the types of uncertainty should be defined. Miliken’s partition into the situation uncertainty, effect, and response is useful, as it unifies the understanding of the notion between the different members of the expert team.

Breaking down the treated process into categories and uncertainty factors actually represents the part, the contents of which differ in various system environments. The team of experts, treating the uncertainty of production movements to a geographically distant location, will identify other factors and categories than the expert team for the protection system, treating the implementation of peace operation on the geographically distant location. The breakdown to categories and factors of uncertainty represents the decomposition of a complex issue, thus enabling the start of implementing the process work.

2 METHODOLOGY

The double methodological approach was used for the underlying paper due to the need for coordination between the holistic management of a scientific issue and analytical-numerical accuracy of the formed heuristic approach. In most cases, the developed numerical models represent only an abstract model of the real system and are developed without any empirical, qualitative grounds, which



Sl. 1. *Struktura dvojnega metodološkega postopka*
Fig. 1. *The structure of the double methodological approach*

stvarnost sistema. Uporaba dvojnega metodološkega postopka pomeni novost v obravnavanju tovrstne problematike. Dosedanje raziskave so se predvsem naslanjale na monometodološke postopke, ki so bodisi natančno opisovali dejavnike, ki oblikujejo stvarnost organizacijskega sistema, ali pa so natančno modelirale podsisteme obravnavanega sistema in pri tem numerični natančnosti žrtvovali celosten pogled na obravnavani pojav. Na sliki 1 je prikazana struktura uporabljene metodologije.

Raziskava se je začela s podrobno analizo zmogljivosti v livarskem sistemu. Za obravnavanje projekta so bile kot metode zbiranja podatkov uporabljeni dokumentacija in intervjuji z usposobljenimi posamezniki. Interpretacija podatkov je bila izvedena skupaj z nekaterimi člani Laboratorija za načrtovanje proizvodnih sistemov, kar je omogočilo zmanjšanje subjektivnosti raziskovalca.

Poglobljeno kakovostno delo v okviru obravnavanega projekta je pripeljalo do podatkov, na katerih je bilo mogoče oblikovati hevristični sistemski postopek. Razlogi za izbiro tega projekta so naslednji:

- gre za projekt, ki zahteva razvoj strateških zmogljivosti,
- projekt ni povezan zgolj z investicijami v posamične tehnične sisteme,
- obravnava postopke, ki zahtevajo evolucijsko

determine the complex reality of a system. The use of the double methodological approach is a novelty in dealing with such issues. Past studies have mostly relied on mono-methodological approaches, which either included a detailed description of factors shaping the reality of an organisational system or the detailed modelling of subsystems of the underlying system and sacrificed the holistic view of the phenomena in question to numerical accuracy. The structure of the used methodology is presented in Figure 1.

The study started with a detailed analysis of the capabilities in a casting system. The data-collection methods used in the project were documents and interviews with qualified individuals. The data interpretation was carried out in cooperation with certain members of the Production Systems Planning Laboratory, which resulted in a lower level of subjectivity of the researcher.

In-depth, qualitative work within the project in question resulted in data that could be used to form the heuristic systemic approach. The reasons for selecting the project in question were:

- It is a project requiring the development of strategic capabilities;
- The project is not linked solely to investments in individual technological systems;
- It deals with processes requiring evolutionary

učenje,
- projekt je omejen z visoko stopnjo negotovosti,
- negotovost je mogoče dojemati skozi različne vidike,
- matematično modeliranje stvarnih možnosti ne omogoča celovitega obravnavanja problematike.

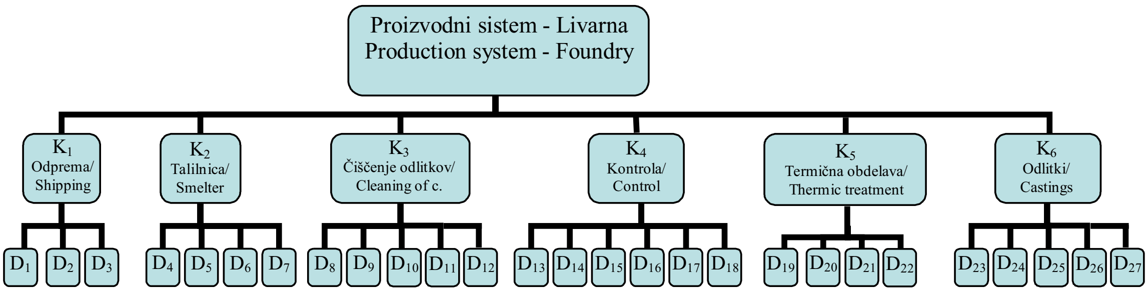
Livarski sistem v okviru proizvodnega sistema je ustrezen sistem za proučevanje.

learning;
- The project has a high level of uncertainty;
- The uncertainty can be perceived through various aspects;
- The mathematical modelling of real options does not enable a holistic dealing with the issue at hand.

The casting system as a part of the production system is a suitable system for studying.

3 UPORABA MODELA NA PRIMERU LIVARNE

3 CASE STUDY ON THE MODEL OF A PRODUCTION SYSTEM – CASTING SYSTEM



Sl. 2. *Primer strukturiranja hevrističnega modela za proizvodnji sistem - livarna*
Fig. 2. *Example of the structuring of the heuristic model for a production system - foundry*

Preglednica 1. *Kategorije K in dejavniki D v livarskem sistemu*
Table 1. *Categories K and Factors D in the foundry system*

K1 Odprema Shipping	D1 - cestni road D2 - železniški railway D3 - letalski air	K4 nadzor control	D13 - mehanske lastnosti mechanical properties D14 - kemijske vsebnosti chemical contents D15 - trdnostna hardness D16 - razsežnostna dimensional D17 - radiografska radiographic D18 - ultrazvočna ultrasound
K2 Talilnica/litje Smelter/casting	D4 - indukcijske peči induction furnace D5 - vakumske peči vacuum furnace D6 - litje v jeklena orodja croning D7 - peskovno litje sand casting	K5 toplotna obdelava thermal treatment	D19 - nitritranje nitrating D20 - vakumska obdelava vacuum treatment D21 - popuščanje yielding D22 - normalizacija normalisation
K3 Čiščenje odlitkov Cleaning of casts	D8 - peskalne komore sand blast chambers D9 - ročni strojčki manual appliances D10 - dobava od zunaj outsourcing D11 - doma home D12 - razmaščevanje fatcleaning	K6 odlitki castings	D23 - majhni small D24 - srednji middle D25 - veliki large D26 - ogljična jekla carbon steel D27 - nerjavna jekla stainless steel

3.1 Določitev pomembnosti dejavnikov negotovosti

Razmerja med kategorijami oz. dejavniki so izražena z vprašanjem: "Kolikokrat bolj je kategorija/dejavnik *i* pomemben od kategorije/dejavnika *j* glede na cilj oz. nadrejeno kategorijo?"

S primerjavo dejavnikov in kategorij po dvojicah (po podani ocenitveni lestvici) in rabo trikotno porazdeljenih mehkih števil dobimo mehke matrike na vseh ravneh hierarhije.

Mehke matrike → stopnja zaupanja (α) → stopnja optimističnosti (μ) → preračun uteži
Npr. za K4:

3.1 Definition of the importance of importance factors

The ratios between the categories or factors are expressed with the question: "How many times is the category/factor i more important than category/factor j according to the aim or the superior category?"

With a pair-wise comparison of the factors and categories (according to the provided estimation scale) and the use of triangularly divided fuzzy numbers, we arrive at the following fuzzy matrix on all levels of hierarchy.

Fuzzy matrix → level of trust estimate (α)→ level of optimistic estimates (μ) → weights calculation (where K4):

$$K_4: \mathrm{MM}_4 = \begin{array}{c} \\ D_{13} \\ D_{14} \\ D_{15} \\ D_{16} \\ D_{17} \\ D_{18} \end{array} \begin{array}{c} \begin{array}{cccccc} D_{13} & D_{14} & D_{15} & D_{16} & D_{17} & D_{18} \end{array} \\ \begin{bmatrix} 1 & \tilde{2} & \tilde{2}^{-1} & \tilde{2}^{-1} & \tilde{7}^{-1} & \tilde{5}^{-1} \\ \tilde{2}^{-1} & 1 & \tilde{1} & \tilde{2} & \tilde{1} & \tilde{3}^{-1} \\ \tilde{2} & \tilde{1}^{-1} & 1 & \tilde{2}^{-1} & \tilde{5}^{-1} & \tilde{3}^{-1} \\ \tilde{2} & \tilde{2}^{-1} & \tilde{2} & 1 & \tilde{4}^{-1} & \tilde{5}^{-1} \\ \tilde{7} & \tilde{1}^{-1} & \tilde{5} & \tilde{4} & 1 & \tilde{3} \\ \tilde{5} & \tilde{3} & \tilde{3} & \tilde{5} & \tilde{3}^{-1} & 1 \end{bmatrix} \end{array}$$

$$K_4: \mathrm{MM}_4^{\alpha=0,5} = \begin{bmatrix} 1 & \frac{17}{8} & \frac{17}{30} & \frac{17}{30} & \frac{7}{48} & \frac{5}{24} \\ \frac{17}{30} & 1 & \frac{4}{3} & \frac{17}{8} & \frac{4}{3} & \frac{3}{8} \\ \frac{17}{8} & 1 & 1 & \frac{17}{30} & \frac{5}{24} & \frac{3}{8} \\ \frac{17}{8} & \frac{17}{30} & \frac{17}{8} & 1 & \frac{4}{15} & \frac{5}{24} \\ 7 & 1 & 5 & 4 & 1 & 3 \\ 5 & 3 & 3 & 5 & \frac{3}{8} & 1 \end{bmatrix}$$

$$K_4: \mathrm{MM}_{4_{\mu=0,5}}^{\alpha=0,5} = \begin{bmatrix} 1 & \left[\frac{5}{4},3\right] & \left[\frac{1}{3},\frac{4}{5}\right] & \left[\frac{1}{3},\frac{4}{5}\right] & \left[\frac{1}{8},\frac{1}{6}\right] & \left[\frac{1}{6},\frac{1}{4}\right] \\ \left[\frac{1}{3},\frac{4}{5}\right] & 1 & \left[\frac{2}{3},2\right] & \left[\frac{5}{4},3\right] & \left[\frac{2}{3},2\right] & \left[\frac{1}{4},\frac{1}{2}\right] \\ \left[\frac{5}{4},3\right] & \left[\frac{1}{2},\frac{3}{2}\right] & 1 & \left[\frac{1}{3},\frac{4}{5}\right] & \left[\frac{1}{6},\frac{1}{4}\right] & \left[\frac{1}{4},\frac{1}{2}\right] \\ \left[\frac{5}{4},3\right] & \left[\frac{1}{3},\frac{4}{5}\right] & \left[\frac{5}{4},3\right] & 1 & \left[\frac{1}{5},\frac{1}{3}\right] & \left[\frac{1}{6},\frac{1}{4}\right] \\ [6,8] & \left[\frac{1}{2},\frac{3}{2}\right] & [4,6] & [3,5] & 1 & [2,4] \\ [4,6] & [2,4] & [2,4] & [4,6] & \left[\frac{1}{4},\frac{1}{2}\right] & 1 \end{bmatrix}$$

Numerična rešitev (lastni vektorji matrike → uteži), npr. za K4 (pri $\alpha = 0,5$ in $\mu = 0,5$):

Numerical solution (eigenvector of matrix → weight) where K4 (at $\alpha = 0.5$ and $\mu = 0.5$):

$$\sqrt[6]{1 \cdot \frac{17}{8} \cdot \frac{17}{30} \cdot \frac{17}{30} \cdot \frac{7}{48} \cdot \frac{5}{24}} = 0,5241 \qquad \sqrt[6]{\frac{17}{30} \cdot 1 \cdot \frac{4}{3} \cdot \frac{17}{8} \cdot \frac{4}{3} \cdot \frac{3}{8}} = 0,9640$$

$$\sqrt[6]{\frac{17}{8} \cdot 1 \cdot 1 \cdot \frac{17}{30} \cdot \frac{5}{24} \cdot \frac{3}{8}} = 0,6744 \qquad \sqrt[6]{\frac{17}{8} \cdot \frac{17}{30} \cdot \frac{17}{8} \cdot 1 \cdot \frac{4}{15} \cdot \frac{5}{24}} = 0,7224$$

$$\sqrt[6]{7 \cdot 1 \cdot 5 \cdot 4 \cdot 1 \cdot 3} = 2,7366 \qquad \sqrt[6]{5 \cdot 3 \cdot 3 \cdot 5 \cdot \frac{3}{8} \cdot 1} = 2,0943$$

$$\sum 7,7158 \;\Rightarrow\; \tilde{x}_4 = \begin{Bmatrix} D_{13} & D_{14} & D_{15} & D_{16} & D_{17} & D_{18} \\ 0,0679, & 0,1249, & 0,0874, & 0,0936, & 0,3547, & 0,2715 \end{Bmatrix}^T$$

$$UD_{13} = 0,3279 \cdot 0,0679 = 0,0223 \qquad UD_{14} = 0,3279 \cdot 0,1249 = 0,0410$$

$$UD_{15} = 0,3279 \cdot 0,0874 = 0,0287 \qquad UD_{16} = 0,3279 \cdot 0,0936 = 0,0307$$

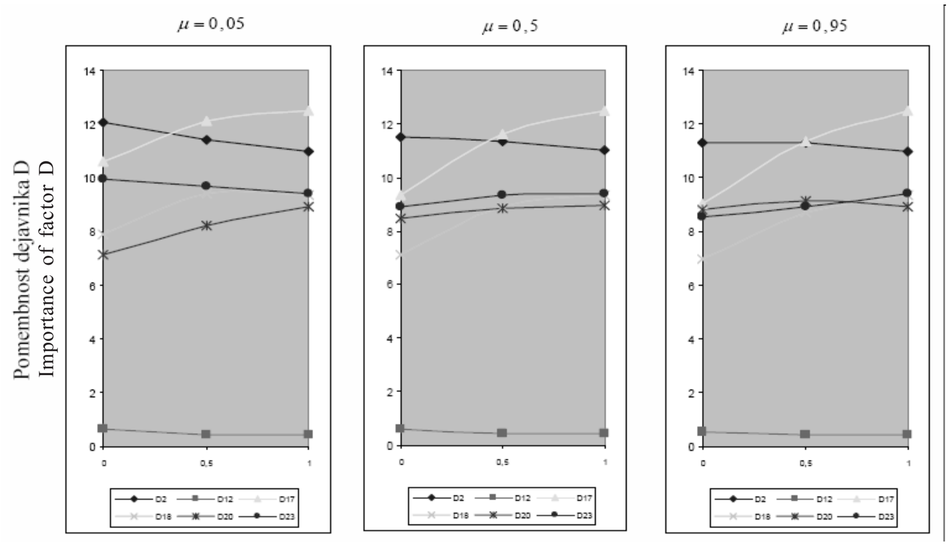
$$UD_{17} = 0,3279 \cdot 0,3547 = 0,1163 \qquad UD_{18} = 0,3279 \cdot 0,2715 = 0,0890$$

Preglednica 2. *Pomembnost kategorij negotovosti v odvisnosti od stopnje zaupanja in optimističnosti ocene*
Table 2. *The importance of uncertainty categories in relation to the level of trust in optimistic estimates*

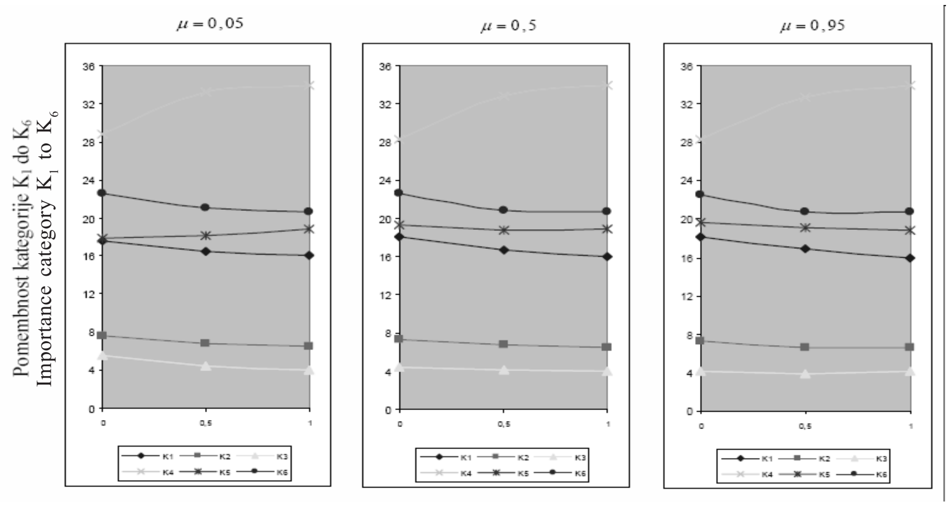
	Pomembnost kategorije (utež) / Importance of category (weight)						
Kategorija Category	$\alpha = 0$			$\alpha = 0,5$			$\alpha = 1$
	$\mu = 0,05$	$\mu = 0,5$	$\mu = 0,95$	$\mu = 0,05$	$\mu = 0,5$	$\mu = 0,95$	
K_1	0,1753	0,1801	0,1814	0,1641	0,1675	0,1691	0,1600
K_2	0,0765	0,0737	0,0728	0,0681	0,0669	0,0662	0,0653
K_3	0,0553	0,0446	0,0415	0,0446	0,0411	0,0391	0,0406
K_4	0,2879	0,2828	0,2835	0,3324	0,3279	0,3264	0,3388
K_5	0,1788	0,1926	0,1960	0,1809	0,1879	0,1913	0,1884
K_6	0,2262	0,2262	0,2248	0,2099	0,2087	0,2079	0,2069

Preglednica 3. *Pomembnost dejavnika negotovosti (utež)*
Table 3. *Importance of the uncertainty factor (weight)*

Dejavnik negotovosti Factor of uncertainty	$\alpha = 0$			$\alpha = 0,5$			$\alpha = 1$
	$\mu = 0,05$	$\mu = 0,5$	$\mu = 0,95$	$\mu = 0,05$	$\mu = 0,5$	$\mu = 0,95$	
D_1	0,0295	0,0344	0,0357	0,0298	0,0318	0,0329	0,0298
D_2	0,1208	0,1151	0,1132	0,1138	0,1134	0,1129	0,1099
D_3	0,0249	0,0306	0,0324	0,0204	0,0222	0,0233	0,0202
D_4	0,0277	0,0281	0,0282	0,0267	0,0269	0,0269	0,0253
D_5	0,0296	0,0294	0,0292	0,0263	0,0262	0,0260	0,0265
D_6	0,0123	0,0103	0,0098	0,0099	0,0090	0,0086	0,0088
D_7	0,0069	0,0059	0,0056	0,0052	0,0048	0,0046	0,0046
D_8	0,0082	0,0079	0,0077	0,0069	0,0070	0,0070	0,0063
D_9	0,0255	0,0171	0,0151	0,0217	0,0185	0,0169	0,0192
D_{10}	0,0083	0,0078	0,0075	0,0068	0,0065	0,0063	0,0063
D_{11}	0,0068	0,0061	0,0058	0,0048	0,0048	0,0047	0,0045
D_{12}	0,0065	0,0057	0,0054	0,0044	0,0043	0,0042	0,0043
D_{13}	0,0213	0,0216	0,0216	0,0226	0,0223	0,0221	0,0225
D_{14}	0,0306	0,0400	0,0433	0,0366	0,0410	0,0436	0,0380
D_{15}	0,0254	0,0289	0,0301	0,0274	0,0287	0,0294	0,0290
D_{16}	0,0258	0,0275	0,0282	0,0305	0,0307	0,0310	0,0310
D_{17}	0,1059	0,0936	0,0904	0,1213	0,1163	0,1135	0,1247
D_{18}	0,0790	0,0712	0,0699	0,0941	0,0890	0,0868	0,0936
D_{19}	0,0648	0,0563	0,0532	0,0599	0,0578	0,0562	0,0588
D_{20}	0,0716	0,0844	0,0881	0,0824	0,0883	0,0915	0,0894
D_{21}	0,0209	0,0237	0,0243	0,0206	0,0217	0,0223	0,0212
D_{22}	0,0215	0,0282	0,0304	0,0180	0,0201	0,0213	0,0191
D_{23}	0,0997	0,0892	0,0856	0,0966	0,0932	0,0894	0,0938
D_{24}	0,0323	0,0318	0,0315	0,0295	0,0294	0,0288	0,0287
D_{25}	0,0523	0,0588	0,0604	0,0486	0,0490	0,0524	0,0486
D_{26}	0,0156	0,0140	0,0134	0,0121	0,0117	0,0112	0,0113
D_{27}	0,0263	0,0324	0,0340	0,0231	0,0254	0,0262	0,0246



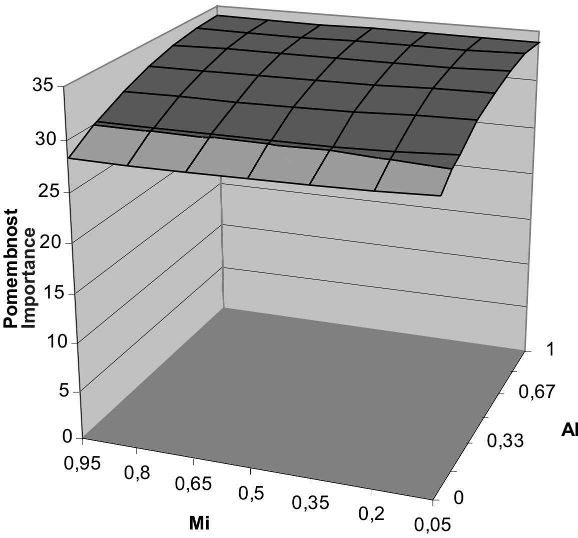
Sl. 3. *Pomembnost kategorij in dejavnikov negotovosti*
Fig. 3. *Importance of factors in relation to the level of trust in optimistic estimates*



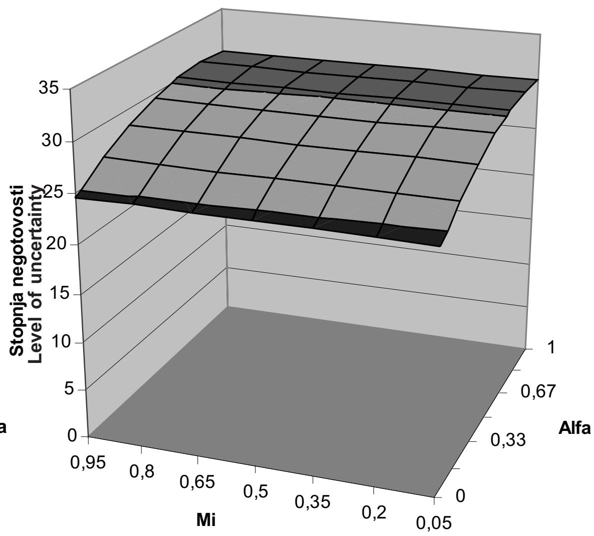
Sl. 4. *Pomembnost kategorij in dejavnikov negotovosti*
Fig. 4. *Importance of categories and uncertainty factors*

Preglednica 3. *Stopnja negotovosti kategorij v odvisnosti od stopnje zaupanja in optimističnosti ocene*
Table 3. *The level of uncertainty of categories in relation to the level of trust in optimistic estimates*

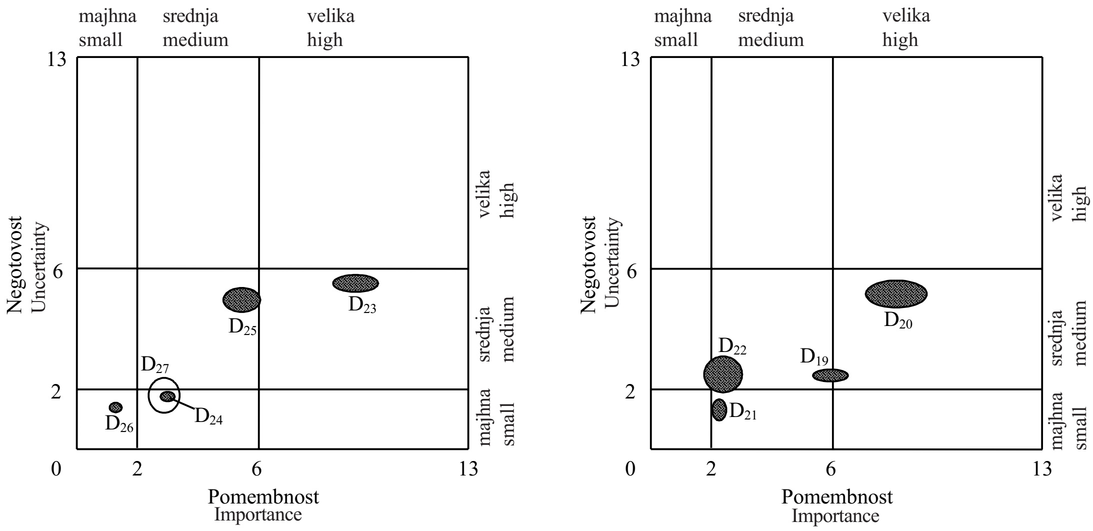
	Negotovost kategorije (utež) / Uncertainty of category (weight)						
Kategorija Category	α= 0			α = 0,5			α = 1
	μ = 0,05	μ = 0,5	μ = 0,95	μ = 0,05	μ = 0,5	μ = 0,95	
K_1	0,1101	0,1041	0,1021	0,0994	0,0991	0,0986	0,0944
K_2	0,2542	0,2378	0,2328	0,2639	0,2572	0,2535	0,2613
K_3	0,2423	0,2451	0,2465	0,2943	0,2944	0,2949	0,3023
K_4	0,1187	0,1215	0,1224	0,1018	0,1042	0,1053	0,1028
K_5	0,1190	0,1263	0,1284	0,0997	0,1015	0,1026	0,0979
K_6	0,1557	0,1652	0,1678	0,1409	0,1436	0,1451	0,1413



Sl. 5. *Prostorski diagram pomembnosti kategorije K4*
Fig. 5. *Space diagram of the importance of category K4*



Sl. 7. *Prostorski diagram stopnje negotovosti kategorije K3*
Fig. 7. *Space diagram of the level of uncertainty of category K3*



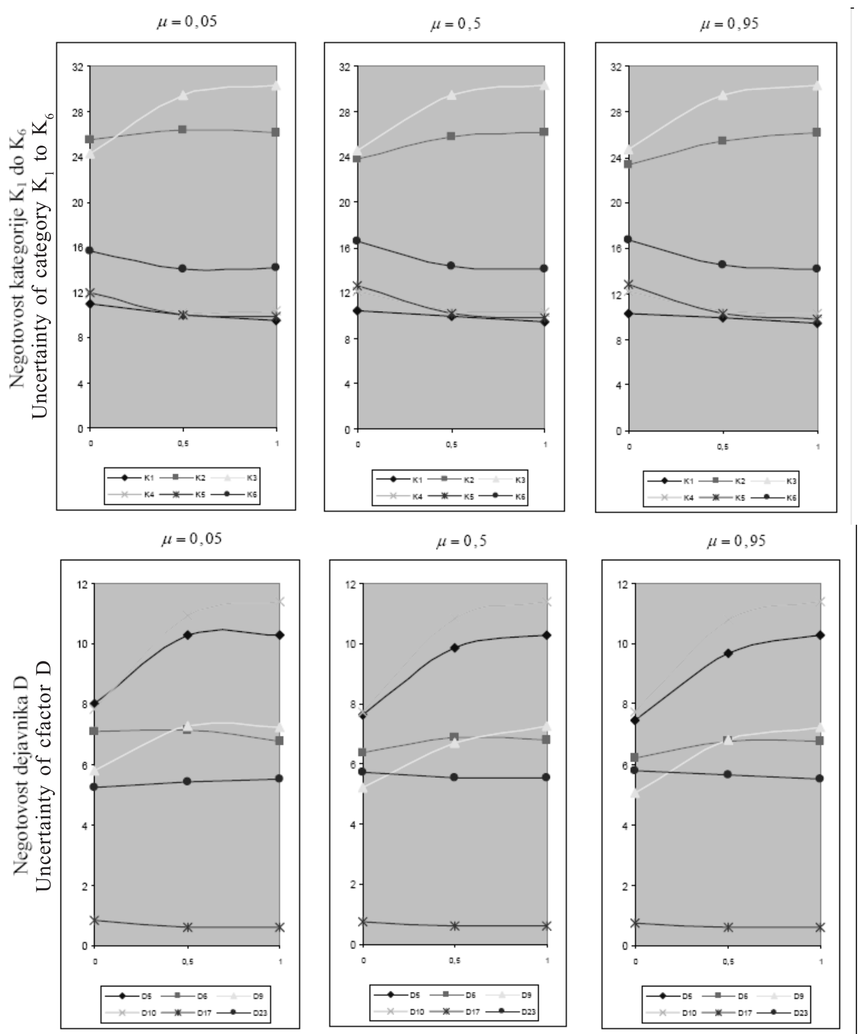
Sl. 8. *Lega dejavnikov kategorije K5 in K6*
Fig. 8. *Position of the factors of categories K5 and K6*

Določitev stopnje negotovosti dejavnikov: Razmerja med kategorijami oz. dejavniki so izražena z vprašanjem: "Kolikokrat bolj je kategorija/dejavnik *i* negotov od kategorije/dejavnika *j* glede na cilj oz. nadrejeno kategorijo?"

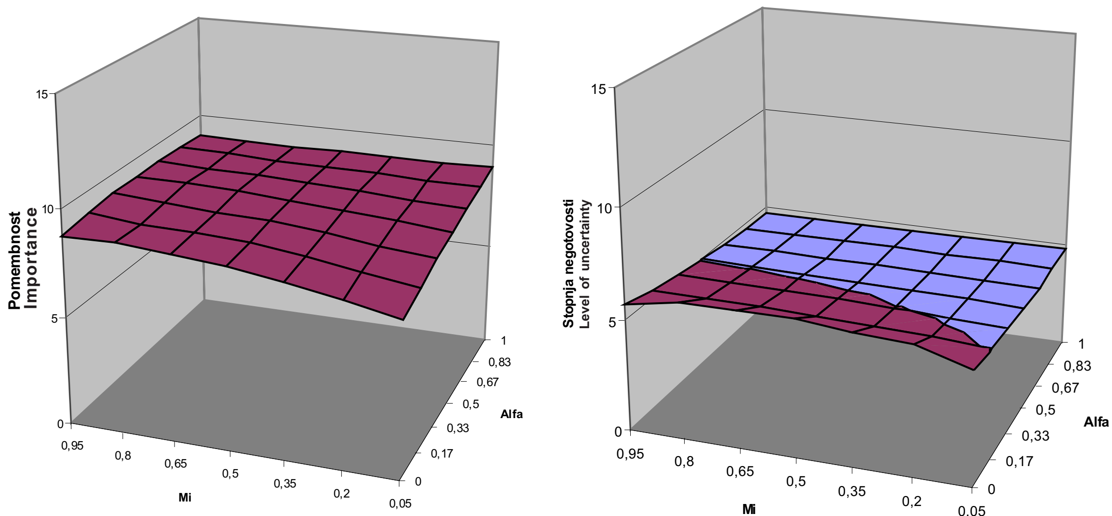
S primerjavo dejavnikov in kategorij po dvojicah (po podani ocenitveni lestvici, prirejeni na stopnjo negotovosti) in rabo trikotno porazdeljenih mehkih števil dobimo mehke matrike po vseh ravneh hierarhije.

The ratios between the categories or factors are expressed with the question: "How many times is the category/factor *i* more important than the category/factor *j* according to the aim or the superior category?"

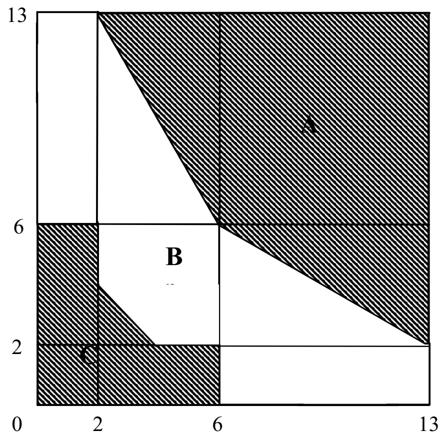
With a pair-wise comparison of the factors and categories (according to the provided estimation scale, adapted for the level of uncertainty) and the use of triangularly divided fuzzy numbers, we arrive at the following fuzzy matrix on all levels of hierarchy:



Sl. 6. *Negotovost kategorij in dejavnikov*
Fig. 6. *Uncertainty categories and factors*



Sl. 9. *Prostorski diagrami npr.: pomembnost in stopnja negotovosti za dejavnik D20*
Fig. 9. *Space diagrams of the importance and level of uncertainty for the factor D20*



Sl. 10. *Področje pozornosti (A $\rightarrow$ večje, B $\rightarrow$ srednje, C $\rightarrow$ manjše)*
Fig. 10. *Area of attention (A $\rightarrow$ larger, B $\rightarrow$ medium, C $\rightarrow$ smaller)*

3.2 Integralna ocena negotovosti

Z metodo mehkega AHP smo določili področja stopnje pomembnosti in negotovosti za vsak dejavnik, ki so omogočila tudi ustrezen izbor bolj ali manj kritičnih dejavnikov. Omejena področja vrednosti uporabimo za:

- izgradnjo vektorja pomembnosti dejavnikov,
- izgradnjo vektorja negotovosti dejavnikov.

Integralna (celotna) ocena negotovosti (ION) je skalarni produkt obeh vektorjev:

3.2 Integral uncertainty estimate

With the method of fuzzy AHP we have determined the areas (intervals) of the level of importance and the uncertainty for every factor, which has given us the opportunity for a correct selection of the more or less critical factors. The mentioned areas of value can be used for the following:

- design of the factor importance vector,
- design of the uncertainty factor vector.

The integral (total) uncertainty estimate (ION) is a scalar product of vectors $\vec{P}$ and $\vec{N}$:

$$ION = \vec{P} \cdot \vec{N}$$

Mejno integralno oceno negotovosti dobimo z uporabo enakih povprečnih uteži pri vseh komponentah vektorjev, torej pri *n* dejavnikih:

The fringe integral uncertainty estimate can be obtained by using the same mean weights with all the vector components, therefore, with *n* factors:

$$ION_m = \sum_{i=1}^{n} \left[\left(\frac{100}{n} \right) \cdot \left(\frac{100}{n} \right) \right] = n \cdot \frac{100}{n} \cdot \frac{100}{n} = \frac{10000}{n}$$

Pri konkretnem obravnavanem primeru razvoja proizvodnih zmogljivosti imamo 27 dejavnikov. Mejna integralna ocena negotovosti znaša:

In this actual example of the development of production capacity we have 27 factors. The fringe integral uncertainty estimate is:

$$ION_m = \frac{10000}{27} = 370$$

Vektor $\vec{P}$ ima naslednje člene:

Vector $\vec{P}$ has the following terms:

$$\vec{P} = \{3{,}26;\ 11{,}54;\ 2{,}63;\ 2{,}68;\ 2{,}78;\ 1{,}05;\ 0{,}58;\ 0{,}73;\ 2{,}03;\ 0{,}73;\ 0{,}57;\ 0{,}54;\ 2{,}20;\ 3{,}71;\ 2{,}78;\ 2{,}84;\ 10{,}76;\ 8{,}2;\ 5{,}9;\ 8{,}16;\ 2{,}25;\ 2{,}42;\ 9{,}27;\ 3{,}05;\ 5{,}45;\ 1{,}34;\ 2{,}86\}$$

Vektor $\vec{N}$ ima naslednje člene:

Vector $\vec{N}$ has the following terms:

$$\vec{N} = \{4{,}05;\ 3{,}88;\ 2{,}45;\ 4{,}33;\ 8{,}89;\ 6{,}66;\ 5{,}17;\ 5{,}22;\ 6{,}16;\ 9{,}56;\ 2{,}42;\ 3{,}72;\ 2{,}65;\ 1{,}03;\ 1{,}38;\ 2{,}56;\ 0{,}72;\ 3{,}05;\ 2{,}42;\ 5{,}23;\ 1{,}29;\ 2{,}46;\ 5{,}52;\ 1{,}78;\ 4{,}88;\ 1{,}43;\ 1{,}77\}$$

4 SKLEP

Prispevek obsega izvirno sintezo teorije stvarnih možnosti, upravljanja tveganja, modeliranja negotovosti, metode analitičnega hierarhičnega postopka in mehke logike ter pomeni prispevek pri izgradnji orodij za podporo odločanju pri usmerjanju razvoja zmogljivosti v organizacijskem sistemu. Postopek je zasnovan na zmernem in obvladljivem številu vplivnih veličin in zagotavlja celovito obvladovanje problematike pri iskanju sprejemljivih rešitev. Izdelan hevristični model razvoja zmogljivosti je ustrezen, kar potrjuje tudi izveden praktični primer na livarskem sistemu.

V prikazanem primeru z odpravljanjem negotovosti praktično zmanjšamo možnosti negativnih učinkov in se s tem, z vidika vseh virov, približamo optimizaciji proizvodnega sistema.

Postopkovni del je namenjen vrednotenju analiziranih dejavnikov. Osnovna uporabljena metoda je mehki analitični hierarhični postopek (v osnovi se uporablja za podporo večkriterijskemu odločanju), ki temelji na medsebojnem določanju razmerij med posameznimi kategorijami in dejavniki negotovosti (najprej glede pomembnosti, v naslednji fazi pa še glede stopnje negotovosti dejavnikov) in na matematičnem preračunu uteži, ki kažejo že omenjeno pomembnost in stopnjo negotovosti. Prednost metode je prav v medsebojnem določanju razmerij, saj bistveno lažje ocenjujemo s primerjanjem po dvojicah, in v uporabi mehkih števil, ko v samo ocenitev vgradimo možnost napake ocenjevalca za en razred (v levo ali desno, večja napaka je praktično izločena) in to računsko upoštevamo, saj se rezultati kažejo v določenih koračnih območjih. Pomanjkljivost uporabljene metode je v razmeroma velikem številu potrebnih ocenitev, čemur pa se izognemo s tem, da imamo dejavnike že v analitičnem delu razvrščene po kategorijah, ter v nevarnosti pretirano neskladnih ocenitev, kar bi terjalo ponovitev postopka primerjanja oziroma popravek izbranih ocenitev.

V prispevku smo uporabili intervalne rezultate mehke metode AHP za izgradnjo vektorja pomembnosti dejavnikov in vektorja negotovosti dejavnikov, katerih skalarni produkt nam daje integralno oceno negotovosti, ki v primerjavi z mejno oceno opredeljuje tveganje obravnavanega postopka. Na osnovi izvirnih diagramov 'Negotovost/Pomembnost' je bil oblikovan diagram

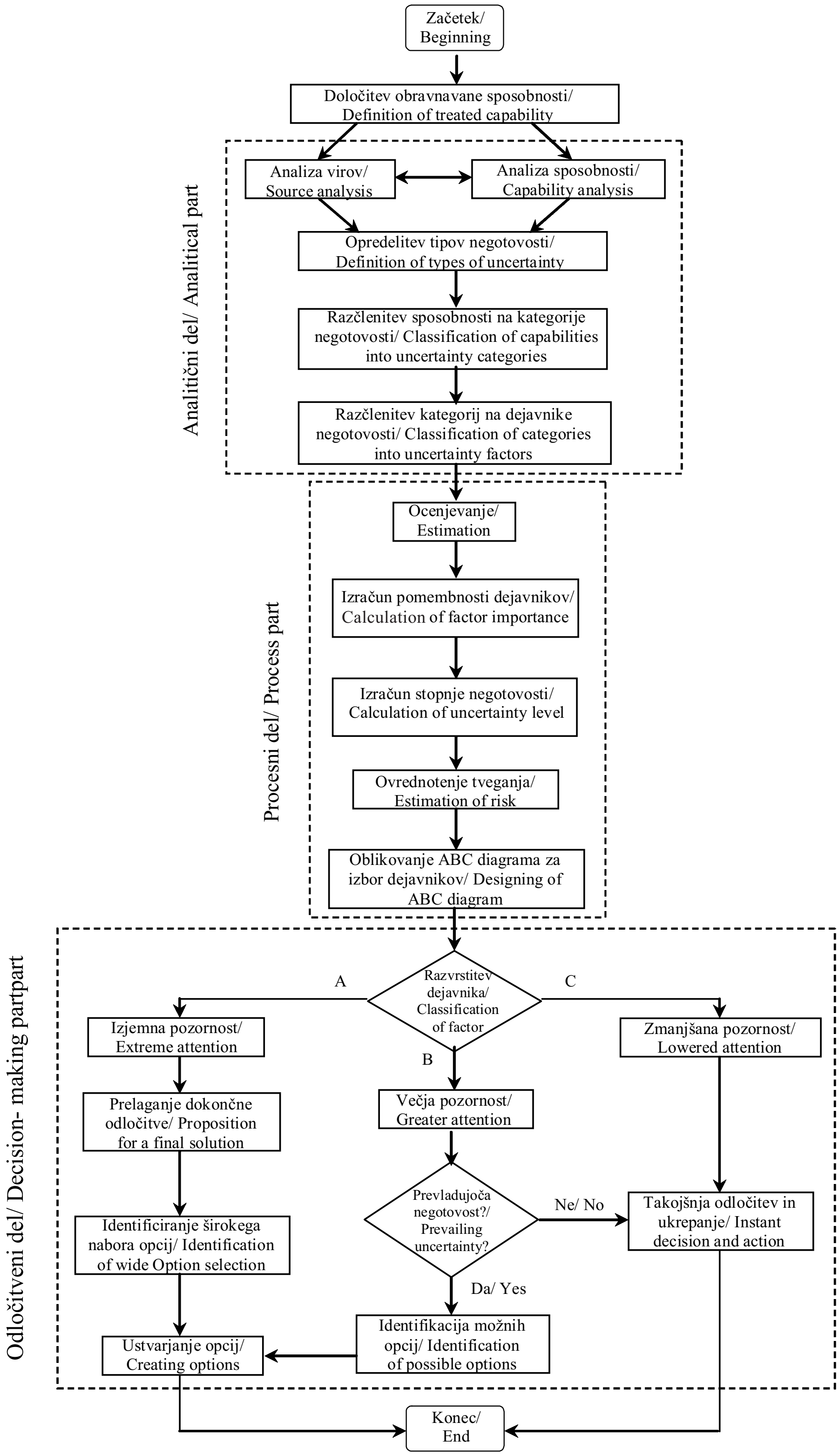
4 CONCLUSION

This paper encompasses the original synthesis of the theory of real options, risk management, modelling uncertainty, the method of analytic hierarchy process and fuzzy logic, and it represents a contribution to the construction of tools for decision-making support for directing the capability development process in an organisational system. The procedure is based on a moderate and manageable number of influential sizes and provides a comprehensive management of the problem by searching for suitable solutions. The designed heuristic model of the development of capabilities is appropriate, which we confirmed by the practical example on a castings system.

In the presented example, with the elimination of the uncertainties, we practically minimise the possibilities of negative effects, and with it, from the viewpoint of all the sources, come close to optimisation of the production system.

The processing part is intended for an evaluation of the analysed factors. The basic method used is the soft analytical hierarchical process (basically used as a support to multiple criteria decision-making), based on a mutual determining of the relationships between individual categories and the factors of uncertainty (first with regard to importance and in the second stage with regard to the uncertainty level of factors) and on the mathematical calculation of weights reflecting the aforementioned importance and level of uncertainty. The advantage of this method lies in the mutual determining of relationships, as the evaluation is much easier with a comparison by pairs, and in the use of soft numbers when the evaluation itself includes the possibility of the evaluator's error by a class (to the left or to the right, a bigger error is virtually excluded) and the calculation takes it into account as the results are presented in particular intervals. The disadvantage of the used method lies in the relatively large number of evaluations required, which can be avoided by grouping factors in the categories already in the analytical part, and in the danger of excessively diverging evaluations, which would require repeating the procedure of the comparison and adjustment of the selected evaluations.

In the paper we have used interval results of the soft AHP method to build the vector of the importance of factors and the vector of the uncertainty of factors, the scalar product of which provides us with the integral evaluation of uncertainty, which in comparison with the limit evaluation determines the risk of the underlying process. On the basis of the original diagrams "Uncertainty/Importance", we have formed



Sl. 11. *Sistemski postopek za obravnavanje razvoja zmogljivosti*
Fig. 11. *A systematic approach to handling-capability development*

pozornosti ABC, ki je namenjen izbiri oziroma razvrstitvi dejavnikov negotovosti, na kateri gradi odločitveni del sistemskega postopka.

Odločitveni del je najpomembnejši del postopka glede na kriterij uporabnosti modela. V tem delu je bila logika modela prenesena v resnične odločitve. Odločitveni model se prične z razvrstitvijo dejavnika. Dejavniki C so tisti, ki jim ni treba dajati večje pozornosti glede na stopnjo pomembnosti in negotovosti. Kadar tovrstni dejavniki terjajo določene odločitve ali ukrepe, je te mogoče hitro in učinkovito izvesti, ne da bi nas skrbelo, kako lahko negotovost vpliva na posledice odločitve. Dejavniki A predstavljajo nasprotni pol dejavnikov glede na pomembnost in negotovost. Tovrstnim dejavnikom je treba posvetiti izjemno pozornost. Podrobneje je treba osvetliti navodilo, naj se predlagajo dokončne odločitve. To navodilo se ne sme razumeti kot predlog za nesprejetje odločitev. Navodilo pravi, da se v tem primeru ne smejo sprejemati odločitve, ki bi bile dokončne in ne bi omogočale prilagodljivega ravnanja. Te odločitve morajo biti usmerjene v ustvarjanje širokega nabora možnosti, ki omogočajo ukrepanje v primeru različnih scenarijev razvoja. Preden se sprejmejo odločitve, ki ustvarjajo možnosti v prihodnosti, je treba razpoznati širok nabor mogočih možnosti. Dejavniki B ležijo, glede na svoj pomen in glede na stopnjo negotovosti, med dejavniki A in C. Gre vsekakor za dejavnike, ki jim je treba posvetiti ustrezno pozornost. Delež pozornosti je seveda odvisen tudi od števila dejavnikov, ki so opredeljeni kot dejavniki stopnje A. Če dobimo veliko število dejavnikov stopnje A, potem bo pozornost dejavnikom stopnje B nekoliko manjša kakor v primeru, če imamo med A zgolj nekaj dejavnikov. V primeru, ko so dejavniki prišli v kategorijo B zato, ker so pomembni, niso pa nagnjeni k negotovosti, je mogoče sprejeti iste ukrepe kakor za dejavnike C. V primeru večje negotovosti se morajo tudi za dejavnike B sprejemati odločitve, ki omogočajo prilagodljivo ravnanje v prihodnosti.

Izvirni prispevek v prispevku obsega:

- Obravnavanje ustreznosti – uporabnosti logike teorije stvarnih možnosti pri razvoju strateških zmogljivosti, kakor tudi ovir, ki omejujejo njeno uporabnost (na primerih odločanja v proizvodnem sistemu).
- Razvoj hevrističnega sistemskega postopka, ki na podlagi teorije stvarnih možnosti podpira odločanje pri razvoju zmogljivosti v organizacijskih sistemih.

the ABC diagram of attention, which is used for selecting and classifying the uncertainty factors on which the decision-making part of the systematic approach builds.

The decision-making part represents the most important part of the approach with regard to the model's applicability criterion. In this part the model's logic was transferred to real-life decisions. The decision-making model begins by classifying factors. C factors are those that do not require larger attention with regard to the levels of importance and uncertainty. When such factors require certain decisions or measures, they can be implemented quickly and effectively without worrying about how the uncertainty might affect the consequences of the decision. A factors are the opposite pole of factors with regard to importance and uncertainty. These factors require extra attention. The instructions regarding the proposing of the final decisions should be elaborated in greater detail. These instructions should not be interpreted as a proposal for not taking any decisions. The instructions say that in such a case no decisions can be taken that would be final and prevent the flexibility of action. These decisions should be directed towards creating a wide range of options, enabling reaction in the case of different development scenarios. Before adopting decisions that create future options, the wide range of available options should be identified. B factors lie between A and C factors with regard to their importance and the level of uncertainty. These are by all means factors that require an appropriate level of attention. The proportion of attention naturally also depends on the number of factors being defined as A-level factors. If we get a large number of A-level factors, the attention given to B-level factors will be slightly lower than in cases where there are only a few A-level factors. In the case that factors are classified in the B category, because they are important but not subject to uncertainty, the same measures as for C factors can be adopted. In the case of increased uncertainty, decisions enabling the flexibility of future actions should also be adopted for B factors.

The original contribution in this paper is composed of:

- Dealing with suitability – usefulness of the logic of the theory of real options with the development of strategic capacities, as well as obstacles, which limit its usefulness (with the examples of decision-making in the production process).
- The development of a heuristic system approach which, on the basis of the theory of real options, encourages the decision-making in capabilities-development in organisational systems.

- Dopolnitev hevrističnega postopka za učinkovito razlago numeričnih rezultatov in njihovo podporo postopku odločanja:
  - uporaba mehke metode AHP za določanje stopnje negotovosti je popolnoma izvirna zamisel, saj se omenjena metoda uporablja le za določanje pomembnosti,
  - izvirni sestavljeni diagrami 'Pomembnost – Negotovost' in diagram pozornosti ABC omogočajo izbiro in razvrstitev dejavnikov (in kategorij),
  - integralna ocena negotovosti (ION) je izvirni prispevek pri ovrednotenju negotovosti. Razvita je tudi metodologija za določitev mejne integralne ocene, tako da je omogočena splošna opredelitev tveganja vsake obravnavane dejavnosti.

Osnovni izziv za prihodnost je izdelava enovitega programskega orodja, ki bi vključevalo vse v raziskavi uporabljene tehnike in metode in zajelo celotne preračune, od vnosa potrebnih podatkov do izpisa rezultatov in izrisa vseh diagramov ter predlaganih smernic pri sprejemanju odločitev.

- The completion of a heuristic approach for the effective interpretation of numerical results and their support in the decision making process:
  - the use of the fuzzy AHP method for determining the uncertainty level is an entirely original idea, for the above-mentioned method it is used only for defining the importance,
  - the original combined diagrams "Importance – Uncertainty" and the ABC diagram of attention, which enable the selection and classification of factors (and categories),
  - the integral uncertainty estimation (ION) represents an original method for estimating uncertainty. There is also the methodology for determining the fringe integral estimate, which enables the common estimation of risk for every activity involved.

The fundamental challenge for the future is the design of a uniform software tool that would incorporate all the used techniques and methods, and encompass all the calculations, from the input of the necessary data to the printout of results, and the design of all the diagrams and the proposed guidelines for decision-making.

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5 LITERATURE

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Diskretni plinski kavitacijski model z upoštevanjem vpliva nestalnega kapljevinskega trenja v cevi

A Discrete Gas-Cavity Model that Considers the Frictional Effects of Unsteady Pipe Flow

Anton Bergant - Uroš Karadžić - John Vítkovský - Igor Vušanović - Angus R. Simpson

Prehodni kavitacijski tok pare v cevi vzbudi padec tlaka na parni tlak kapljevine. Podan je kratek oris metode karakteristik, temu slede osnove nestalnega kapljevinskega trenja in prehodnega kavitacijskega toka v cevi. Glavni cilj tega prispevka je predstavitev novega plinskega kavitacijskega modela (DPKM) z upoštevanjem vplivov nestalnega trenja. Rezultati izračuna so primerjani z rezultati meritev v laboratoriju. Upoštevanje nestalnega trenja v DPKM da bolj natančne računske rezultate.

(Ključne besede: sistemi cevni, udari vodni, tok kavitacijski, modeli kavitacijski diskretni plinski, trenje nestalno)

Transient, vaporous, cavitating pipe flow occurs when the pressure drops to the liquid's vapour pressure. A brief description of the method of the characteristics and fundamentals of unsteady pipe-flow friction and transient, cavitating pipe flow are given. The main objective of this paper is to present a novel, discrete gas-cavity model (DGCM) with a consideration of unsteady frictional effects. The numerical results are compared with the results from laboratory measurements. The inclusion of unsteady friction into the DGCM significantly improves the numerical results.

(Keywords: piping systems, water hammer, cavitating flow, discrete gas cavity models, unsteady friction)

0 UVOD

Hidravlični cevni sistemi morajo varno delovati v širokem pasu obratovalnih režimov. Vodni udar vzbudi nihanje tlaka v cevnih sistemih, spremembo vrtilne frekvence (narastek, nasprotno vrtenje) v hidravličnih strojih in nihanje gladine vode v izravnalnikih. Prehodni pojavi v ceveh lahko povzročijo zadosten padec tlaka, ki vodi do prekinitve homogenosti in kontinuitete kapljevine (pretrganje kapljevinskega stebra). Neželeni vplivi vodnega udara lahko ustavijo obratovanje hidravličnih sistemov (hidroelektrarna, črpalni sistem) in poškodujejo elemente sistema; na primer zrušitev cevovoda. Obremenitve vodnega udara v dopustnih mejah lahko dosežemo z ustreznim krmiljenjem obratovalnih režimov, vgradnjo elementov za blažitev vodnega udara ali prerazporeditvijo elementov cevnega sistema ([1] in [2]). Umerjanje in nadzor

0 INTRODUCTION

Hydraulic piping systems should work safely over a broad range of operating regimes. Water hammer induces pressure fluctuations in piping systems, rotational speed variations (overspeed, reverse rotation) in hydraulic machinery or water-level oscillations in surge tanks. Transients in pipelines can cause a drop in pressure large enough to break the liquid's homogeneity and continuity (liquid column separation). Undesirable water-hammer effects can disturb the overall operation of hydraulic systems (hydroelectric power plant, pumping system) and damage system components; for example, pipe rupture can occur. Water-hammer loads can be kept within the prescribed limits by the adequate control of the operational regimes, the installation of surge-control devices or the redesign of the original pipeline layout ([1] and [2]). The calibration and monitorhidravličnih sistemov narekujeta potrebo po globljem poznavanju fizike tlačnih valov [3].

Prvi del prispevka obravnava matematična orodja za modeliranje nestalnega kapljevinskega trenja in prehodnega parnega kavitacijskega toka (pretrganje kapljevinskega stebra). Premena enačb nestalnega toka v cevi z uporabo metode karakteristik da osnove algoritma za vodni udar. V deltoidno mrežo metode karakteristik je vgrajen konvolucijski model nestalnega trenja z uporabo zmogljivih računskih orodij [4]. Vgradnja diskretnih kavitacij v model vodnega udara da diskretni kavitacijski model ([2] in [5]). V prispevku je podan nov diskretni plinski kavitacijski model (DPKM) z upoštevanjem vpliva nestalnega kapljevinskega trenja v cevi. Podan je kratek oris preizkusne postaje za meritev vodnega udara. V zaključnem delu prispevka so podani številni primeri, iz katerih izhaja, da upoštevanje nestalnega kapljevinskega trenja v DPKM pomembno vpliva na napoved tlačnih valov v preprostem cevnem sistemu z ventilom.

ing of hydraulic systems requires a detailed knowledge of water-hammer waveforms [3].

The first part of the paper deals with mathematical tools for modeling unsteady pipe-flow friction and transient vaporous cavitation (liquid column separation). The method of characteristics transformation of the unsteady pipe-flow equations gives the water-hammer solution procedure. A convolution-based unsteady friction model using state-of-the-art numerical tools [4] is explicitly incorporated into the staggered grid of the method of characteristics. Incorporating discrete cavities into the water-hammer model leads to the discrete-cavity model ([2] and [5]). A novel discrete gas-cavity model (DGCM) with consideration of the unsteady pipe-flow friction effects is presented in the paper. The experimental apparatus for measurements of the water-hammer pressure waves is briefly described. The paper concludes with a number of case studies showing how the inclusion of unsteady friction into the DGCM significantly affects the pressure traces in a simple reservoir-pipeline-valve system.

1 TEORETIČNI MODEL

1 THEORETICAL MODEL

Vodni udar popisuje potovanje tlačnih valov v ceveh s kapljevino. Nestalni tok v cevi popišemo s kontinuitetno in gibalno enačbo [2]:

Water hammer is the transmission of pressure waves in liquid-filled pipelines. Unsteady pipe flow is described by the continuity equation and the equation of motion [2]:

$$\frac{\partial H}{\partial t}+V\frac{\partial H}{\partial x}-V\sin\theta+\frac{a^2}{g}\frac{\partial V}{\partial x}=0 \qquad (1)$$

$$g\frac{\partial H}{\partial x}+\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+f\frac{V|V|}{2D}=0 \qquad (2).$$

Naj omenimo, da so vse označbe definirane v poglavju 6. Postavimo tok v eni razsežnosti (po prerezu povprečena hitrost in tlak), tlak večji od parnega tlaka kapljevine, linearen elastični odziv stene cevi in kapljevine, nestalno trenje kapljevine nadomeščamo s stalnim, zanemarljivo količino prostih plinskih kavitacij v kapljevini in šibko interakcijo med kapljevino in ogrado. Konvektivni členi $V(\partial H/\partial x)$, $V(\partial V/\partial x)$ in $V\sin\theta$ so majhni v primerjavi s preostalimi členi in jih v inženirski uporabi lahko zanemarimo ([1] in [2]). Z vpeljavo pretoka $Q = VA$ namesto povprečne pretočne hitrosti V se poenostavljeni sistem enačb (1) in (2) glasi:

Note that all the symbols are defined in Section 6. The flow in the pipe is assumed to be one-dimensional (cross-sectional averaged velocity and pressure distributions), the pressure is greater than the liquid vapour pressure, the pipe wall and the liquid behave linearly elastically, unsteady friction losses are approximated as steady friction losses, the amount of free gas in the liquid is negligible and the fluid-structure coupling is weak. For most engineering applications, the transport terms $V(\partial H/\partial x)$, $V(\partial V/\partial x)$ and $V\sin\theta$, are very small compared to the other terms and can be neglected ([1] and [2]). A simplified form of Eqs. (1) and (2) using the discharge $Q=VA$ instead of the flow velocity V is:

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0 \qquad (3)$$

$$\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+f\frac{Q|Q|}{2gDA^2}=0 \qquad (4).$$

Premena poenostavljenih enačb (3) in (4) z metodo karakteristik (MK) da združljivostne enačbe vodnega udara, ki veljajo vzdolž karakterističnih krivulj. Združljivostne enačbe v koračni obliki so numerično stabilne razen v primeru velikih izgub zaradi trenja in redke računske mreže. Obravnavane enačbe, zapisane za računsko točko i (sl. 1), se glase [2]:

- vzdolž C^+ karakteristike ($\Delta x/\Delta t = a$)

The method of characteristics (MOC) transformation of the simplified equations (3) and (4) produces the water-hammer compatibility equations, which are valid along the characteristics lines. The compatibility equations in finite-difference form are numerically stable unless the friction is large and the computational grid is coarse and, when written for a computational section i (Fig. 1), are [2]

- along the C^+ characteristic line ($\Delta x/\Delta t = a$)

$$H_{i,t} - H_{i-1,t-\Delta t} + \frac{a}{gA}\left(\left(Q_u\right)_{i,t} - \left(Q_d\right)_{i-1,t-\Delta t}\right) + \frac{f\Delta x}{2gDA^2}\left(Q_u\right)_{i,t}\left|\left(Q_d\right)_{i-1,t-\Delta t}\right| = 0 \qquad (5),$$

- vzdolž C^- karakteristike ($\Delta x/\Delta t = -a$)

- along the C^- characteristic line ($\Delta x/\Delta t = -a$)

$$H_{i,t} - H_{i+1,t-\Delta t} - \frac{a}{gA}\left(\left(Q_d\right)_{i,t} - \left(Q_u\right)_{i+1,t-\Delta t}\right) - \frac{f\Delta x}{2gDA^2}\left(Q_d\right)_{i,t}\left|\left(Q_u\right)_{i+1,t-\Delta t}\right| = 0 \qquad (6).$$

V primeru vodnega udara sta pretok na navzgornjem koncu računske točke i ($(Q_u)_i$) in pretok na navzdolnjem koncu točke ($(Q_d)_i$) enaka (nestalni kapljevinski tok). Na robu (rezervoar, ventil) enačba robnega pogoja nadomesti eno od združljivostnih enačb vodnega udara. V tem prispevku bomo uporabili deltoidno mrežo metode karakteristik [2].

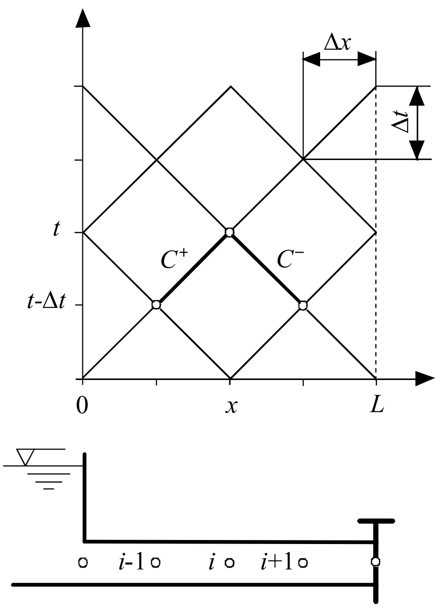
The discharge at the upstream side of the computational section i ($(Q_u)_i$) and the discharge at the downstream side of the section ($(Q_d)_i$) are identical for the water-hammer case (unsteady liquid flow). At a boundary (reservoir, valve), a device-specific equation replaces one of the water-hammer compatibility equations. The staggered grid in applying the method of characteristics [2] is used in this paper.

1.1 Nestalno kapljevinsko trenje v cevi

V algoritmih za vodni udar običajno uporabimo stalni ali navidezno stalni člen trenja. Ta

1.1 Unsteady Pipe Flow Friction

Traditionally, the steady or quasi-steady friction terms are incorporated into the water-hammer



Sl. 1. *Deltoidna mreža metode karakteristik za sistem hram - cevovod - ventil*
Fig. 1. *The method of characteristics staggered grid for a reservoir-pipe-valve system*

postavka velja za počasne prehode, pri katerih so strižne sile navidezno stalne. Uporaba navidezno stalnega modela trenja za hitre prehode da, kakor so pokazale primerjave med rezultati izračuna in meritev ([6] do [8]), znatna odstopanja v dušenju, obliki in času poteka tlačnih valov. Koeficient trenja, zapisan neposredno v enačbah (5) in (6), lahko izrazimo kot vsoto navidezno stalnega dela f_q in nestalnega dela f_u [9]:

algorithms. This assumption is satisfactory for slow transients where the wall shear stress has a quasi-steady behaviour. Previous investigations using the quasi-steady friction approximation for rapid transients ([6] to [8]) showed significant discrepancies in the attenuation, the shape and the timing of the pressure traces when computational results were compared with measurements. The friction factor, explicitly used in Eqs. (5) and (6), can be expressed as the sum of the quasi-steady part f_q and the unsteady part f_u [9]:

$$f = f_q + f_u \qquad (7).$$

Navidezno stalni koeficient trenja f_q je odvisen od Reynoldsovega števila in relativne hrapavosti cevi. V literaturi so predlagani številni modeli nestalnega trenja, ki jih delimo na enorazsežne (1D) in dvorazsežne (2D) modele. V 1D modelih približamo dejanski 2D prečni profil hitrosti in ustrezajoče izgube trenja. Z 2D modeli računamo dejanski prečni profil hitrosti med prehodnim pojavom. Modele trenja lahko razporedimo v šest skupin [7]:

1) člen trenja je odvisen od trenutne povprečne hitrosti V,
2) člen trenja je odvisen od trenutne povprečne hitrosti V in trenutnega krajevnega pospeška $\partial V/\partial t$,
3) člen trenja je odvisen od trenutne povprečne hitrosti V, trenutnega krajevnega pospeška $\partial V/\partial t$ in trenutnega konvektivnega pospeška $a\partial V/\partial x$ (Brunonejev model),
4) člen trenja je odvisen od trenutne povprečne hitrosti V in difuzije $\partial^2 V/\partial x^2$,
5) člen trenja je odvisen od trenutne povprečne hitrosti V in uteži za hitrostne spremembe v preteklosti $W(\tau)$ (konvolucijski model),
6) člen trenja je odvisen od trenutne porazdelitve hitrosti po prerezu (2D modeli).

V prispevku bomo obravnavali konvolucijski model nestalnega trenja ([4], [10] do [12]).

The quasi-steady friction factor, f_q, depends on the Reynolds number and the relative pipe roughness. A number of unsteady-friction models have been proposed in the literature including one-dimensional (1D) and two-dimensional (2D) models. The 1D models approximate the actual 2D cross-sectional velocity profile and the corresponding viscous losses in different ways. The 2D models compute the actual cross-sectional velocity profile continuously during the water-hammer event. The friction term can be classified into six groups [7]:

1) The friction term is dependent on instantaneous mean flow velocity, V,
2) The friction term is dependent on instantaneous mean flow velocity, V, and the instantaneous local acceleration, $\partial V/\partial t$,
3) The friction term is dependent on the instantaneous mean flow velocity, V, the instantaneous local acceleration, $\partial V/\partial t$, and the instantaneous convective acceleration, $a\partial V/\partial x$ (Brunone's model),
4) The friction term is dependent on the instantaneous mean flow velocity, V, and the diffusion, $\partial^2 V/\partial x^2$,
5) The friction term is dependent on the instantaneous mean flow velocity, V, and the weights for past velocity changes, $W(\tau)$ (convolution-based model),
6) The friction term is based on the cross-sectional distribution of instantaneous flow velocity (2D models).

This paper deals with the convolution-based unsteady-friction model ([4], [10] to [12]).

1.2 Prehodni kavitacijski tok

Kavitacijski tok v cevi se pojavi pri nizkih tlakih med prehodnimi pojavi. Prehodna kavitacija znatno vpliva na obliko tlačnega vala. Enačbe vodnega udara postavljene za enofazni prehodni tok, ne veljajo za dvofazni prehodni tok. Prehodna kavitacija v ceveh se pojavi v dveh

1.2 Transient Cavitating Pipe Flow

Cavitating pipe flow usually occurs as a result of low pressures during a transient event. Transient cavitation significantly changes the water-hammer waveform. Water-hammer equations developed for a one-phase liquid are not valid for the two-phase transient fluid flow. There are two basic types of

oblikah ([2] in [3]):
1) enokomponentni dvofazni tok (parna kavitacija, pretrganje stebra),
2) dvokomponentni dvofazni tok (plinska kavitacija, prost plin v kapljevinskem toku).

V prispevku obravnavamo parno kavitacijo v ceveh. Kavitacija se lahko pojavi kot krajevna kavitacija z velikim kavitacijskim razmernikom - kavitacija na robu ali visokem kolenu vzdolž cevi, ali kot nepretrgani kavitacijski tok z majhnim kavitacijskim razmernikom - enakomerno porazdeljeni mehurčki v kapljevini.

Parna kavitacija v ceveh se pojavi, ko se tlak kapljevine zniža na parni tlak kapljevine. Postavimo zanemarljivo majhno količino prostega in/ali izločenega plina v kapljevini. Ta postavka velja v večini industrijskih cevnih sistemov. Tlačni val v cevi potuje s stalno hitrostjo pri tlaku, večjem od parnega tlaka kapljevine. Tlačni valovi ne obstajajo v področju nepretrganega parnega kavitacijskega toka. Nezmožnost potovanja tlačnega vala v področju nepretrganega parnega toka je karakteristična ločnica med parno in plinsko kavitacijo. Razviti so bili številni modeli za popis parne kavitacije, to so diskretni parni kavitacijski model (DPAKM), diskretni plinski kavitacijski model (DPKM) z upoštevanjem majhnega plinskega razmernika ($\alpha_g \leq 10^{-7}$) in kombinirani parni kavitacijski model ([2] in [5]). Diskretni plinski kavitacijski model je preprost in daje natančne rezultate v širokem pasu obratovanja sistema [13]. V prispevku podajamo nov DPKM z upoštevanjem nestalnega kapljevinskega trenja v cevi.

2 DISKRETNI PLINSKI KAVITACIJSKI MODEL Z UPOŠTEVANJEM NESTALNEGA TRENJA

Diskretni plinski kavitacijski model (DPKM) dopušča plinske kavitacije v računskih točkah numerične mreže metode karakteristik. V cevnih odsekih med numeričnimi točkami obstaja kapljevina, kjer potujejo udarni valovi s stalno hitrostjo a. Diskretno plinsko kavitacijo popišemo z združljivostnima enačbama vodnega udara (5) in (6), kontinuitetno enačbo za prostornino plinske kavitacije in plinsko enačbo [14]. V računski točki deltoidne mreže metode karakteristik se kontinuitetna enačba za prostornino plinske kavitacije in plinska enačba glasita:
- kontinuitetna enačba za prostornino plinske kavitacije

transient cavitating flow in pipelines ([2] and [3]):
1) One-component two-phase transient flow (vaporous cavitation, column separation),
2) Two-component two-phase transient flow (gaseous cavitation, free gas in liquid flow).

This paper deals with vaporous cavitating pipe flow. Cavitation can occur as localized cavitation with a large void fraction, such as when a cavity forms at a boundary or at a high point along the pipeline, or as distributed cavitation with a small void fraction, such as when cavity bubbles are distributed homogeneously in a liquid.

Vaporous cavitation occurs in pipelines when the liquid pressure drops to the vapour pressure of the liquid. The amount of free and/or released gas in the liquid is assumed to be small. This is usually the case in most industrial piping systems. The water-hammer wave propagates at a constant speed as long as the pressure is above the vapour pressure. Pressure waves do not propagate through an established mixture of liquid and vapour bubbles. The inability of pressure waves to propagate through a distributed vaporous cavitation zone is a major feature distinguishing the flow with vaporous cavitation from the flow with gaseous cavitation. A number of numerical models have been developed to describe vaporous cavitation, including the discrete vapour-cavity model (DVCM), the discrete gas-cavity model (DGCM) by utilizing a low gas void fraction ($\alpha_g \leq 10^{-7}$) and the interface vaporous cavitation model ([2] and [5]). The discrete gas-cavity model is simple and performs accurately over a broad range of input parameters [13]. An improved DGCM that considers unsteady pipe friction is presented in this paper.

2 A DISCRETE GAS-CAVITY MODEL THAT CONSIDERS UNSTEADY FRICTION

The discrete gas-cavity model (DGCM) allows gas cavities to form at computational sections in the method of characteristics numerical grid. A liquid phase with a constant wave speed a is assumed to occupy the computational reach. The discrete gas-cavity model is described by the water-hammer compatibility equations (5) and (6), the continuity equation for the gas volume, and the ideal-gas equation [14]. Numerical forms of the continuity equation for the gas volume and the ideal gas equation within the staggered grid of the method of characteristics are:
- the continuity equation for the gas volume

$$\left(\forall_g\right)_{i,t}=\left(\forall_g\right)_{i,t-2\Delta t}+\left(\psi\left(\left(Q_d\right)_{i,t}-\left(Q_u\right)_{i,t}\right)+\left(1-\psi\right)\left(\left(Q_d\right)_{i,t-2\Delta t}-\left(Q_u\right)_{i,t-2\Delta t}\right)\right)2\Delta t \quad (8),$$

- plinska enačba

- the ideal-gas equation

$$\left(\forall_g\right)_{i,t}=\frac{\left(H_0-z_0-H_v\right)}{\left(H_{i,t}-z_i-H_v\right)}\alpha_{g0}A_i\Delta x \quad (9).$$

DPKM se uspešno uporablja za simuliranje plinske in parne ($\alpha_{g0} \le 10^{-7}$) kavitacije. V slednjem primeru se izračun prostornine diskretne kavitacije po enačbi (9) ponovi, ko je izračunana prostornina po enačbi (8) negativna.

The DGCM model has been successfully used for the simulation of both gaseous and vaporous ($\alpha_{g0} \le 10^{-7}$) cavitation. In the latter case, when the discrete cavity volume calculated by Eq. (8) is negative, then the cavity volume is recalculated by Equation (9).

2.1 Konvolucijski nestalni model trenja

2.1 Convolution-Based Unsteady Friction Model

Zielke [10] je s pomočjo analitičnih orodij razvil konvolucijski model (KM) nestalnega trenja za prehodni laminarni tok. Nestalni del koeficienta trenja v enačbi (7) popišemo kot konvolucijo utežne funkcije s krajevnimi pospeški v opazovanem časovnem pasu:

Zielke [10] analytically developed the convolution-based model (CBM) of unsteady friction for transient laminar flow. The unsteady part of the friction factor in Eq. (7) is defined by the convolution of a weighting function with past temporal accelerations:

$$f_u=\frac{32\nu A}{DQ|Q|}\int_0^t\frac{\partial Q}{\partial t^*}W_0\left(t-t^*\right)dt^* \quad (10).$$

Zielke je rešil enačbo (10) z upoštevanjem polne konvolucije, ki pa je računsko obsežna, saj obsega hitrosti v celotnem opazovanem časovnem pasu. Prispevek avtorjev k računsko učinkoviti in dovolj natančni rešitvi KM je v aproksimaciji utežne funkcije $W(\tau)$ kot končne vsote z N eksponentnimi členi [4]:

Zielke evaluated Eq. (10) using the full convolution scheme, which is computationally intensive because it requires convolution with a complete history of past velocities. The most recent approach to evaluate the CBM, which is efficient and accurate, makes an approximation of the weighting function $W(\tau)$ by a finite sum of N exponential terms [4]:

$$W_{app}\left(\tau\right)=\sum_{k=1}^{N}m_k e^{-n_k\tau} \quad (11).$$

Nestalni del koeficienta trenja je tedaj definiran kot:

The unsteady part of the friction factor is now defined as:

$$f_u=\frac{32\nu A}{DQ|Q|}\sum_{k=1}^{N}y_k\left(t\right) \quad (12),$$

kjer so členi $y_k(t)$ izraženi:

where the component $y_k(t)$ is expressed as follows:

$$y_k\left(t\right)=\int_0^t\frac{\partial Q}{\partial t^*}m_k e^{-n_k K\left(t-t^*\right)}dt^* \quad (13).$$

Pri tem konstanta K (= $4\nu/D^2$) spremeni čas t v brezrazsežni čas $\tau = 4\nu t/D^2$. V času $t + 2\Delta t$ člen y_k izrazimo z enačbo:

And where the constant K (= $4\nu/D^2$) converts the time t into the dimensionless time $\tau = 4\nu t/D^2$. At time $t + 2\Delta t$ the component y_k is:

$$y_k\left(t+2\Delta t\right)=\int_0^{t+2\Delta t}\frac{\partial Q}{\partial t^*}m_k e^{-n_k K\left(t+2\Delta t-t^*\right)}dt^* \quad (14).$$

Rešitev gornjega integrala v obliki zapisa z brezrazsežnim časovnim korakom $\Delta\tau$ (= $K\Delta t$) da učinkovit vrnilni izraz za člen y_k in s tem tudi za f_u:

Solving the integral and writing it in terms of the dimensionless time step $\Delta\tau$ (= $K\Delta t$) finally gives an efficient recursive expression for the component y_k and hence for f_u:

$$y_k\left(t+2\Delta t\right)=e^{-n_k K\Delta t}\left\{e^{-n_k K\Delta t}y_k\left(t\right)+m_k\left[Q\left(t+2\Delta t\right)-Q\left(t\right)\right]\right\} \tag{15}$$

Člen $y_k(t)$ je izračunan v predhodnem časovnem koraku in je znan v času $t + 2\Delta t$. Tako ni treba izvajati konvolucije v celotnem opazovanem pasu. Izpeljali smo koeficiente eksponente vrste m_k in n_k za Zielkejevo utežno funkcijo za prehodni laminarni tok [10] in za Vardy-Brownove utežne funkcije za prehodni turbulentni tok ([11] in [12]), dobimo jih v [4].

CBM model nestalnega trenja ne napove rahlega faznega odmika tlaka, ki ga razberemo iz rezultatov meritev ([15] in [16]). Fazni odmik je posledica nizkofrekvenčnih komponent karakteristik prehodnega pojava, ki so običajno reda velikosti osnovne frekvence. Iz tega izhaja, da je dejanska hitrost širjenja valov rahlo nižja od napovedane. Kapljevina ima dodatno vztrajnost zaradi nestalne porazdelitve hitrosti po prerezu, ki jo popišemo z vztrajnostnim popravnim koeficientom β [16]. Vztrajnostni popravni koeficient (VPF) definiramo:

The component $y_k(t)$ was calculated during a previous time step and is known at time $t + 2\Delta t$. There is now no convolution with the complete history of velocities required. The coefficients of the exponential sum m_k and n_k were developed both for Zielke's weighting function for transient laminar flow [10] and for Vardy-Brown's weighting functions for transient turbulent flow ([11] and [12]) and can be found in [4].

The CBM of unsteady friction cannot produce the small low-frequency shift observed in experimental results ([15] and [16]). The low-frequency shift is related to the lowest-frequency components of the transient event, which are normally at the fundamental frequency. This suggests that the true wave speed is slightly lower than expected and the liquid has an extra inertia due to the velocity distribution, which is related to the momentum correction factor β [16]. The momentum correction factor (MCF) is defined as:

$$\beta=\frac{1}{AV^2}\int_A v^2 dA \tag{16}$$

Dejansko se β malo spreminja med prehodnim pojavom ([17] in [18]). Postavimo, da je koeficient β nespremenjen in sloni na začetnih pretočnih pogojih, tj. $\beta = \beta_0$. Obravnavni postopek je uporabljen tudi v podobnih primerih, kakor je izpeljava Vardy-Brownove utežne funkcije. VPF lahko določimo iz logaritmičnega ali potenčnega zakona porazdelitve hitrosti [19]. Uporabimo Reynoldsov transportni teorem, postavimo nespremenljivo vrednost VPF in dobimo gibalno enačbo, ki se razlikuje od enačbe (4):

Realistic values of β do not vary greatly during a transient event ([17] and [18]). It is assumed that β is constant and based on the steady conditions preceding the transient event, i.e., $\beta = \beta_0$. This is common to other analyses, such as the Vardy and Brown unsteady-friction weighting function. The MCF can be determined from either the log or power laws for the velocity distribution [19]. Using the Reynolds transport theorem, it can be shown that if the constant MCF is considered, then the equation of motion (4) becomes:

$$\frac{\partial H}{\partial x}+\frac{\beta_0}{gA}\frac{\partial Q}{\partial t}+f\frac{Q|Q|}{2gDA^2}=0 \tag{17}$$

Premena enačb (3) in (17) z metodo karakteristik da združljivostne enačbe vodnega udara, ki se v koračni obliki glase:
- vzdolž C^+ karakteristike $\left(\Delta x/\Delta t=a/\sqrt{\beta_0}\right)$

The finite-difference form of water-hammer compatibility equations obtained by the MOC transformation of Equations (3) and (17) is
- along the C^+ characteristic line $\left(\Delta x/\Delta t=a/\sqrt{\beta_0}\right)$

$$H_{i,t}-H_{i-1,t-\Delta t}+\frac{a\sqrt{\beta_0}}{gA}\left(\left(Q_u\right)_{i,t}-\left(Q_d\right)_{i-1,t-\Delta t}\right)+\frac{f\Delta x}{2gDA^2}\left(Q_u\right)_{i,t}\left|\left(Q_d\right)_{i-1,t-\Delta t}\right|=0 \tag{18}$$

- vzdolž C^- karakteristike $\left(\Delta x/\Delta t=-a/\sqrt{\beta_0}\right)$

- along the C^- characteristic line $\left(\Delta x/\Delta t=-a/\sqrt{\beta_0}\right)$

$$H_{i,t}-H_{i+1,t-\Delta t}-\frac{a\sqrt{\beta_0}}{gA}\left(\left(Q_d\right)_{i,t}-\left(Q_u\right)_{i+1,t-\Delta t}\right)-\frac{f\Delta x}{2gDA^2}\left(Q_d\right)_{i,t}\left|\left(Q_u\right)_{i+1,t-\Delta t}\right|=0 \tag{19}$$

Vpeljava β_0 v enačbe vodnega udara da manj strme karakteristike, ki upočasnijo potek prehodnega pojava.

The inclusion of β_0 in the water-hammer equations causes the slope of the characteristics to decrease, representing a slowing of the transient.

3 PREIZKUSNA POSTAJA

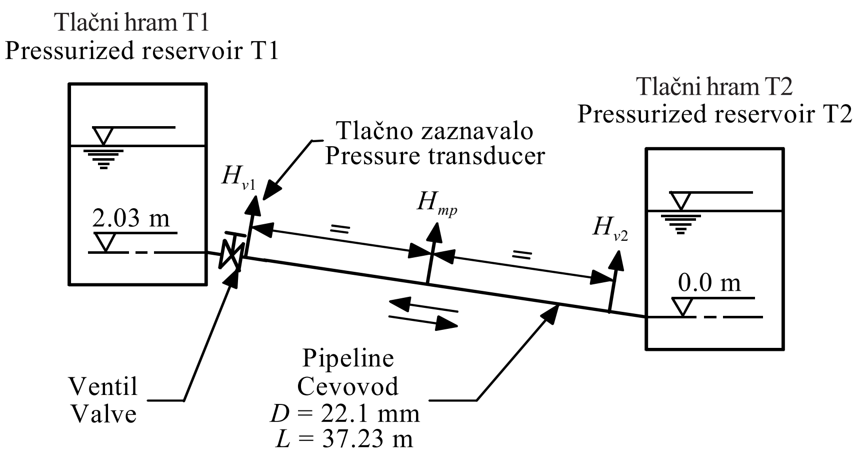
Preizkusna postaja za raziskave vodnega udara in kavitacijskega toka v ceveh je postavljena v Robinovem hidravličnem laboratoriju univerze v Adelaidi, Avstralija [20]. Merilna postaja je sestavljena iz ravnega bakrenega cevovoda z nagnjeno strmino dolžine 37,23 m ($U_x = \pm$ 0,01 m), notranjega premera 22,1 mm ($U_x = \pm$ 0,1 mm) in debeline stene cevi 1,63 mm ($U_x = \pm$ 0,05 mm). Cevovod je priključen na tlačni hram z leve in tlačni hram z desne strani (sl. 2). Merilna negotovost U_x je definirana kot kvadratni koren vsote kvadratov relativne in absolutne napake [21]. Strmina cevovoda je nagnjena s 5,45 % ($U_x = \pm$ 0,01 %).

Želeni tlak v obeh tlačnih hramih krmilimo z računalnikom. Neto prostornina vode v obeh tlačnih hramih in zmogljivost kompresorja omejujeta največjo stalno hitrost na 1,5 m/s in največji delovni tlak (tlačno višino) v obeh hramih na 400 kPa (40 m). Prehodni pojav na postaji je vzbujen s hitrim zapiranjem kroglastega zasuna. Hitro zaprtje ventila se lahko izvede z zapiralnim mehanizmom na torzijsko vzmet (čas zapiranja ventila t_c je nastavljiv od 5 do 10 milisekund) ali pa ročno. Vsak preizkus je izveden v dveh fazah. V prvi fazi dosežemo stalno pretočno hitrost ($U_x = \pm$ 1 % za prostorninsko metodo). V drugi fazi hitro zapiranje ventila vzbudi prehodni pojav. Hitrost širjenja udarnih valov ($U_x = \pm$ 0,1 %) je določena iz časa potovanja primarnega udarnega vala (prvi val, ki ga zazna tlačno zaznavalo) med zaprtim ventilom in bližnjo četrtino dolžine cevovoda.

3 EXPERIMENTAL APPARATUS

Laboratory apparatus for investigating water-hammer and column-separation events in pipelines was constructed in the Robin Hydraulics Laboratory at the University of Adelaide, Australia [20]. The apparatus comprises a straight 37.23 m ($U_x = \pm$0.01 m) long sloping copper pipe of 22.1 mm ($U_x = \pm$0.1 mm) internal diameter and of 1.63 mm ($U_x = \pm$0.05 mm) wall thickness connecting two pressurized tanks (Fig. 2). The uncertainty in a measurement, U_x, is expressed as a root-sum-square combination of the bias and precision error [21]. The pipe slope is constant at 5.45% ($U_x = \pm$0.01 %).

A specified pressure in each of the tanks is controlled by a computerized pressure-control system. The net water volume in both tanks and the capacity of the air compressor limits the maximum steady-state velocity to 1.5 m/s and the maximum operating pressure (pressure head) in each tank to 400 kPa (40 m). A transient event in the apparatus is initiated by a rapid closure of the ball valve. Fast closure of the valve is carried out either by a torsional spring actuator (the valve closure time t_c may be set from 5 to 10 milliseconds) or manually by hand. Each experiment using the apparatus consists of two phases. First, an initial steady-state velocity condition ($U_x = \pm$1% for the volumetric method) is established. Second, a transient event is initiated by a rapid closure of the valve. The wave-propagation velocity ($U_x = \pm$0.1%) is obtained from the measured time for the initial pressure wave (the first pressure wave passing the transducers) to travel between the closed valve and the quarter point nearest to the valve.



Sl. 2. *Preizkusna postaja*
Fig. 2. *Experimental apparatus layout*

Na navzgornjem in navzdolnjem koncu cevovoda ter na polovici dolžine cevovoda so na notranji premer cevi vgrajena piezoelektrična tlačna zaznavala (Kistler 610 B, $U_x = \pm 0,7$ %). Temperatura vode ($U_x = \pm 0,5$ °C) je stalno merjena v hramu T1. Lega ventila med zapiranjem je merjena z optičnimi zaznavali ($U_x = \pm 0,0001$ s). Meritev je registrirana in analizirana z merilnim računalnikom Concurrent 6655 v okolju UNIX.

4 PRIMERJAVA REZULTATOV IZRAČUNA IN MERITEV

Rezultati izračunov in meritev prehodnih pojavov v preizkusni postaji (sl. 2) so podani za dva primera z začetnima pretočnima hitrostima V_0 = {0,30; 1,40} m/s pri stalni statični višini v tlačnem hramu T2 H_{T2} = 22 m [5]. Računski rezultati, dobljeni z DPKM z upoštevanjem nestalnega trenja po KM in vztrajnostnega popravnega koeficienta (DPKM + KM + VPF), so primerjani z rezultati meritev. Izračuni in meritve so bili izdelani za primer hitrega zapiranja ventila na navzdolnjem koncu cevovoda s pozitivno strmino pri tlačnem hramu T1 (sl. 2). Čas zapiranja ventila za oba primera je bil enak, t_c = 0,009 s, kar je precej krajše od odbojnega časa udarnega vala $2L/a = 2\times37,23/1319 = 0,056$ s (a = 1319 m/s je izmerjena hitrost udarnega vala). Ventil začne hitro zapirati v času t = 0,0 s. V izračunu je izbran nabor števila cevnih odsekov N = {16, 32, 64, 128, 256}, da se preveri grobost računskega modela [22]. V enačbi (8) je bil izbran utežni koeficient ψ = 1,0, v enačbi (9) pa je bila izbrana dovolj majhna vrednost plinskega kavitacijskega razmernika $\alpha_{g0} = 10^{-7}$ ([13] in [14]). Vztrajnostni koeficient v enačbah (18) in (19) je odvisen od začetne pretočne hitrosti [19]; za V_0 = 0,30 m/s znaša β_0 = 1,0332, za V_0 = 1,40 m/s pa β_0 = 1,0224. Izdelali smo tudi izračune z DPKM z upoštevanjem navidezno stalnega modela trenja (DPKM+NST), da bi izluščili vpliv modelov trenja na rezultate izračuna. Izračunani in izmerjeni rezultati so primerjani pri ventilu (H_{v1}) in na polovici dolžine cevovoda (H_{mp}) (sl. 2).

Primerjava rezultatov izračuna in meritev za primer z začetno pretočno hitrostjo V_0 = 0,30 m/s in dveh števil računskih cevnih odsekov N = {32, 128} je podana na slikah 3 in 4. Manjše število cevnih odsekov je običajno izbrano v inženirskih analizah vodnega udara. Večje število cevnih odsekov bi moralo dati bolj natančne rezultate izračuna (konvergenčni in stabilnostni kriterij).

Three flush-mounted piezoelectric-type pressure transducers (Kistler 610 B, $U_x = \pm 0.7$ %) are positioned at the endpoints and at the midpoint. The water temperature ($U_x = \pm 0.5$°C) in reservoir T1 is continuously monitored and the valve position during closure is measured using optical sensors ($U_x = \pm 0.0001$ s). Data acquisition and processing were performed with a Concurrent 6655 real-time UNIX data-acquisition computer.

4 COMPARISON OF COMPUTATIONAL AND EXPERIMENTAL RESULTS

A numerical and experimental analysis of the transient events in the laboratory apparatus (Fig. 2) is presented for two different initial flow-velocity cases V_0 = {0.30; 1.40} m/s at a constant static head in the pressurized reservoir T2 H_{T2} = 22 m [5]. The numerical results from the DGCM and the CBM of unsteady friction with the momentum correction factor (DGCM+CBM+MCF) are compared with the results of measurements. Computational and experimental runs were performed for a rapid closure of the valve positioned at the downstream end of the upward sloping pipe at the pressurized tank T1 (Fig. 2). The valve closure time for the two runs was identical, t_c = 0.009 s, which is significantly shorter than the water-hammer wave-reflection time of $2L/a = 2\times37.23/1319 = 0.056$ s (a = 1319 m/s is the measured water-hammer wave speed). The rapid valve closure begins at time t = 0.0 s. Different numbers of reaches were selected for each computational run N = {16, 32, 64, 128, 256} to examine the numerical robustness of the model [22]. The value of the weighting factor ψ = 1.0 was used in Eq. (8), and a small gas void fraction of $\alpha_{g0} = 10^{-7}$ was selected in Eq. (9) ([13] and [14]). The momentum correction factor depends on the initial flow velocity [19] and its value used in Eqs. (18) and (19) is β_0 = 1.0332 for V_0 = 0.30 m/s and β_0 = 1.0224 for V_0 = 1.40 m/s. In addition, the DGCM and the quasi-steady friction model (DGCM+QSF) results are included in the analysis to compare the effect of friction modelling on the computational results. The computational and experimental results are compared at the valve (H_{v1}) and at the midpoint (H_{mp}) (Fig. 2).

A comparison of the numerical and experimental results for an initial flow velocity V_0 = 0.30 m/s and different numbers of computational reaches N = {32, 128} is presented in Figs. 3 and 4 respectively. Traditionally, a lower number of reaches is used in water-hammer analysis. A higher number of reaches should give more accurate results (convergence and stability criteria).

Hitro zapiranje ventila v primeru za H_{T2} = 22 m in začetno hitrost V_0 = 0,30 m/s vzbudi vodni udar s pretrganjem kapljevinskega stebra. Največjo izmerjeno višino pri ventilu $H_{v1;max}$ = 95,6 m razberemo po zrušitvi prve kavitacije v obliki ozkega tlačnega utripa. Obremenitev z največjo višino je kratkotrajna (0,00628 s). Največja izračunana višina z DPKM+NST je $H_{v1;max}$ = 99,6 m in z DPKM+KM+VPF $H_{v1;max}$ = 95,1m. Rezultati izračuna, dobljeni z DPKM+NST, se dobro ujemajo z izmerjenimi rezultati za prvi in drugi tlačni utrip. Odstopanja med rezultati se večajo s časom prehoda. Rezultati, dobljeni z DPKM+KM+VPF, se dobro ujemajo z izmerjenimi rezultati v širokem pasu opazovanja prehodnega pojava.

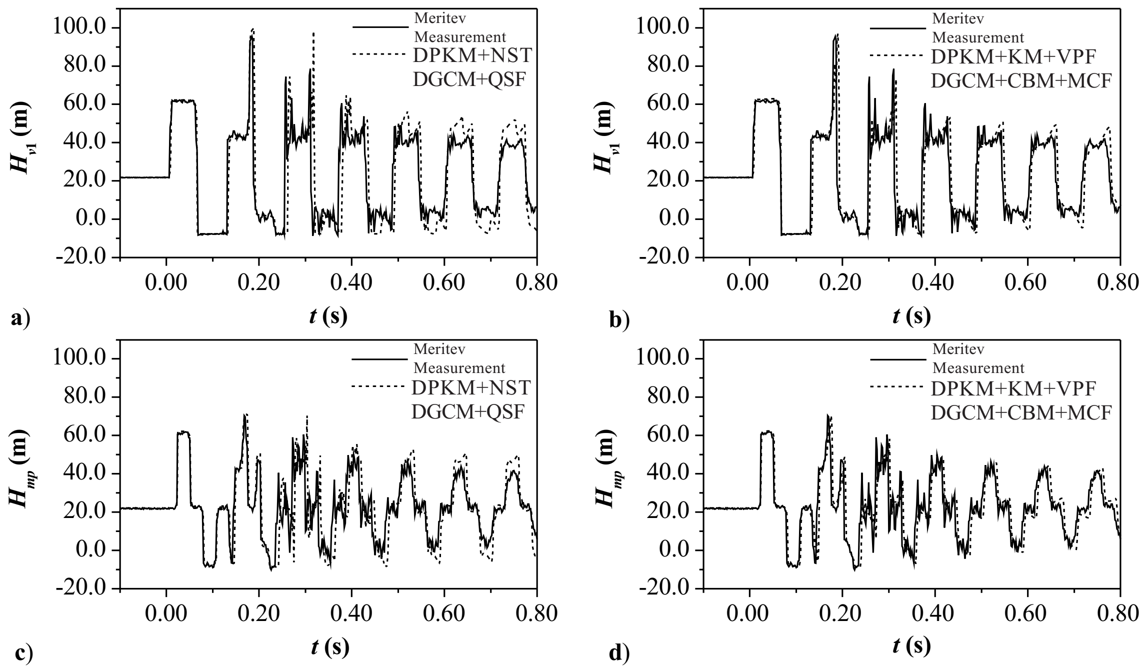
Primerjava rezultatov izračuna in meritev za primer z začetno pretočno hitrostjo V_0 = 1,40 m/s in dveh števil računskih cevnih odsekov N = {32, 128} je podana na slikah 5 in 6.

V obravnavanem primeru je največja višina pri ventilu enaka višini vodnega udara v času $2L/a$ po zaprtju ventila. Izmerjena največja višina je $H_{v1;max}$ = 210,9 m. Največji višini, določeni z DPKM+NST in DPKM+KM+VPF, se dobro ujemata

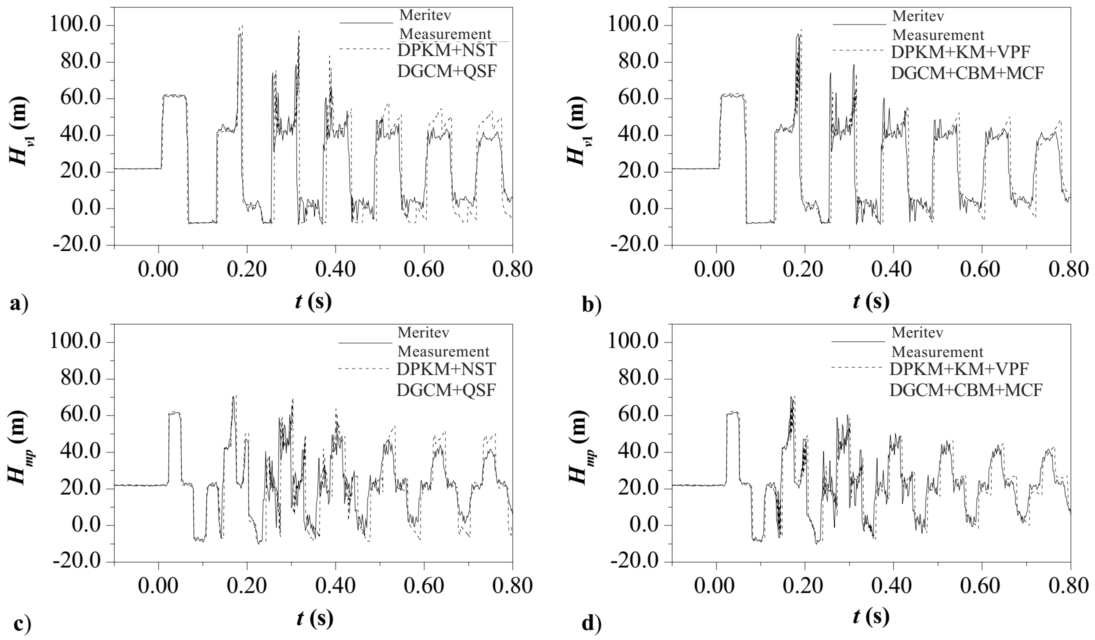
A rapid valve closure for H_{T2} = 22 m and an initial flow velocity V_0 = 0.30 m/s generates a water-hammer event with liquid column separation. The maximum measured head at the valve $H_{v1;max}$ = 95.6 m occurs as a short-duration pressure pulse after the first cavity collapses. The duration of the maximum head is very short (0.00628 s). The maximum computed heads predicted by DGCM+QSF and DGCM+CBM+MCF are $H_{v1;max}$ = 99.6 m and $H_{v1;max}$ = 95.1m, respectively. The computational results obtained by the DGCM+QSF agree well with the experimental results for the first and the second pressure-head pulse. The discrepancies between the results are greater for later times. The results obtained using the DGCM+CBM+MCF give pressure histories that are in good agreement with the experimental results for longer time periods.

A comparison of the numerical and experimental results for an initial flow velocity V_0 = 1.40 m/s and different numbers of computational reaches N = {32, 128} is presented in Figs. 5 and 6, respectively.

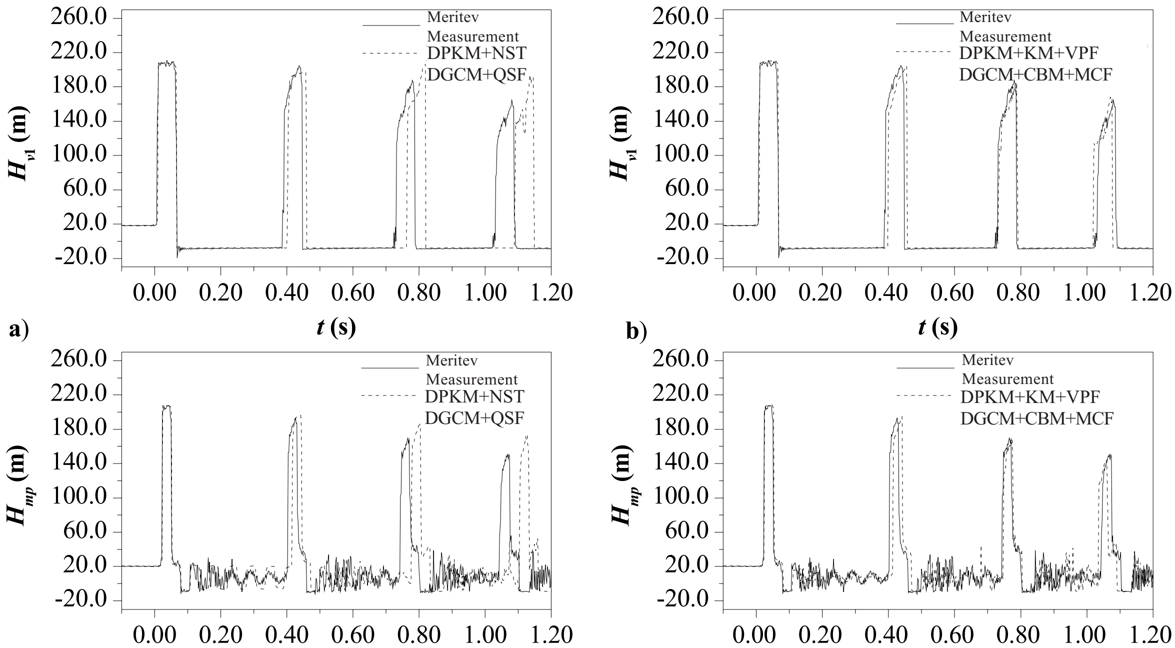
The maximum head at the valve for this case is the water-hammer head generated at a time of $2L/a$ after the valve closure. The value of the maximum measured head is $H_{v1;max}$ = 210.9 m. The maximum head predicted by the DGCM+QSF and



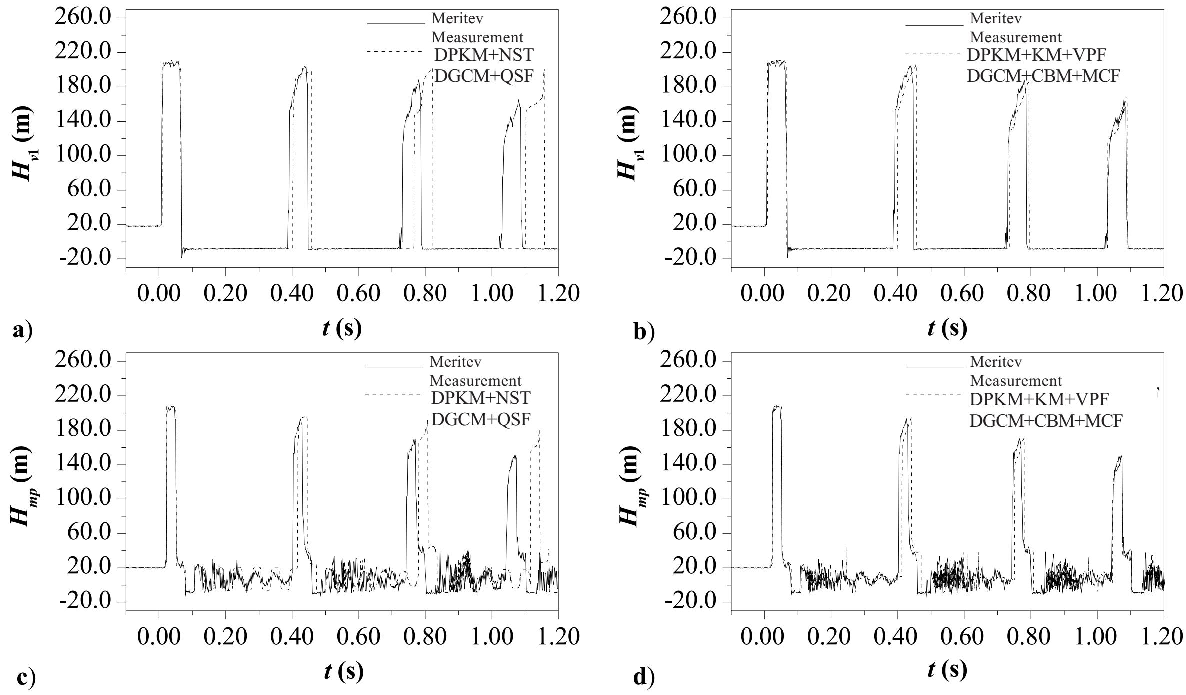
Sl. 3. *Primerjava višin pri ventilu (H_{v1}) in na polovici dolžine cevovoda (H_{mp}):*
Fig. 3. *Comparison of heads at the valve (H_{v1}) and at the midpoint (H_{mp}):*
V_0 = 0.30 m/s, H_{T2} = 22 m, N = 32



Sl. 4. *Primerjava višin pri ventilu (H_{v1}) in na polovici dolžine cevovoda (H_{mp}):*
Fig. 4. *Comparison of heads at the valve (H_{v1}) and at the midpoint (H_{mp}):*
$V_0 = 0.30$ m/s, $H_{T2} = 22$ m, $N = 128$



Sl. 5. *Primerjava višin pri ventilu (H_{v1}) in na polovici dolžine cevovoda (H_{mp}):*
Fig. 5. *Comparison of heads at the valve (H_{v1}) and at the midpoint (H_{mp}):*
$V_0 = 1.40$ m/s, $H_{T2} = 22$ m, $N = 32$



Sl. 6. *Primerjava višin pri ventilu (H_{vl}) in na polovici dolžine cevovoda (H_{mp}):*
Fig. 6. *Comparison of heads at the valve (H_{vl}) and at the midpoint (H_{mp}):*
V_0 = 1.40 m/s, H_{T2} = 22 m, N = 128

z izmerjeno višino. Čas obstoja prve kavitacije pri ventilu, določen z DPKM+KM+VPF, se bolje ujema od časa, določenega z DPKM+NST (meritev: 0,318 s; DPKM+NST: 0,331 s; DPKM+KM+VPF: 0,325 s). Rezultati izračuna, dobljeni z DPKM+NST, se dobro ujemajo z rezultati meritve do zrušitve prve kavitacije pri ventilu. Iz rezultatov, dobljenih z DPKM+KM+VPF, razberemo znatno izboljšanje napovedi dušenja in faznega odmika tlačnih utripov v primerjavi z rezultati, dobljenimi z DPKM+NST. Rezultati izračuna z večjim številom cevnih odsekov se bolje ujemajo z rezultati meritev. Sklepamo, da upoštevanje modela nestalnega trenja v DPKM (DPKM+KM+VPF) da bolj natančne rezultate v primerjavi z rezultati, dobljenimi z upoštevanjem modela navidezno stalnega trenja (DPKM+NST).

4.1 Konvergenca in stabilnost

Numerični model DPKM+KM+VPF, vgrajen v MK računsko mrežo, mora zadostiti konvergenčnim in stabilnostnim kriterijem. Konvergenca definira stalno rešitev, ko se Δx in

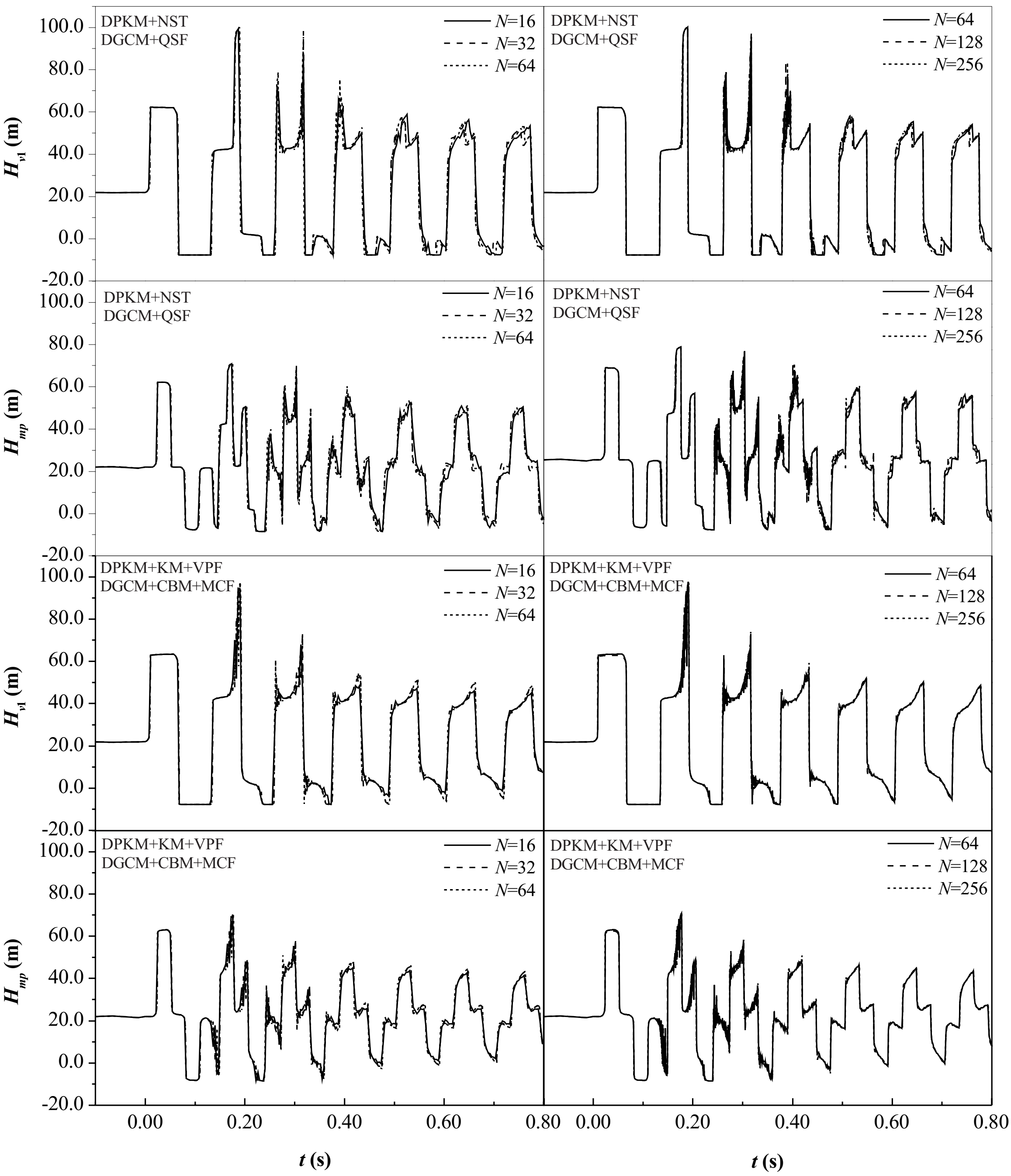
DGCM+CBM+MCF closely matches the measured head. The duration of the first cavity at the valve is predicted better by the DGCM+CBM+MCF than by the DGCM+QSF (measurement: 0.318 s; DGCM+QSF: 0.331 s; DGCM+CBM+MCF: 0.325 s). Computational results obtained with the DGCM+QSF agree well with experimental results until the first cavity at the valve collapses. The results from the DGCM+CBM+MCF show significant improvement in terms of both the attenuation and phase shift of the pressure-head traces when compared to the DGCM+QSF results. When the number of computational reaches is increased, the computational and measured results agree better. Inclusion of the unsteady-friction model into the DGCM (DGCM+CBM+MCF) significantly improves the results compared to those using the quasi-steady friction model (DGCM+QSF).

4.1 Convergence and Stability

The numerical solution of the DGCM+CBM+MCF incorporated into the MOC computational grid should satisfy the convergence and stability criteria. Convergence relates to the behaviour of

Δt približujeta ničli, stabilnost rešitve pa je odvisna od napake zaokrožitve [1]. V tem prispevku sta konvergenca in stabilnost DPKM+KM+VP in DPKM+NST preverjena z metodo nabora cevnih odsekov [22] v pasu N = {16, 32, 64, 128, 256}. Na sliki 7 so podani rezultati izračuna za primer z

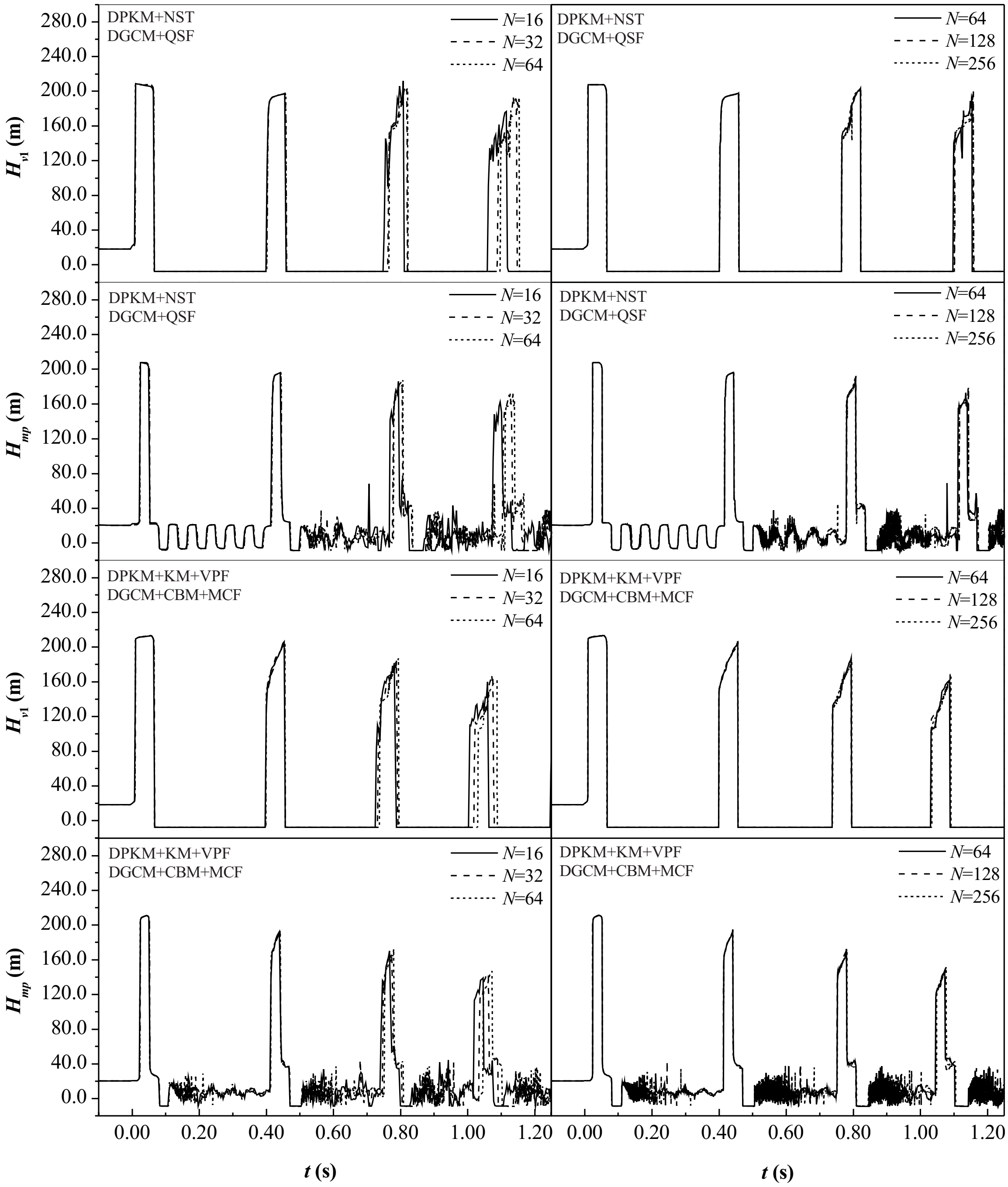
the solution as *Δx* and *Δt* tends to zero, while stability is concerned with the round-off error growth [1]. The influence of the different numbers of computational reaches N = {16, 32, 64, 128, 256} is investigated for the DGCM+CBM+MCF [22]. In addition, a numerical analysis of the DGCM+QSF model is included as well. Fig. 7



Sl. 7. *Računska analiza: V_0 = 0,30 m/s, H_{T2} = 22 m*
Fig. 7. *Numerical analysis: V_0 = 0.30 m/s, H_{T2} = 22 m*

začetno pretočno hitrostjo V_0 = 0,30 m/s z blago kavitacijo. Rezultati, dobljeni z obema modeloma so konzistentni s povečanjem števila odsekov. To pa ne velja za rezultate izračuna v primeru z začetno hitrostjo V_0 = 1,40 m/s na sliki 8. Intenzivna kavitacija vzdolž cevi v obliki področij

shows the numerical results for the case with an initial flow velocity V_0 = 0.30 m/s with moderate cavitation. The results for both models are consistent as the number of reaches is increased. This is not the case for the numerical runs with initial velocity V_0 = 1.40 m/s in Fig. 8. Severe cavitation along the pipeline forms distributed,



Sl. 8. *Računska analiza: V_0 = 1,40 m/s, H_{T2} = 22 m*
Fig. 8. *Numerical analysis: V_0 = 1.40 m/s, H_{T2} = 22 m*

nepretrganega parnega kavitacijskega toka in diskretnih kavitacij, ki jih razberemo iz meritev, je v DPKM modelih (sl. 5 in 6) popisana približno. Zrušitev velike kavitacije pri ventilu in diskretnih kavitacij vzdolž cevovoda vzbudi strma tlačna valovna čela, ki potujejo vzdolž cevi. Primerjava rezultatov izračuna in meritev (sl. 5 in 6) jasno pokaže, da DPKM+KM+VPF bolje popiše fizikalni pojav pri večjem številu cevnih odsekov. V splošnem amplituda in časovni potek glavnih tlačnih utripov, določenih z upoštevanjem navidezno stalnega in nestalnega trenja, konvergirata s povečanjem števila cevnih odsekov (vsak model konvergira k nekoliko različnemu rezultatu). DPKMne vzbudi visokih fizikalno nerealnih tlačnih utripov v primerjavi z diskretnim parnim kavitacijskim modelom (DPAKM) ([7] in [13]). Računska modela pa ne napovesta nekaterih visokofrekvenčnih utripov, razbranih v meritvah. Dosedanje preizkusne raziskave so pokazale, da prehodne kavitacije vzdolž cevi niso homogene ([23] in [24]), zato nekateri visokofrekvenčni pulzi niso ponovljivi in tudi ne vplivajo na glavne tlačne utripe. Podoben pojav lahko izluščimo v rezultatih izračuna z DPKM, pri katerih so nekateri visokofrekvenčni tlačni utripi vplivani s številom cevnih odsekov. Ta pojav zaznamo v področjih z blago kavitacijo vzdolž cevovoda (nepretrgani parni kavitacijski tok, diskretne kavitacije) kot posledico popisa kavitacije z različnim številom cevnih odsekov. Ta vpliv pa je zanemarljiv v primerjavi z odzivom na veliki skali.

vaporous cavitation zones and intermediate cavities that have been recorded by measurements and only approximately accounted for in the DGCMs (Figs. 5 and 6). The collapse of a large cavity at the valve and intermediate cavities along the pipe create steep pressure wave fronts that travel along the pipe. Comparisons between the measured and computed results clearly showed (Figs. 5 and 6) that the DGCM+CBM+MCF better represents the real flow situation as the number of computational reaches is increased. Generally, the magnitude and timing of the main pressure pulses predicted by the DGCM model using either the quasi-steady or the convolution-based model converge as the number of reaches is increased (although each method converges to a slightly different solution). The DGCM model does not generate large, unrealistic pressure spikes in comparison to the discrete vapour-cavity model (DVCM) ([7] and [13]). However, there still remain some high-frequency peaks in the experimental measurements that are not reproduced by either numerical model. Previous experimental studies clearly showed that transient cavities along the pipeline are not distributed homogeneously ([23] and [24]); therefore, some high-frequency peaks are not repeatable and do not affect the main pressure pulses significantly. A similar behaviour is revealed in the DGCM computational results in that some high-frequency peaks vary with the different numbers of reaches. This behaviour occurs in regions with distributed vaporous cavitation and intermediate cavities where small-scale cavitation takes place in slightly different ways for different numbers of computational reaches. However, typically this behaviour is small compared to the bulk transient response.

5 SKLEP

Podana je primerjava med rezultati izračuna in meritev za primer hitrega zapiranja navzdolnjega ventila v preprostem cevnem sistemu. Primerjana sta diskretni plinski kavitacijski model z upoštevanjem navidezno stalnega kapljevinskega trenja (DPKM+NST) in nestalnega trenja z uporabo konvolucijega modela (DPKM+KM+VPF). Primerjalna analiza obsega primer z blago in primer z intenzivno kavitacijo. Konvolucijski model nestalnega trenja bolj natančno popiše nestalno kapljevinsko trenje v primerjavi z navidezno stalnim približkom. Upoštevanje nestalnega trenja v DPKM da zato bolj natančne računske rezultate. Raziskali smo tudi vpliv izbire števila cevnih odsekov. Računska analiza pokaže, da je DPKM+KM+VPF grob s povečanjem števila cevnih

5 CONCLUSION

Results from the discrete gas-cavity model with the quasi-steady friction approximation (DGCM+QSF) and with the convolution-based unsteady-friction model (DGCM+CBM+MCF) are compared with the results of measurements for a fast-downstream end-valve closure in a simple reservoir-pipeline-valve laboratory apparatus. A comparative analysis includes experimental tests for two different flow conditions with moderate and severe cavitation. The convolution-based unsteady-friction model better captures the behaviour of unsteady fluid friction than the quasi-steady friction approximation. The results clearly show that the inclusion of unsteady friction into the DGCM significantly improves the numerical results. The influence of the different numbers of reaches is also investigated. The examination of the computational results reveals the numerically robust odsekov. Obravnavani model zaradi dobrega ujemanja rezultatov izračuna z meritvami in računske grobosti priporočamo za inženirsko uporabo.

behaviour of the DGCM+CBM+MCF as the number of reaches increases. Due to the excellent matches with experimental data and the robust numerical algorithm this model is recommended for engineering practice.

Zahvala

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6 OZNAČBE
6 SYMBOLS

prečni prerez	A	pipe area
hitrost širjenja udarnih (tlačnih) valov	a	water-hammer (pressure) wave speed
premer cevi	D	pipe diameter
Darcy-Weisbachov koeficient trenja	f	Darcy-Weisbach friction factor
zemeljski pospešek	g	gravitational acceleration
piezometrična višina (višina)	H	piezometric head (head)
parna tlačna višina	H_v	gauge vapour pressure head
dolžina cevi	L	pipe length
koeficienti eksponentne vrste	m_k, n_k	exponential sum coefficients
število cevnih odsekov	N	number of computational reaches
pretok	Q	discharge
navzdolnji pretok	Q_d	node downstream end discharge
navzgornji pretok	Q_u	node upstream end discharge
Reynoldsovo število = VD/ν	R_e	Reynolds number = VD/ν
čas	t, t^*	time
čas zapiranja ventila	t_c	valve closure time
merilna negotovost	U_x	uncertainty in a measurement
povprečna pretočna hitrost	V	average flow velocity
pretočna hitrost	v	flow velocity
utežna funkcija	W	weighting function
kordinata vzdolž cevi	x	distance along the pipe
člen utežne funkcije	y_k	component of the weighting function
geodetska višina	z	pipeline elevation
plinski kavitacijski razmernik	α_g	gas void fraction
vztrajnostni korekcijski koeficient	β	momentum correction factor
časovni korak	Δt	time step
dolžina cevnega odseka	Δx	reach length
brezrazsežni časovni korak	$\Delta \tau$	dimensionless time step
strmina cevovoda	θ	pipe slope
kinematična viskoznost	ν	kinematic viscosity
brezrazsežni čas	τ	dimensionless time
utežni koeficient	ψ	weighting factor
diskretna prostornina kavitacije	$\forall$	discrete cavity volume

Indeksi:		*Subscripts:*
približen	app	approximate
plin	g	gas
računska točka	i	node number
polovica dolžine cevovoda	mp	midpoint
navidezno stalni del	q	quasi-steady part
hram	T	tank (reservoir)
čas	t	time
nestalni del	u	unsteady part
ventil	v	valve
stalen (začeten) ali referenčen	0	steady state (initial) or reference

Okrajšave:		*Abbreviations:*
diskretni plinski kavitacijski model	DPKM/DGCM	discrete gas-cavity model
diskretni plinski kavitacijski model z navidezno stalnim trenjem	DPKM+NST/ DGCM+QSF	discrete gas-cavity model with quasi-steady friction
diskretni plinski kavitacijski model s konvolucijskim modelom in vztrajnostnim popravnim faktorjem	DPKM+KM+ +VPF/DGCM+ +CBM+MCF	discrete gas-cavity model with convolution-based model and momentum correction factor
diskretni parni kavitacijski model	DPAKM/DVCM	discrete vapour-cavity model
metoda karakteristik	MK/MOC	method of characteristics

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Statistični pristop k analizi hladilnih sistemov s hladilnimi stolpi na naravni vlek

A Statistical Approach to the Analysis of Cooling Systems with Natural-Draft Cooling Towers

Jure Smrekar - Janez Oman - Brane Širok

Povečevanje in zaostrovanje zahtev pri obratovanju termoelektrarn, z namenom da bi pocenili proizvodnjo električne energije in zagotovili čistejše okolje, je pripeljalo do potrebe po optimizaciji celotnega postopka. Leta je v načelu sestavljen iz dovoda toplote v krožni proces, iz samega krožnega postopka in iz odvoda toplote v okolico. Optimizacija vseh treh sklopov energetskega postrojenja zagotavlja najboljše rezultate.

Prispevek se nanaša na analizo meritev energijskih parametrov bloka 4 Termoelektrarne Šoštanj in prikazuje vpliv hladilnega sistema na izkoristek termoelektrarne. Analiza obsega statistične pristope analize termoenergetskega postrojenja, ki omogočajo vpogled v medsebojno odvisnost posamičnih parametrov in vplive na povečevanje izkoristka termoelektrarne. V našem primeru je glavni element hladilnega sistema hladilni stolp na naravni vlek, saj pomeni povezavo termoelektrarne z okolico. Približevanje optimalnejšemu obratovanju hladilnega sistema tako prispeva znatne prihranke pri porabi goriva in zmanjšani emisiji dimnih plinov. Prispevek vsebuje potrditev značilne linearne soodvisnosti med prenesenim toplotnim tokom na okolico in močjo na sponkah generatorja.

(Ključne besede: sistemi hladilni, stolpi hladilni, analize sistemov, postopki statistični)

Changes to the operating requirements at power plants, with the intention of lowering energy costs and ensuring a cleaner environment, have brought optimization to the whole process. In principle, the process consists of an inlet heat stream to the process, the steam cycle itself and the rejected heat stream to the environment. The optimization of all three parts of the energetic system will ensure the best results. This study relates to an analysis of the measurements of energetic parameters at Block 4 of the Šoštanj power plant and shows the influence of the cooling system on the power plant's efficiency.

The paper includes a statistical approach to the analysis of a thermo-energetic system that enables an understanding of the relations between the parameters and shows guidelines for enlarging the thermo-energetic efficiency. The main part of the cooling system is the natural-draft cooling tower, which represents the interaction between the power plant and the environment. Approaching the optimal operating point of the cooling system contributes to fuel savings and decreasing the amount of exhaust-gas pollution. This paper also includes a verification of the typical linear relation between the heat transferred to the environment and the generation of power.

(Keywords: cooling systems, cooling towers, systems analysis, statistical approach)

0 UVOD

Optimalno delovanje hladilnega sistema se izraža v največjem pridobljenem delu iz turbine in tako večjem celotnem izkoristku termoelektrarne zaradi najmanjše odvedene toplote iz sistema. Učinkovitost delovanja hladilnega sistema je eden

0 INTRODUCTION

The optimal operating condition of a cooling system results in the maximum acquired work from the turbine and overall power-plant efficiency because of the minimal amount of heat rejected to the environment. The efficiency of the cooling system izmed odločilnih dejavnikov, ki pomembno vplivajo na izkoristek termoenergetskega sistema kot celote. Kakovosten hladilni sistem pomeni manjšo izgubo toplote, kar omogoča manjše hladilne naprave in manj hladilne vode.

Količina toplote, odvedene s hladilnim sistemom, je večja od toplote, ki se v parnem krožnem postopku spremeni v delo. V današnjih hladilnih sistemih, novih in starih termoelektrarn, je odvedena toplota od 1,3 do 2,5-krat večja od koristno pridobljenega dela iz termoelektrarne.

Pri načrtovanju stolpov je najpomembnejši parameter izkoristek hlajenja hladilnega stolpa. Z zmanjšanjem odvedene toplote se izkoristek krožnega postopka sam po sebi izboljša. Za ocenjevanje omenjenih izboljšav se med drugim uporablja tudi koeficient $\dot{Q}_{od} / P$ [1]. Z zmanjšanjem koeficienta je mogoče izboljšati učinkovitost celotnega termoenergetskega postrojenja, kar pa je odvisno od celovitih in lokalnih karakteristik hladilnega sistema, pri katerem je v analiziranem primeru glavni element hladilni stolp.

Večina današnjih hladilnih stolpov je starih 30 do 50 let in njihovo obratovanje ni več optimalno. Naletimo na velike temperaturne in hitrostne neenakosti, ki se kažejo v različnih temperaturnih in hitrostnih stanjih zraka po prečnem prerezu hladilnega stolpa, kar ima za posledico manjšo učinkovitost stolpa ([2] in [6]). Anomalije so odvisne od konstrukcijskih lastnosti delilnih vodnih sistemov, prenosnikov toplote v hladilnih stolpih ali od vplivov okolja na hitrostne razmere zraka, ki vteka v stolp. Z odpravo krajevnih nepravilnosti hitrostnega in temperaturnega polja se izkoristek hladilnega stolpa poveča, kar posledično povečuje izkoristek celotnega termoenergetskega sistema.

Dosedanje analize delovanja hladilnih stolpov večinoma temeljijo le na poznavanju parametrov okoliškega zraka ter parametrov vstopne in izstopne hladilne vode. S takšno analizo je mogoče ugotoviti le celotne lastnosti delovanja hladilnega stolpa, ki pa so vsekakor odvisne od učinkovitosti prenosa toplote na krajevni ravni. Analiza obsega proučevanje povezave med učinkovitostjo prenosa toplote na krajevni in celoviti ravni z močjo generatorja. Povezanost parametrov je prikazana z uporabo statističnih orodij. Prispevek vsebuje tudi predloge za izboljšave učinkovitosti prenosa toplote v hladilnih stolpih.

is one of the most important parameters that have a large impact on the power plant's efficiency. A high-quality cooling system represents lower heat losses, which leads to smaller cooling devices and less demand for cooling water.

Heat rejected with the cooling system is larger than the heat converted by the steam cycle into useful work. In currently operating systems, old and new, the heat extracted varies from 1.3 to 2.5 times the useful work extracted from the thermodynamic system.

When constructing a cooling tower the most important parameter is the tower's efficiency. With the reduction of heat rejected to the environment, the overall power-plant efficiency improves by itself. For estimating this kind of improvement the coefficient $\dot{Q}_{od} / P$ [1] is often used. With a reduction of this coefficient it is possible to increase the efficiency of the power plant, which depends on the local characteristics of the cooling system, which in our case is the main part of the natural-draft cooling tower.

The majority of today's cooling towers are 30 to 50 years old, and their operation is no longer optimal. We come across large inhomogeneities in the air, which are shown in different temperatures and velocities across the cross-section of the cooling tower. This has the consequences of lower efficiency of the tower ([2] and [6]). The anomalies depend on the construction properties of the distribution water system, the heat exchangers in the cooling towers or the atmospheric influences on the air velocity distribution entering the cooling tower. Cooling-tower efficiency increases with the elimination of local irregularities of the temperature and velocity fields, which consequently increases the overall efficiency of the thermo-energetic system.

Previous operation analyses of the cooling towers were mostly based just on measurements of atmospheric quantities and the parameters of the inlet and outlet cooling water. This kind of analysis enables only a determination of the integral characteristics of cooling towers that depend on heat and mass transfer on a local basis. Our analysis compared the research of the correlation between heat-transfer efficiency on a local and integral basis with the power of the generator. The connection between the parameters is shown with the help of statistical tools. The paper also includes proposals for heat-transfer improvement in cooling towers.

1 ODVISNOST DELOVANJA HLADILNEGA STOLPA IN GENERATORJA

Hladilni stolpi na naravni vlek se pogosto uporabljajo v industriji in kot sestavni del termoelektrarn. Ker je hladilni stolp sestavni del celotnega postrojenja termoelektrarne, njegova učinkovitost delovanja vpliva na toplotni izkoristek celotnega postrojenja. V elektrarnah so energijski tokovi veliki, kar pomeni, da že majhne izboljšave izkoristka na postrojenju pomenijo velik prihranek pri porabi goriva in zmanjšanju emisije dimnih plinov.

V hladilnem stolpu poteka hlajenje vode z neposrednim stikom med vodo in hladilnim zrakom [3]. Pri tem se zrak segreje, njegova relativna vlažnost se poveča, zniža pa se temperatura hladilne vode. Za dosego največjega odvoda toplote iz vode na okolico je potrebno optimalno delovanje hladilnega stolpa pri njegovih imenskih karakteristikah.

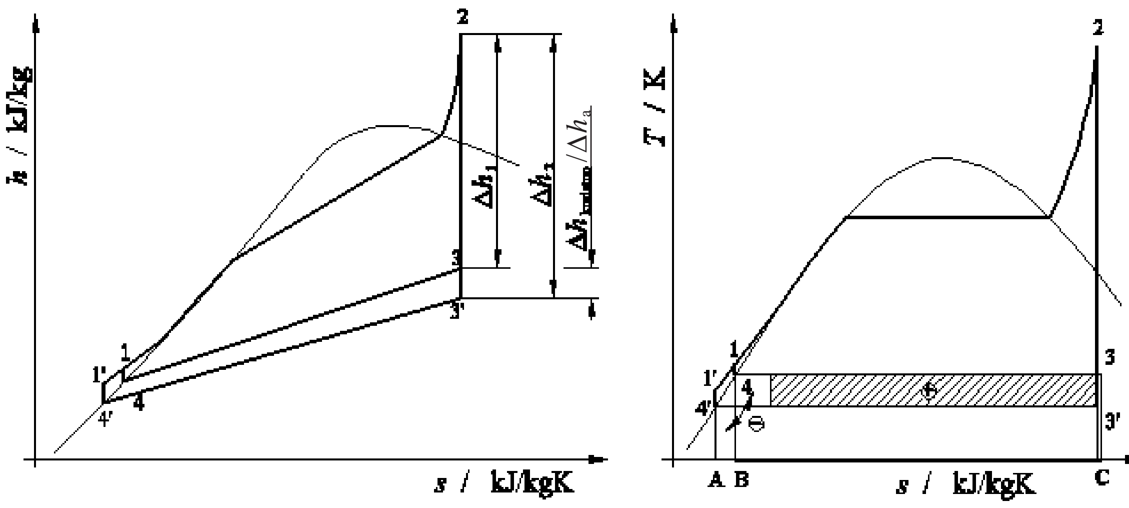
Na sliki 1 si poglejmo vpliv hladilnega sistema na količino pridobljenega dela iz termodinamičnega krožnega procesa. Naloga hladilnega sistema je odvod toplote v okolico pri temperaturah, ki so čim bližje temperaturi okolice. Intenzivnejši odvod toplote na sedanjem hladilnem sistemu se kaže v nižji temperaturi in tlaku v kondenzatorju, kar prinaša večjo entalpijsko razliko, npr. iz Δh_1 na Δh_2, in s tem dodatno pridobljeno delo $\Delta h_{\text{koristno}}$ iz turbine. Učinkovit hladilni sistem tako omogoča manjše izgube toplote na enoto pare, ta se je na primeru s slike 1 zmanjšala iz površine 4-3-C-B, ki pomeni

1 THE OPERATIONAL DEPENDENCE BETWEEN COOLING TOWER AND GENERATOR

Natural-draft cooling towers are usually used in the process industry and are often part of a thermal power plant. Because it is a part of the whole thermo-energetic system, its efficiency has an influence on the overall power-plant efficiency. In power plants we are faced with large energetic flows, which means that little efficiency improvements in the system represent large fuel savings and a reduction in pollution from exhaust gases.

In natural-draft cooling towers the heat is transferred by direct contact between the water and the cooling air that flow in opposite directions [3]. The air temperature rises and the humidity increases through the cooling-tower packings, where, on the other hand, the water temperature decreases. To achieve the largest heat transfer from the water to the air on a given cooling tower, it has to operate at its optimum point

Figure 1 shows the influence of the cooling system on the work extracted from thermodynamic steam cycle. The task of the cooling system is rejecting heat to the environment at temperatures that should be close to atmospheric temperature. More intensive heat rejection for the given cooling system results in a lower water temperature and lower pressure in the condenser, which brings a larger enthalpy difference, for example, from Δh_1 to Δh_2, and more acquired work, Δh_a, from the turbine. A more efficient cooling system enables less heat loss, which is reduced in Figure 1 from the area 4-3-C-B,



Sl. 1. *Povezava med pridobljenim delom in odvodom toplote*
Fig. 1. *Connection between acquired work and rejected heat*

odvedeno toploto na površino 4'-3'-C-A. Senčena ploskev ponazarja razliko toplote, ki se je pri tem spremenila v koristno pridobljeno delo.

Odvedeno toploto iz hladilnega sistema lahko ocenimo po sledeči enačbi [1]:

which represents the rejected heat, to area 4'-3'-C-A. The hatched area represents the heat difference that was additionally converted to useful work.

The rejected heat from a cooling system can be estimated by the equation [1]:

$$\dot{Q}_{od} = \left(\frac{1}{\eta} - 1\right) \cdot P \qquad (1),$$

kjer so: $\dot{Q}_{od}$ odvedena toplota iz hladilnega sistema, P moč generatorja in η izkoristek krožnega postopka.

Povezavo med močjo generatorja in hladilnim stolpom lahko utemeljimo tudi s statističnimi orodji na podlagi meritev. Odvisnost pridobljenega dela generatorja s parametri, ki vplivajo na delovanje stolpa, lahko dobimo z matričnim zapisom koeficientov odvisnosti, ki povedo medsebojne odvisnosti posamičnih spremenljivk. Na podlagi matrike koeficientov odvisnosti lahko sistematično določimo parametre, ki pomembno vplivajo na delovanje hladilnega stolpa. S tovrstnimi izračuni se ukvarja regresijska analiza [7].

where $\dot{Q}_{od}$ is the rejected heat from the cooling system, P is the generator power and η is the efficiency of the thermodynamic system.

The connection between the generator and the cooling tower can also be shown with statistical tools based on measurements. The dependence of the generated power on parameters that influence the cooling-tower operation can be acquired with a matrix of correlation coefficients that tell us the mutual dependence between two variables. With the help of a correlation matrix we can systematically determine the parameters that have a significant impact on the operation of the cooling tower. This kind of analysis can be described as a regression analysis [7].

2 OPIS MERITEV IN MERILNE OPREME

Meritve obsegajo podatke na bloku 4 Termoelektrarne Šoštanj [9] in ustreznem hladilnem stolpu bloka 4 [8]. Celoviti parametri, ki so simultano merjeni po standardu DIN 1947 [5] so: vstopna in izstopna temperatura hladilne vode iz hladilnega stolpa, celotni masni pretok vode, ki je merjen z ultrazvočnim merilnikom pretoka in izhodna moč generatorja. Merilni sistem obsega še naprave za zbiranje merjenih podatkov v hladilnem stolpu.

Merilna negotovost temperaturnih zaznaval je bila ocenjena na manj ko 0,25 °C. Meritve so obsegale različne režime obratovanja, tj. pri različnih močeh generatorja ter 34000 m^3/h prostorninskem pretoku hladilne vode. Sočasno so potekale meritve parametrov okoliškega zraka, ki so obsegale hitrost okoliškega zraka v štirih točkah (v_A, v_B, v_C, v_D), temperaturo okolice v bližini hladilnega stolpa (t_Z) in gostoto zraka v bližini hladilnega stolpa (ρ).

V preglednici 1 so predstavljene povprečne vrednosti okoliških parametrov, izmerjenih v celotnem času trajanja meritev. Iz preglednice 1 je razvidno, da se parametri okolice niso bistveno spreminjali in zaradi tega tudi niso vplivali na rezultate meritev znotraj hladilnega stolpa.

2 DESCRIPTION OF THE EXPERIMENT AND THE MEASUREMENT EQUIPMENT

Measurements include data acquired at Block 4 of the Šoštanj power plant [9] and the corresponding cooling tower of Block 4 [8]. The integral parameters that are simultaneously measured by the DIN 1947 standard [5] are as follows: inlet and outlet cooling-water temperature from the cooling tower; the total water-mass flow rate, which is measured with an ultrasonic flow meter and the power on the generator. The measurement system also includes equipment for collecting data in the cooling tower.

The measurement uncertainty of the temperature sensors was estimated to be less than 0.25°C. The measurements included different operating points, i.e., from different power outputs on the generator, and were conducted by a constant volumetric water flow of 34000 m^3/h. Simultaneously, we measured atmospheric parameters, which included the air velocity at four points (v_A, v_B, v_C, v_D), the ambient temperature near the cooling tower (t_0) and the air density near the cooling tower (ρ_0).

Table 1 shows the average values of the atmospheric parameters measured through the whole duration of the measurement. From the table it is clear that the variations of the parameters were not significant, which means that the measurements in the cooling tower were not influenced by the environmental conditions.

Preglednica 1. *Parametri okoliškega zraka*
Table 1. *Parameters of ambient air*

kvadrant quadrant	*1*	*2*	*3*	*4*
v_A **[m/s]**	1,8	2,2	2,1	2,3
v_B **[m/s]**	2,2	1,9	2,7	2,4
v_C **[m/s]**	1,6	2,2	1,8	1,9
v_D **[m/s]**	2,2	2	2,1	1,8
t_Z **[m/s]**	21,8	22,8	21,4	20,9
ρ **[kg/m^3]**	1,17	1,17	1,16	1,16

3 MERITVE LOKALNIH PARAMETROV NA NAVPIČNEM SEGMENTU

Za določitev osnovnih karakteristik prenosa toplote in snovi opazovanega hladilnega stolpa so bile izvedene meritve aerodinamičnih in termodinamičnih veličin na navpičnem segmentu, prikazanem na sliki 2. Segment je bil izbran kot primerjalna točka v področju hladilnega stolpa, kjer imamo brezhibne konstrukcijske lastnosti in je obsegal tlorisno površino okoli 9 m^2. Namen segmenta je tudi določitev prenosa toplote na lokalni ravni v hladilnem stolpu. V osnovi je izkoristek krajevnega delovanja stolpa moč izračunati samo prek krajevnih meritev parametrov vlažnega zraka ali vode, ki ga popisuje enačba [10]:

3 MEASUREMENT OF THE LOCAL PARAMETERS IN A VERTICAL SEGMENT

To determine the basic characteristics of heat and mass transfer in the cooling tower we conducted measurements of the aero- and thermo-energetic quantities in the vertical segment shown in Figure 2. The segment was chosen as a reference point in the cooling tower where the construction characteristics were fault-free and the segment was occupying a ground plane of approximately 9 m^2. The purpose of the vertical segment is also to determine the heat transfer on a local base in the cooling tower. In principle, this can be the local efficiency, calculated by measurements of moist air or water parameters, and its definition can be written as [10]:

$$\varepsilon = \frac{h_{w1} - h_{w2}}{h_{w1} - h_{wm}} \qquad (2),$$

kjer so: h_{w1} vstopna specifična entalpija vode, h_{w2} izstopna specifična entalpija vode, h_{wm} specifična entalpija vode ovrednotena pri temperaturi mokrega termometra okoliškega zraka, ki predstavlja največji temperaturni potencial, do katerega lahko vodo ohladimo.

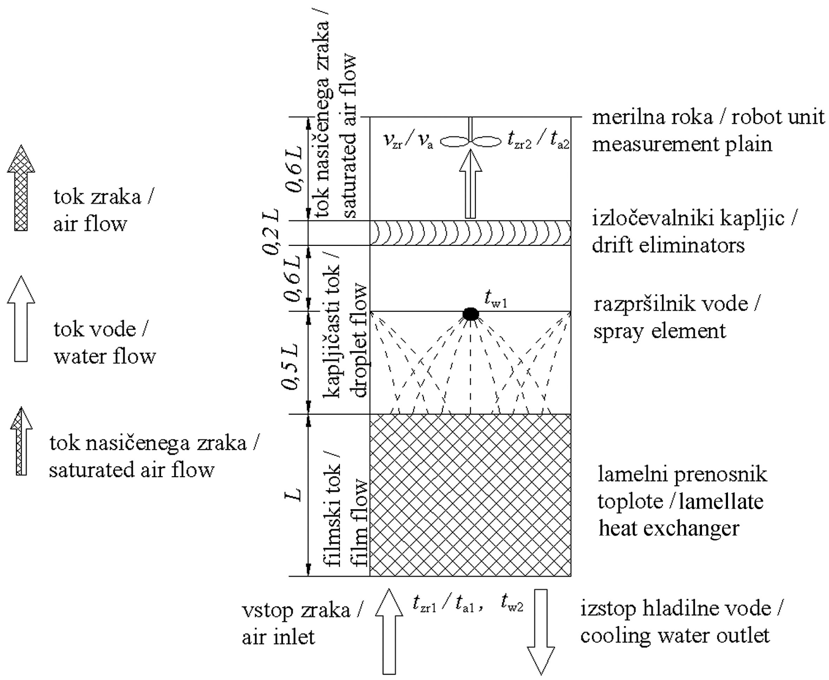
Navpični segment na sliki 2 je sestavljen iz lamelnega prenosnika toplote, ki je v spodnjem področju, razpršilnika vode, ta je v sredini in izločilnikov vodnih kapljic v zgornjem delu segmenta. Na opazovanem delu so bili merjeni naslednji parametri: vstopna temperatura vlažnega zraka t_{zr1}, izstopna temperatura nasičenega zraka t_{zr2}, vstopna temperatura vode t_{w1}, izstopna temperatura vode t_{w2}, masni pretok vode $\dot{m}_w$, masni pretok vlažnega zraka $\dot{m}_{zr}$.

Merilna negotovost temperaturnih zaznaval Pt-100 je manjša od 0,25 °C. Hitrost vlažnega zraka

where h_{w1} is the inlet-specific enthalpy of the water, h_{w2} is the-outlet specific enthalpy of the water, h_{wm} is the specific enthalpy of the water evaluated at the wet-bulb temperature of atmospheric air, which represents the maximum temperature potential to which water can be cooled.

The vertical segment in Figure 2 consists of a lamellate heat exchanger, which is at the bottom, spray elements, which are in the middle, and drift eliminators, which are placed at the top of the segment. For the observed segment we conducted measurements of the following parameters: inlet temperature of moist air t_{a1}, outlet temperature of saturated air t_{a2}, inlet water temperature t_{w1}, outlet water temperature t_{w2}, mass flow of water $\dot{m}_w$, mass flow of air $\dot{m}_{zr}$.

The measurement uncertainty of the Pt-100 temperature sensors was estimated to be less than 0.25°C. The air velocity was measured with a pre-



Sl. 2. *Navpični segment v hladilnem stolpu [4]*
Fig. 2. *Vertical segment in the cooling tower [4]*

se je merila s predhodno umerjenim anemometrom na vetrnico. Perioda vzorčenja je bila 1 min in celotni čas zbiranja podatkov je bil 3,4 dni.

Vlažnost vstopnega zraka je bila določena s temperaturami suhega in mokrega termometra. Relativna vlažnost okolice in prav tako temperatura okolice sta bili dobljeni z meritvami v meteorološki postaji Šoštanj. Vse meritve v hladilnem stolpu so bile izvedene v skladu s standardom DIN 1947 [5].

4 ODVISNOST PARAMETROV, POVEZANIH Z OBRATOVANJEM HLADILNEGA STOLPA

Pri iskanju povezav med močjo generatorja in hladilnim stolpom smo uporabili statistične postopke, pri katerih smo s korelacijskimi koeficienti dobili stopnje odvisnosti med posamičnimi spremenljivkami. Povezanost parametrov z delovanjem hladilnega stolpa in posredno z močjo generatorja je prikazana v preglednici 2, kjer smo za izračun koeficientov odvisnosti izbrali naslednje parametre: moč generatorja P; celotni odvedeni toplotni tok Q_{od} iz hladilnega stolpa; krajevni toplotni tok Q_{lok}, ki se prenese iz vode na hladilni zrak; temperaturo okolice t_{ok}; tlak okolice p_{ok}; relativno

calibrated vane anemometer. The period of the data sampling was 1 min, and the total measurement time was 3.4 days.

The relative humidity of the inlet air was determined with the help of a dry-bulb and a wet-bulb thermometer. The relative humidity and the temperature of the ambient air were acquired from the Šoštanj meteorological station. All the measurements in the cooling tower were carried out according to the DIN 1947 standard [5].

4 DEPENDENCE OF THE PARAMETERS ASSOCIATED WITH THE COOLING TOWER'S OPERATION

When seeking a connection between the generator and the cooling tower we used statistical methods to determine the degree of correlation between the variables. The connections of the parameters to the cooling-tower operation and indirectly to the power generation are shown in Table 2, where for the calculation of the correlation coefficient we used the following parameters: power at the generator P, total rejected heat from the cooling tower Q_R, local heat transfer at the vertical segment Q_{loc}, ambient temperature t_0, ambient pressure p_0, relative humidity of ambient φ_0, outlet temperature of moist air

Preglednica 2. *Tabela koeficientov odvisnosti, ki povezujejo moč generatorja s celovitim in krajvenim prenosom toplote v hladilnem stolpu*
Table 2. *Table of correlation coefficients that associate the power on the generator with integral and local heat transfer in the cooling tower*

	P	Q_{od}/Q_R	Q_{lok}/Q_{loc}	t_{ok}/t_0	p_{ok}/p_0	φ_{ok}/φ_0	t_{zr2}/t_{a2}	t_{zr1}/t_{a1}	$t_{wv}/t_{w,i}$	$t_{wiz}/t_{w,o}$	$t_{wvk}/t_{w,i,c}$	$t_{wizk}/t_{w,o,c}$
P	1,00	**0,99**	**0,95**	0,22	-0,61	-0,90	0,98	0,24	0,98	0,96	0,94	0,97
Q_{od} / Q_R	0,99	1,00	**0,95**	0,20	-0,57	-0,89	0,99	0,21	0,99	0,96	0,95	0,98
Q_{lok} / Q_{loc}	0,95	0,95	1,00	-0,01	-0,67	**-0,95**	**0,97**	0,01	**0,97**	**0,97**	0,95	0,95
t_{ok} / t_0	0,22	0,20	-0,01	1,00	-0,02	-0,14	0,20	1,00	0,19	0,19	0,22	0,21
p_{ok} / p_0	-0,61	-0,57	-0,67	-0,02	1,00	0,82	-0,61	-0,03	-0,61	-0,63	-0,61	-0,57
φ_{ok} / φ_0	-0,90	-0,89	-0,95	-0,14	0,82	1,00	-0,93	-0,15	-0,93	-0,94	-0,93	-0,90
t_{zr2} / t_{a2}	0,98	0,99	0,97	0,20	-0,61	-0,93	1,00	0,21	1,00	0,99	0,98	0,99
t_{zr1} / t_{a1}	0,24	0,21	0,01	1,00	-0,03	-0,15	0,21	1,00	0,21	0,20	0,23	0,23
t_{wv} / $t_{w,i}$	0,98	0,99	0,97	0,19	-0,61	-0,93	1,00	0,21	1,00	0,99	0,98	0,99
t_{wiz} / $t_{w,o}$	0,96	0,96	0,97	0,19	-0,63	-0,94	0,99	0,20	0,99	1,00	0,99	0,99
t_{wvk} / $t_{w,i,c}$	0,94	0,95	0,95	0,22	-0,61	-0,93	0,98	0,23	0,98	0,99	1,00	0,99
t_{wizk} / $t_{w,o,c}$	0,97	0,98	0,95	0,21	-0,57	-0,90	0,99	0,23	0,99	0,99	0,99	1,00

vlažnost okolice φ_{ok}; temperaturo vlažnega zraka t_{zr2} na izstopu iz navpičnega segmenta nad izločevalniki kapljic; temperaturo zraka na vstopu v navpični segment t_{zr1}, tj. v laminarni prenosnik toplote; temperaturo hladilne vode na vstopu v hladilni stolp t_{wv}; temperaturo hladilne vode na izstopu iz hladilnega stolpa t_{wiz}; temperaturo hladilne vode na vstopu v kondenzator t_{wvk} in temperaturo hladilne vode na izstopu iz kondenzatorja t_{wizk}. Matrika koeficientov odvisnosti je zaradi velikega števila obravnavanih spremenljivk in preglednosti zapisana v pregledniční obliki v preglednici 2. Preglednica je simetrična, kar pomeni, da se lahko osredotočimo na vrednosti nad glavno diagonalo ali pod njo.

Odvisnost med močjo generatorja in celotnim odvedenim toplotnim tokom znaša 0,99, kar pomeni izredno veliko odvisnost. Ta podatek ponazarja izredno tehtno informacijo, ki potrjuje pomembnost kakovostnega obratovanja hladilnega sistema na celotni izkoristek termoelektrarne. Seveda pa je treba za učinkovito delovanje hladilnega stolpa kot celote zagotoviti dober prenos toplote na krajevni ravni.

Osredotočimo se na vrednosti koeficientov odvisnosti med celotnim odvedenim toplotnim tokom iz hladilnega stolpa in krajevnim toplotnim tokom, merjenim na navpičnem segmentu. Odvisnost med njima znaša kar 0,95. Vrednost koeficienta odvisnosti je v tako dinamičnem okolju izredno velika, kar nakazuje predvsem na dva pojava. Prvi je ta, da je krajevni toplotni tok v hladilnem stolpu odvisen od moči generatorja, kar tudi potrjuje koeficient odvisnosti med njima, oz. da morebitne spremembe

from the vertical segment t_{a2}, inlet temperature of the moist air in the vertical segment t_{a1}, inlet cooling-water temperature to the cooling tower $t_{w,i}$, outlet cooling-water temperature from the cooling tower $t_{w,o}$, inlet cooling-water temperature to the condensator $t_{w,i,c}$, outlet cooling-water temperature from the condensator $t_{w,o,c}$. Because of the large number of studied variables and for clarity, the matrix is written in tabular form in Table 2. The table is symmetrical, which means that we can concentrate on the values above or under the main diagonal.

The correlation between the power on the generator and total heat transfer from the cooling tower is 0.99, which represents a very high dependence. This data gives us very powerful information that confirms the importance of the quality of the operation of the cooling system on the overall efficiency of the power plant. Of course, we have to, for effective operation, ensure good heat transfer on a local basis.

It is reasonable for the next step to focus on the correlation coefficient between the total heat transfer from the cooling tower and the local heat transfer measured on a vertical segment. Their correlation coefficient is 0.95. This value is in a very dynamic environment, which gives us two important pieces of information. First of all, we know that the local heat transfer in the cooling tower depends on the power generation, which tells us the correlation between them, or that the potential construction element modifications of the cooling tower has an influence on the state in the condensator, and consequently on power generation. Secondly, we konstrukcijskih elementov hladilnega stolpa vplivajo na stanje v kondenzatorju in s tem na moč generatorja. Drugi sklep, ki ga omenjeni koeficient podaja, je, da je prenos toplote po celotni površini razmeroma enakomeren. Segment je namreč izbran v področju hladilnega stolpa, kjer imamo brezhibne konstrukcijske lastnosti. Izmerjene vrednosti temperatur vode na navpičnem segmentu so zelo podobne temperaturam vode, ki vstopajo in izstopajo iz stolpa, kar govori o relativni enakomernosti prenosa toplote po celotni površini v danih razmerah obratovanja. V nasprotnem primeru lahko sklepamo, da bi drugačne vrednosti izmerkov nad opazovanim segmentom glede na celotno dejansko površino nakazovale na področja velikih nehomogenosti v temperaturnem in hitrostnem polju. Posledica tega bi bila nizka odvisnost med celotnim odvedenim toplotnim tokom Q_{od} in krajevnim prenosom toplote Q_{lok}.

V naslednjem koraku je primerno pogledati parametre, ki pomembno vplivajo na krajevni prenos toplote Q_{lok}, saj smo ugotovili, da s tem vplivamo posredno na moč generatorja. Prenos toplote je povezan s stanjem okolice, od katerih sta pomembna relativna vlažnost φ_{ok} in temperatura okolice t_{ok}, ter vstopnimi parametri hladilne vode, ki predstavljajo robne pogoje. Relativna vlažnost je zelo povezana s prenosom toplote, in sicer manjša ko je relativna vlažnost, večji je mogoči preneseni toplotni tok, kar pove tudi negativni predznak. Temperatura okolice in krajevni toplotni tok sta šibko povezana. To trditev je treba podrobneje proučiti. Dinamika prenosa toplote v hladilnem stolpu je bistveno večja glede na spremembe stanja okolice, kar se kaže v slabi odvisnosti. Medtem ko je znano, da je temperatura vlažnega okoliškega termometra izrednega pomena pri razpoložljivi temperaturni razliki za prenos toplote, kar vpliva na velikostni red prenosa toplote. Nižja ko je temperatura okolice, nižja je temperatura vlažnega zraka na vstopu v polnilo in večja je temperaturna razlika pri danem obratovalnem stanju nad izločevalniki in okolico za prenos toplote.

Poleg relativne vlažnosti so zelo povezani parametri še temperatura vlažnega zraka nad izločevalniki t_{zr2}, temperatura izstopne t_{wiz} in vstopne t_{wv} hladilne vode v hladilni stolp. Temperatura nad izločevalniki je neposredno odvisna od temperature hladilne vode na vstopu, kar pove tudi odvisnost med njima, ki ima vrednost 1. Večja ko je temperatura nad izločevalniki glede na dano stanje okolice, več

know that the homogeneity of heat transfer through the entire cross-sectional area of cooling tower is relatively good. Namely, we have chosen the vertical segment in the area of the cooling tower where the construction elements are fault-free. The measured temperatures of the water on the vertical segment are very similar to those measured at the inlet and outlet positions of the tower, which tells us about the relative homogeneity of the heat transfer through the entire tower surface for given operational conditions. In the opposite case we could consider that we would have different measured values on a vertical segment relative to the entire area of the tower, indicating very large areas of air temperature and velocity inhomogeneities. The consequence would be a low correlation between the total Q_R and the local Q_{loc} heat transfer in the cooling tower.

In the next step we can concentrate on parameters that importantly influence the local heat transfer Q_{loc} because we have discovered that it has an indirect influence on power generation. The heat transfer is connected with the state of the atmosphere, of which the most important are the relative humidity φ_0, the ambient temperature $t_{0,}$ and the inlet water temperature $t_{w,I}$, which represent the boundary conditions. The relative humidity is closely correlated with heat transfer, i.e., the lower relative humidity gives a larger potential for heat transfer that tells us a negative sign. The ambient temperature and the local heat transfer are not closely correlated. This statement should be closely investigated. The dynamics of heat transfer in the cooling tower is significantly higher relative to the state of the ambient, which gives us a low correlation. But it is known that the wet-bulb temperature of the ambient signifies the maximum potential to which cooling water can be cooled. Consequently, it follows that a lower temperature of the ambient results in a lower inlet-air temperature in the cooling tower, and that gives a larger temperature difference between the state above the drift eliminators and the ambient for heat transfer for given cooling-tower characteristics.

In addition to the relative humidity the local heat transfer is closely correlated with the outlet-air temperature t_{a2}, the inlet $t_{w,i}$ and the outlet $t_{w,o}$ cooling-water temperature. The air temperature above the drift eliminators is directly connected with the inlet-water temperature, which tells us the correlation between them, i.e., 1. The higher is the air temperature above the drift eliminators relative to the state of the ambient toplote nam je uspelo prenesti na zrak, kar se kaže v nižji temperaturi hladilne vode na izstopu iz hladilnega stolpa.

Veliko odvisnost opazimo tudi med preneseno toploto in temperaturo hladilne vode na izstopu t_{wizk} in vstopu t_{wvk} v kondenzator. Ta povezava je fizikalno povsem logična, saj lahko praktično enačimo vstopno in izstopno temperaturo hladilne vode iz hladilnega stolpa z izstopno in vstopno temperaturo v kondenzator, kar med drugim nakazujejo tudi odvisnosti med njimi.

the more heat was successfully transferred from the water to the air, which results in a lower outlet-water temperature from the cooling tower.

A high correlation can also be seen between the heat transfer, the outlet $t_{w,o,c}$ and the inlet $t_{w,i,c}$ water temperature to the condensator. This connection is physically very logical because we can practically equal the inlet and outlet water temperatures from the cooling tower with the outlet and inlet water temperatures to the condensator, which indicates the correlations between them.

5 REGRESIJSKI MODEL MED MOČJO GENERATORJA IN CELOTNIM TOPLOTNIM TOKOM IZ HLADILNEGA STOLPA

V prejšnem poglavju smo ugotovili veliko odvisnost med prenesenim toplotnim tokom in močjo generatorja. Slika 3 prikazuje njuno medsebojno odvisnost, ki je linearna in jo tako lahko približamo z regresijsko premico.

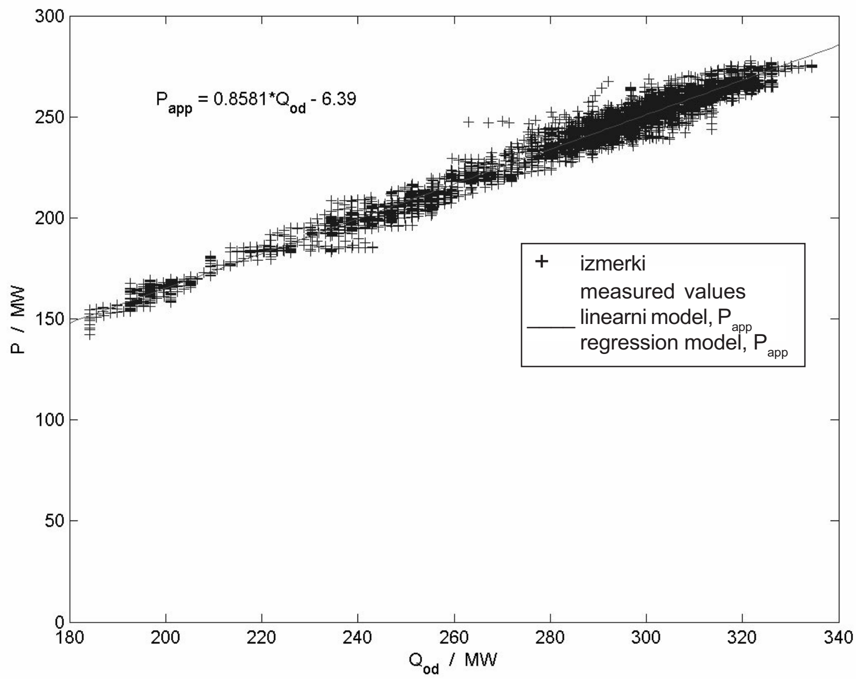
Graf na sliki 3 prikazuje odvisnost med močjo generatorja in celotnim odvedenim tokom iz hladilnega stolpa. Enačba linearnega regresijskega modela za dani primer je:

5 REGRESSION MODEL BETWEEN THE POWER GENERATION AND THE REJECTED HEAT FROM COOLING

In earlier sections we discovered a close dependence between the heat transfer and power generation. Figure 3 shows their relationship, which is linear, and that is why we can approximate it with a linear regression model.

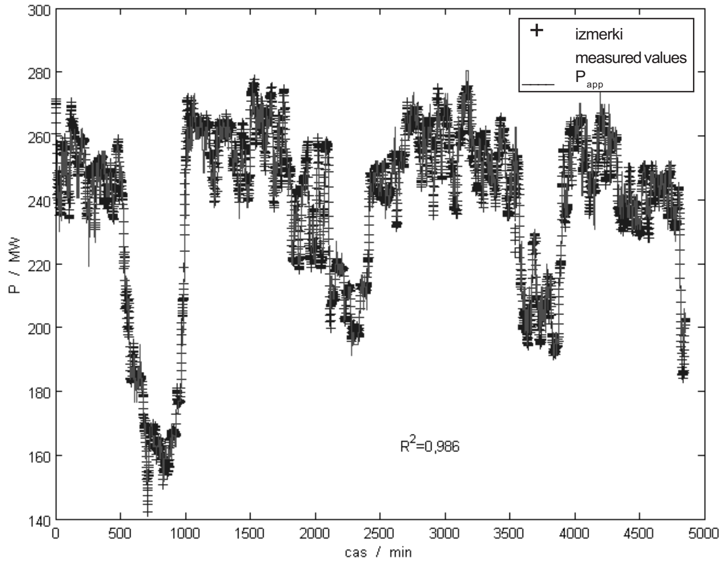
The equation that describes the relationship between the power generation and the rejected heat is:

$$P = 0,8581\ Q_{od} + 6,39 \tag{3}$$



Sl. 3. *Regresijska premica med močjo generatorja in celotnim odvedenim toplotnim tokom*

Fig. 3. *Linear regression model between the power generation and rejected heat from the cooling tower*



Sl. 4. *Izmerjena in približna moč generatorja*
Fig. 4. *Measured and approximated power on the generator*

Razpršenost izmerkov okoli regresijske premice je posledica naključnosti nihanj moči generatorja, ki je prikazana na sliki 4, in spreminjanja stanja okolice v času merjenja, ki je trajalo 3,4 dni. Regresijski model predstavlja karakteristično funkcijo za blok 4 Termoelektrarne Šoštanj. Strmina in presečišče regresijske premice z osjo *y* podajata tudi informacije o kakovosti obratovanja termoelektrarne. In sicer bolj ko je strma regresijska premica in bolj ko je premica premaknjena navpično navzgor, boljše je obratovanje postrojenja. Slika 4 prikazuje rezultate izmerjene in približne moči po enačbi (3).

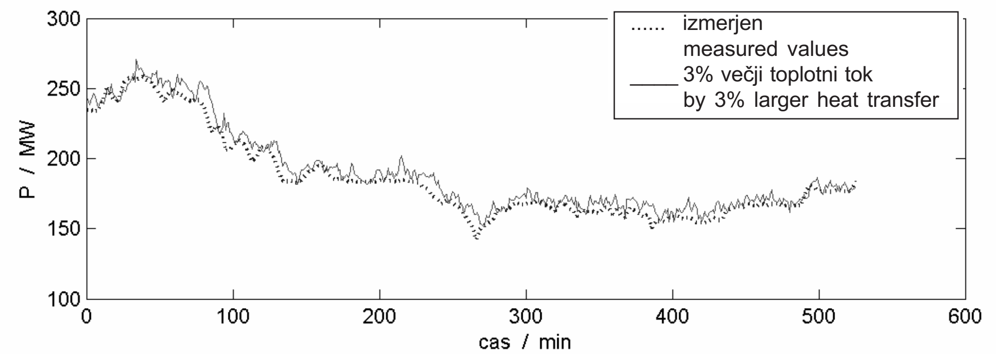
S slike 4 opazimo zelo dobro približnost moči z linearnim regresijskim modelom, kjer je koeficient odvisnosti 0,986. Enačba (3) je lahko izhodišče za morebitne spremembe na hladilnem stolpu, ki imajo posredno vpliv na moč generatorja.

Velik koeficient odvisnosti med močjo generatorja in krajevnim toplotnim tokom nakazuje visoko raven enakomernosti v delovanju hladilnega stolpa. To pomeni, da lahko predpostavimo nespremenljiv prenos toplote po celotni dejanski površini pri morebitnih spremembah konstrukcijskih elementov stolpa. Na podlagi sočasnega merjenja veličin pri večjem številu konstrukcijsko spremenjenih navpičnih segmentih lahko ugotovimo, katera kombinacija elementov največ prispeva k moči generatorja in za koliko. Pri tem je treba paziti, da so izbrani segmenti pravilno razporejeni glede na razmerje masnih tokov vode in zraka v hladilnem

Dissipation around the regression model is a consequence of the random oscillation of power on the generator, which can be seen in Figure 4, and the variation of the ambient conditions through the duration of the measurements, which took us 3.4 days. The regression model represents the characteristic function for Block 4 of the Šoštanj power plant. The gradient and *y*-axis cross-section of the regression model gives information about the quality of the power-plant operation. The steeper and higher regression model is better, as is the operation quality. Figure 4 shows the results of the measured and the approximated (Equation 3) values of the power on the generator.

Figure 4 shows a very good approximation with the linear regression model of the power on the generator, where the correlation coefficient is 0.986. Equation (3) can be a guideline for potential modifications in the cooling tower, which have an indirect influence on the generator.

The high correlation coefficient between the power on the generator and the local heat transfer indicates a high level of homogeneity in the operation of the cooling tower. This means it can be assumed to have constant heat transfer through the entire area of the cooling tower by a potential construction-element modification. On the basis of simultaneous measurements on different modified vertical segments we can determine which combination of construction elements contributes the most to the power generation, and for what quantity. We



Sl. 5. *Moč generatorja pri 3-odstotnem večjem odvodu toplote iz hladilnega stolpa*
Fig. 5. *Power on generator by 3 % heat transfer improvement in cooling tower*

stolpu. Ta razmerja morajo biti enaka, kar zagotavlja enake robne pogoje pri analizi različnih spremenjenih navpičnih segmentih. Tako lahko na primeru izračuna, ki ga predstavlja slika 5, ugotovimo, da je bil prenos toplote na najučinkovitejšem spremenjenem navpičnem segmentu za 3 % večji kakor v normalnih razmerah. Teoretično to pomeni: če bi izbrano kombinacijo elementov uporabili po celotni dejanski površini hladilnega stolpa, bi se v danih obratovalnih in okoliških razmerah moč generatorja povečala za povprečno 7,02 MW. To pomeni za blok, ki ima moč 250 MW in izkoristek 35 %, dvig celotnega izkoristka za 0,98 %, kar dolgoročno pomeni pomembne prihranke pri porabi goriva in zmanjšani emisiji dimnih plinov.

Diagram na sliki 5 prikazuje časovno zvečanje moči pri 3-odstotnem večjem prenesenem toplotnem toku iz hladilnega stolpa v danih obratovalnih in okoliških razmerah.

6 KOMENTAR K UČINKOVITOSTI HLADILNEGA STOLPA BLOKA 4 TERMOELEKTRARNE ŠOŠTANJ

Analiza delovanja hladilnega stolpa bloka 4 termoelektrarne Šoštanj pri približno stalni moči generatorja, ki je povprečno znašala 260 MW, je pokazala dobre rezultate. Za merilo kakovosti obratovanja hladilnega stolpa je bil izbran koeficient $\dot{Q}_{od} / P$. Manj odvedene toplote pri dani moči generatorja pomeni, da nam je uspelo spremeniti več toplote na enoto pare v koristno pridobljeno delo, kar pomeni nižje vrednosti koeficienta $\dot{Q}_{od} / P$. Pri danjašnjih hladilnih sistemih, odvedena toplota se spreminja od 1,3 do 2,5-kratne vrednosti iz krožnega postopka pridobljenega dela. Na podlagi koeficienta lahko ugotovimo, da je obratovanje hladilnega stolpa

have to be careful to choose vertical segments so that the water-to-air mass-flow rate is constant, by which we ensure the same boundary conditions. In the example of figure 5 we can see that the heat transfer in the cooling tower was 3% higher than before the modifications were made. This, theoretically, means that if the best combinations of elements would be used on the entire area of the cooling tower for given operating and atmospheric conditions, the power generation would be raised on average by 7.02 MW. This means for a block with 250 MW of power and 35% efficiency, an improvement in the total thermodynamic efficiency of the power plant by 0.98%, which in the long term represents significant fuel savings and less environmental pollution with exhaust gases.

Figure 5 shows the power raised by 3% and the heat-transfer improvement from the cooling tower for given operational and atmospheric conditions.

6 COMMENT ON THE EFFICIENCY OF THE COOLING TOWER AT BLOCK 4 OF THE ŠOŠTANJ POWER PLANT

Our operational analysis of the cooling tower at Block 4 of the Šoštanj power plant by constant power generation, the value of which on average is 260 MW, has shown good results. For the purpose of quality evaluation we chose the coefficient $\dot{Q}_{od} / P$. Less rejected heat at a constant power generation means that more heat is successfully transformed into useful work, which represents the lower value of the coefficient $\dot{Q}_{od} / P$. For today's cooling systems the rejected heat varies from 1.3 to 2.5 times the work extracted from the thermodynamic cycle. On the basis of the coefficient we can determine that the operation of cooling tower at Block 4 of the na bloku 4 Termoelektrarne Šoštanj učinkovito, saj znaša povprečna vrednost koeficienta $\dot{Q}_{od} / P$ 1,45, kar uvršča hladilni sistem Termoelektrarne Šoštanj v sodobnejši razred. Vrednost koeficienta tudi potrjuje, da je bila rekonstrukcija stolpa na bloku 4 učinkovita.

7 SKLEP

Na učinkovitost delovanja hladilnega stolpa vpliva mnogo dejavnikov, ki prispevajo k celotni in krajevni učinkovitosti stolpa. Celotne dejavnike predstavljata predvsem stanje okolice in režim obratovanja termoelektrarne, ki vplivata na velikostni red izkoristka hladilnega stolpa. Iz zgornjih analiz je bilo ugotovljeno, da ima vpliv temperature okolice velik pomen pri učinkovitosti prenosa tolpote, pri kateri njena vrednost vpliva predvsem na entalpijo vstopnega zraka v hladilni stolp in na razliko gostot okoliškega zraka in zraka v hladilnem stolpu. Sama moč generatorja ima vpliv na raven temperatur vstopne hladilne vode v hladilni stolp in na temperature vlažnega zraka v hladilnem stolpu. Večja temperatura zraka v hladilnem stolpu pomeni v danih razmerah večjo količino prenesene toplote iz vode na zrak, kar pomeni večje hlajenje vode. Iz zgornjih ugotovitev lahko sklepamo, da se nižja temperatura okolice, oz. vstopnega zraka, in višja temperatura zraka v hladilnem stolpu izražata v večji učinkovitosti delovanja hladilnega stolpa.

Krajevne dejavnike predstavljajo konstrukcijske karakteristike sestavnih elementov hladilnega stolpa. Učinkovitejša kombinacija konstrukcijskih elementov se kaže v večjem prenosu toplote oz. večjem hlajenju vode. Na krajevni prenos toplote vplivajo tudi hitrostne razmere zraka blizu stolpa, ki predstavljajo robne pogoje in imajo vpliv na homogenost hitrostnega in temperaturnega polja aktivne površine hladilnega stolpa. Hitrostne razmere zraka pa so predvsem odvisne od podnebnih razmer in namestitve stolpa.

Prikazana je pomembnost hladilnega sistema, pri katerem je glavni element hladilni stolp kot izredno pomemben del termoelektrarne. Poiskali smo statistično povezanosti med močjo generatorja in krajevnim ter celovitim odvedenim toplotnim tokom iz hladilnega stolpa. Na podlagi regresijskega modela smo podali domnevo, ki pove, da lahko izboljšanje učinkovitosti obravnavanega hladilnega stolpa za, npr. 3 %, izkaže pri polni obremenitvi 250 MW bloka v dvigu celotnega izkoristka termoelektrarne za 1 %, kar pomeni znatne prihranke v porabi goriva in zmanjšani emisiji dimnih plinov.

Šoštanj power plant is quite efficient. The average value of the coefficient $\dot{Q}_{od} / P$ is 1.45, which classifies the cooling tower in the higher class. The value of the coefficient confirms that the reconstruction of tower at Block 4 was successful.

7 CONCLUSION

Cooling-tower operational efficiency depends on many variables that contribute to the integral and local operating conditions. The integral variables come mostly from the atmospheric state, and power-plant operational points that influence on the high cooling-tower efficiency. From the above analysis we concluded that the ambient temperature has a great influence on heat-transfer efficiency, where its value had an impact on the inlet-air enthalpy to the cooling tower and on the density difference between the cooling tower and the atmospheric air. The power on the generator has an influence on the level of the inlet-water temperature and the moist air temperature in the cooling tower. A higher air temperature in the tower is given by the operating condition, and represents a larger amount of heat transferred from the water to the air, which means better cooling of the water. It can be concluded that a lower atmospheric temperature or a lower inlet-air temperature and a higher air temperature in the cooling tower results in a higher cooling-tower efficiency.

Local factors are the construction characteristics of the elements in the cooling tower. A more efficient combination of construction elements results in a larger heat transfer and a lower water temperature. Local heat transfer also depends on the air velocity near the cooling tower, which represents the boundary conditions that have an influence on the temperature and the velocity homogeneity of the cooling tower's cross-sectional area. The air velocity near the tower depends on the climate characteristics and the location of the cooling tower.

Our study shows the importance of the cooling system where the main element is a natural-draft cooling tower. We searched statistically the connections between the power generation and the local and integral heat transfer from the cooling tower. On the basis of a regression model we presented the hypothesis that tells us that a 3% heat-transfer improvement in the cooling tower can increase the overall efficiency of a 250 MW block by 1%, which represents a large fuel saving and less environment pollution with exhaust gases.

Regresijska analiza je pokazala, kateri parametri so najbolj vplivni na delovanje hladilnega stolpa. Pri danih konstrukcijskih karakteristikah hladilnega stolpa so to obremenitev termoelektrarne ter temperatura in relativna vlažnost okoliškega zraka. Ugotovili smo, da večje ko so obremenitve termoelektrarne, nižja temperatura in večja suhost okoliškega zraka, večja je učinkovitost prenosa toplote in boljši je izkoristek hladilnega stolpa pri danih konstrukcijskih karakteristikah.

Prikazano je, da z linearnim regresijskim modelom, s katerim določimo karakteristično funkcijo termoelektrarne, lahko ocenimo kakovost delovanja postrojenja kot celote. Ta ugotovitev odpira možnost ocenjevanja učinkovitosti stolpov in neposreden vpliv na moč generatorja. S pomočjo regresijske analize je mogoče napovedati področja neenakosti v delovanju po površini hladilnega stolpa.

The regression analysis has shown which parameters are significant for the cooling tower's operation. From the given construction characteristics of the cooling tower these parameters are the load of the power plant, the temperature and the relative humidity of the atmospheric air. A higher load of the power plant, lower temperature and relative humidity of the air give a higher heat-transfer efficiency and efficiency of the cooling tower for the given construction characteristics.

Our analysis shows that it is possible with a simple linear regression model, which represents the characteristics of the power plant, to estimate the quality of the overall thermodynamic process. This statement opens new opportunities for estimating cooling-tower efficiency and evaluating the direct influence of the modifications on power generation. With regression analysis it is also possible to predict the areas of operating non-homogeneities in the cooling tower.

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Vodenje robota na temelju zaznaval sile in računalniškega vida

Robot Control Based on Force and Vision Sensors

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V prispevku je predstavljen postopek za sledenje krivulji. Med sledenjem robot vzdržuje stik s podlago z zahtevano silo. Metoda temelji na zbiranju in analizi vidne informacije ter merjenju sil z ustreznimi zaznavali. Tako pridobljeni podatki se vključijo v algoritem, tako da se zagotovi želeno delovanje sistema. S postopkom je mogoče izboljšati robotske sisteme v industrijskem okolju.

(Ključne besede: sistemi robotski, vodenje robotov, zaznavalne sile, vid računalniški)

In this paper a robot-control algorithm for tracking a curve on a surface is presented. During the tracking the robot maintains contact with the surface at a predefined force. The method is based on visual information provided by a camera mounted on the robot's end effector, and the measured force acquired from a force sensor. The obtained data are analyzed and the required information is employed in the control algorithm to ensure satisfactory operation. The proposed solution gives new enhancement opportunities for industrial robot-based applications.

(Keywords: robotic systems, robotic control, force sensors, computer vision systems)

0 UVOD

V industrijskih uporabah robotskih sistemov se pogosto pojavi zahteva, da je orodje nameščeno na robotsko roko, v stiku s podlago in sledi določeni krivulji. Primeri take uporabe so nanos lepil ali tesnilnih mas na spojne krivulje površin, poliranje posameznih delov površin ali brušenje spojev med površinami in podobno. Hkrati s sledenjem neki krivulji po površini je v nekaterih primerih uporabe pomembno tudi razpoznavanje same površine po krivulji. Tako je v primerih uporabe mogoče med samim opravilom odkriti različne napake v obliki površin, ki so lahko posledica napake v izdelavi posameznih izdelkov ali vgrajenih komponent v izdelke.

V preteklosti so se mnogi avtorji ukvarjali z opisano tematiko in so se problemom posvečali na različne načine. V prvih fazah poskusov vodenja robotov z optičnimi zaznavali so bili ti v večini primerov zasnovani na kalibriranih sistemih, ki so delovali na temelju izgradnje 3D informacije iz stereo ali podobnih sistemov za zajem slik, kjer so bile kamere za zajem večinoma nepremično nameščene, ali vodene

0 INTRODUCTION

In industrial applications there are frequent demands to maintain contact between the tool mounted on the robotic hand and the processed surface. Examples of such demands are the operations where a glue or a sealant needs to be carried to the surface, where the polishing of a surface has to be performed or where a contact between surfaces has to be brushed. For such robotic applications it is also interesting to be able to detect surface defects, or to identify the wrong types of assembled parts. This can be solved by identifying the shape of the surface along the tracked curve.

In the past, several researchers have worked in this field. The first tests of robot control with visual sensors were based on calibrated systems. 3D information about the environment was acquired by stereo or similar visual systems. Cameras were fixed or controlled by special camera-control manipulators. Such systems have some drawbacks that limits their practical use, e.g., high calculation demands and the occlusions of observed scenes in the case of fixed s posebnimi rokami za vodenje kamer. Stereo sistem ima velike računske zahteve, poleg tega pa se posebej v primeru stalno nameščenih kamer pojavijo problemi zakrivanja opazovanih predmetov. Za zmanjšanje računske zahtevnosti so bile opravljene določene poenostavitve na podlagi analize stereo slik med približevanjem robotske roke predmetu. V zadnjih letih so se na področju robotike in vgradnje robotskega vida v sisteme pojavili sistemi z vizualnim zaznavalom, nameščenim na vrh robotske roke. S to postavitvijo se je mogoče izogniti problemu zakrivanja, poveča pa se natančnost zaradi ožjega področja zanimanja [1]. Problem robotskih sistemov, opremljenih zgolj z vizualnimi zaznavali, so optične lastnosti, ki jih morajo za robustno delovanje 3D algoritmov vsebovati opazovani predmeti. Z namenom,da se zagotovi stalen stik s podlago in hkrati omogoči sledenje potem po površinah, so se razvili sistemi, ki vsebujejo kombinacijo vizualnih zaznaval in zaznaval sile, ki merijo silo, s katero robotska roka pritiska na površino. Zaznavalo sile je lahko nameščeno različno. Namestitev zaznavala sile na vrhu orodja se uporablja predvsem za natančno sledenje obrisov [2], vendar taka razporedba onemogoči namestitev orodja, zato se pogosteje gradijo sisteme z zaznavalom sile v zapestju robota.

Kombinacije teh zaznaval je za sledenje krivulji na neznani podlagi z nespremenljivo silo v smeri orodja uporabil Xiao [3]. Opisani način ne omogoča določitve nagiba površine. Sistem poišče točke na ravnini in predpostavi, da je krivulja med sosednjima točkama premica. Kamero, nameščeno na vrh robota, sta uporabila Baeten ([4] in [5]) za predikcijsko sledenje obrisa ravnega predmeta in Malis [6] pri natančni namestitvi orodja. Vsi navedeni primeri vsebujejo zgolj eno s silo vodeno smer, tako da ne pridobijo informacije o usmeritvi orodja na podlago.

V prispevku je opisana metoda, ki omogoča sledenje krivulji in zaznavanje usmeritve in temelji na hitrostno vodenem robotu. Sistem poskrbi za sledenje krivulji, zarisani na površini, tako da vrh orodja, nameščenega na robotski roki, zagotavlja stalen stik s površino, ne glede na njeno obliko. Sistem na vsaki točki poti določi normalo na površino in razpozna točko površine glede na celotni koordinatni sistem.

Sistem je zasnovan na zaznavalu sile in podaja informacijo o silah, ki delujejo na orodje v trirazse□nem prostoru in na slikovnem zaznavalu, ki preslika 3D informacije v dvorazsežni slikovni

cameras. To reduce the calculation demands some simplifications based on image analyses were introduced during the approach to the observed objects. In recent years robotic systems with the image sensor mounted on the end effector appeared. With this configuration the problems of occlusion can be avoided and a higher accuracy, because of a more focused area of interest, can be achieved [1]. The main problem of robotic systems based only on visual sensors are the optical characteristics of the observed objects required in order to achieve robust behavior of the 3D extraction algorithms. To establish and maintain a constant contact with the surface and simultaneously to track the desired trajectory, systems consisting of visual and force sensors were developed. Force sensors can be mounted in various ways. If the sensor is attached to the top of the tool the system is able to attain precise contour tracking [2]. Such a configuration disables the installation of a tool, therefore wrist-mounted force sensors are used in many cases.

The combination of the described sensors for curve tracking on an unknown surface with constant force in the direction of the tool was presented by Xiao [3]. With this approach it was not possible to identify the surface orientation. In the experiment some simplifications were made, and then the system was only capable of moving from the starting point to the end point in a straight line. A camera mounted on the top of the manipulator was used by Beaten ([4] and [5]) for predictive, planar contour tracking and by Malis [6] for the precise placement of the tool. In all these examples the force was controlled in only one direction. Consequently, no information about the orientation between the tool and the surface can be derived, and hence no identification of the surface orientation can be made.

With the method presented in this paper, a velocity-controlled manipulator tracks a curve drawn on an uncalibrated surface and perceives its orientation. The system maintains constant contact with the surface and tracks the curve regardless of the dynamics of the surface or the curve. With the proposed method, in each position of the curve the surface normal is determined and the tool is placed perpendicular to the surface.

Our system consists of a force sensor and a vision system. The force sensor provides six dimensional information about the force and torque acting on the tool, while the camera transforms 3D prostor. Slikovno zaznavalo je v našem primeru nameščeno na zapestje robotske roke, kar preprečuje zakrivanje, hkrati pa ni ovira za izbiro ustreznega orodja. V nadaljevanju prispevka je opisana metoda zbiranja informacije o silah in slikovne informacije, postopek združitve informacij, pridobljenih iz obeh zaznaval, delovni prostor robota. Nazadnje je opisana uporaba modela hibridnega vodenja. Sistem je bil v praksi zgrajen iz gradnikov, ki so opisani v poglavju Eksperimentalni sistem. Prispevek se konča s sklepnim poglavjem, v katerem so opisane naše ugotovitve in podane možnosti izboljšave sistema.

1 METODE IN POSTOPKI

Namen našega sistema je sledenje krivuljam na neznani površini in ob tem ohranjati orodje, usmerjeno pravokotno na podlago. Zadano nalogo je mogoče izvesti s kombinacijo zaznaval različnih veličin. Sledenje krivulji je izvedeno z računalniškim vidom, medtem ko se orodje površini prilagaja na podlagi informacij, pridobljenih iz zaznavala sile. Združevanje različnih informacij, pridobljenih iz zaznaval, ki obsegajo različne veličine in so ob tem še prostorsko odmaknjeni, je treba predstaviti kot celoto in jo uporabiti za učinkovito vodenje robota. Združitev podatkov, zbranih z merilnikom dotika in slikovnim zaznavalom, je zaradi njegovih lastnosti primerno izvajati v delovnem prostoru. Ta prostor omogoča preslikavo sil in leg sledene krivulje, zajete s slikovnim zaznavalom, v različne koordinatne sisteme. S tem opisom okolja se vzpostavi pravokotnost, ki omogoča neodvisno, hibridno vodenje na podlagi slikovne informacije in meritve sil.

1.1 Delovni prostor

Povezavo med silami in lego v delovnem prostoru je prvi definiral Mason [7]. Delovni prostor je postavljen v delovno točko orodja. Vse naloge v delovnem kartezičnem koordinatnem sistemu (KS) se razstavijo na tri premike v smereh x, y, z in tri zavrtitve okrog osi x, y, z. S kombinacijo izvajanja teh podnalog se izvedejo zelo raznolike robotske naloge.

Predstavitev delovnega prostora omogoča tudi preslikavo sil in vrtilnih navorov iz zaznaval v delovni prostor. Z uporabo predstavitve usmeritve z vzponom, odklonom in nagibom (VON - RPY), ki je najpogosteje uporabljena pri vodenju robotov, se

information of the scene into the image space. The camera mounted on the hand of the robotic manipulator reduces the possibility of occlusion and also gives the opportunity to use a fastened-on end-effector. In this paper the method of the force and vision sensors data acquisition and data analysis is described. The extracted data are integrated into a proposed task frame. The proposed method was validated by different tests that were carried out on a testbed described in the section called Experimental system. In the Conclusion the findings and some challenging future improvements of our system are discussed.

1 METHODS

The main goal of our work is to track a curve on an unknown surface. Additionally, the tool has to be oriented perpendicular to the surface. The given task can be executed using the data obtained by sensors of different modalities. The curve tracking is based on a vision system, while the tool adaptation to the surface is controlled by a force sensor. Sensor information, which represents the different modalities and is retrieved in different positions, has to be combined in its entirety to be used for efficient robot control. The integration of the data captured by the force and the vision sensors is reasonable to be done in the task frame. The task frame formalism enables the transformation of forces and the position of the tracked curve captured by the vision sensor, between different coordinate systems (CSs). Within the task frame the orthogonality is established. This enables hybrid control based on visual information and force measurement.

1.1 Task frame

The linkage between the force and the position in the task frame was proposed by Mason [7]. The task frame is positioned on the top of the tool. All tasks in the task frame's Cartesian coordinate system (CS) are divided into three translations in the direction of the coordinate axes and the three rotations around the coordinate axes. Through a combination of the defined basic motions all the robotic tasks can be executed.

In the task frame formalism the forces and torques can be transformed from one coordinate system (CS) to another. If the orientation is represented as roll, pitch, yaw (RPY) (which is most commonly used in manipulator control) then the sile *(F)* in vrtilni navori *(τ)* na posamezne koordinatne sisteme preslikajo takole:

forces and torques between different CSs are transformed in the following way:

$$ {}_{t}\vec{F} = \mathrm{RPY}({}^{t}_{s}\varphi_x, {}^{t}_{s}\varphi_y, {}^{t}_{s}\varphi_z)\, {}_{s}\vec{F} \quad (1), $$

$$ {}_{t}\vec{\tau} = \mathrm{RPY}({}^{t}_{s}\varphi_x, {}^{t}_{s}\varphi_y, {}^{t}_{s}\varphi_z)\, \left(({}^{t}_{s}p_x, {}^{t}_{s}p_y, {}^{t}_{s}p_z)^{\mathrm{T}} \times {}_{s}\vec{F} + {}_{s}\vec{\tau}\right) \quad (2), $$

kjer oznaka ${}^{(.)}$ označuje KS, iz katerega poteka preslikava, ${}_{(.)}$ pa KS, v katerega se sile prenesejo.

V našem delu opazujemo štiri KS. Prvi je pritrjen na vrh orodja in ga označimo s predpono ${}_{t}(.)$, drugi predstavlja kamero ${}_{c}(.)$, tretjega pa določa zaznavalo sile ${}_{s}(.)$. Vse dogajanje je predstavljeno v osnovnem KS robota. KS orodja in merilnika sil in vrtilnih navorov sta enako usmerjena in premaknjena v smeri osi *z* za razdaljo *L*. Razdalja *L* je zaradi podajnega orodja odvisna od sile, ki deluje v smeri orodja in jo določimo posredno prek ${}_{s}F_{z}$:

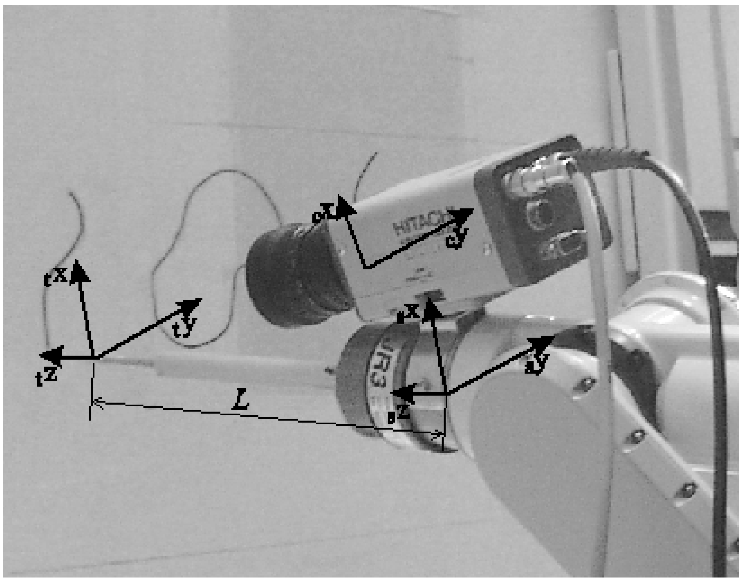
where ${}^{(.)}$ marks the CS from which the data is processed, while ${}_{(.)}$ represents the destination CS.

In our work four CSs are observed. The first one ${}_{t}(.)$is attached to the top of the tool, the second one ${}_{c}(.)$ represents the vision sensor, the third one ${}_{s}(.)$ defines the CS of the force sensor. All the occurrences are presented in base CS of the manipulator. The CS of the tool and the CS of the force sensor have the same orientation and are translated for *L* in the *z* direction. Because of the compliant tool the distance *L* is subjected to the contact force *F* hence, the force *L* is measured indirectly through force ${}_{s}F_{z}$:

$$ L = L_0 + \mu\, {}_{s}F_z \quad (3), $$

kjer sta L_0 razdalja med izhodiščema ${}_{t}$KS in ${}_{s}$KS, ko na orodje ne deluje nobena sila dotika, μ pa koeficient podajnosti orodja. Medtem ko so medsebojne usmeritve med ${}_{t}$KS, ${}_{s}$KS in ${}_{c}$KS stalne, pa se njihova lega glede na osnovni KS spreminja. Preslikavo med KS zaznaval in baznim KS določimo na podlagi kinematike robota.

where L_0 is the distance between ${}_{t}$CS and ${}_{s}$CS, when there is no contact force on the tool, and μ is the coefficient of the tool compliance. The orientations between ${}_{t}$CS, ${}_{c}$CS and ${}_{s}$CS are fixed. However, their position in the base CS is changing. The transformation between these CSs and the base CS is obtained from the direct kinematics of the robot.



Sl. 1. *Postavitev koordinatnih sistemov*
Fig. 1. *Placement of coordinate systems*

1.2 Merilnik sile in vrtilnega navora

Merilnik sile in vrtilnega navora je nameščen v zapestju robota in izveden tako, da kot rezultat vrača izmerjene vrednosti sil in vrtilnih navorov v smereh pravokotnih osi x, y, z. Izmerjena sila $\vec{F}_r$ je sestavljena iz sil dotika $\vec{F}_{co}$, pospeška robota $\vec{F}_a$ in težnosti $\vec{F}_g$:

1.2 Force sensor

The force sensor is mounted on the wrist of the manipulator. We measure the forces and torques in the orthogonal directions x, y, z. The measured forces consist of the contact $\vec{F}_{co}$, inertia $\vec{F}_a$ and gravity $\vec{F}_g$ forces:

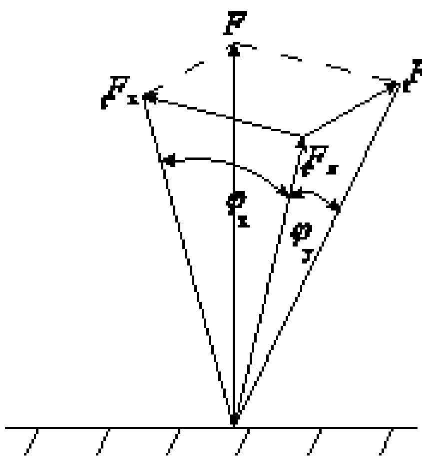
$$\vec{F}_r = \vec{F}_{co} + \vec{F}_a + \vec{F}_g \quad (4).$$

Za namen vodenja je pomembna samo informacija o sili stika, zato je treba iz meritev odstraniti vpliv teže in vztrajnosti. Za izravnavo vztrajnosti je treba poznati pospeške orodja. V večini primerov pospeškov ni mogoče meriti. Ker so pospeški majhni v primerjavi s silami, s katerimi delujemo na obdelovano površino, lahko $\vec{F}_a$ v našem primeru zanemarimo. Vpliv teže orodja izravnamo v fazi kalibracije robotskega sistema na način kakor ga je predlagal Omrčen [8]. Pri tem postopku na podlagi meritev sil in vrtilnih navorov v treh različnih znanih usmeritvah izračunamo maso in težišče orodja. Usmeritev orodja pridobimo v vsaki točki iz zavrtitvene matrike robota. Iz tako pridobljenih podatkov izračunamo $\vec{F}_g$ in jo odštejemo od izmerjene $\vec{F}_r$. Sile, zaznane z zaznavalom sile, se z enačbama (1) in (2) preslikajo na vrh orodja. V nadaljevanju se oznaka F zaradi poenostavitve zapisa nanaša le na sile, ki se vzpostavijo zaradi stika orodja s podlago.

Tako obdelani podatki so uporabljeni za identifikacijo površine. V statičnih razmerah sila podlage deluje na orodje v smeri normale na podlago.

In the control we need only the information about the contact. Therefore, we have to eliminate the contribution of the gravity and the inertia forces from the measured data. If the exact acceleration of the tool were to be known, inertia could be compensated. However, in our case $\vec{F}_a$ is small compared to $\vec{F}_{co}$ and therefore, it can be neglected, i.e., the gravity influence was compensated in the calibration phase of the robotic system as proposed by Omrčen [6]. On the basis of force and torque measurements in three known different orientations of the tool weight and the centre of mass of the tool can be calculated. The orientation of the tool is known in each point (from the rotation matrix of the robot). $\vec{F}_g$ can be calculated and subtracted from the measured $\vec{F}_r$. Using Equations (1) and (2) the forces measured with the force sensor are transformed to the top of the tool. For simplicity we denote in the following the contact forces between the tool and the surface as F.

The processed data are used for the surface identification. In static conditions the force of the surface acts on the tool in the direction normal to the surface.



Sl. 2. *Sila dotika, delujoča na vrh orodja*
Fig. 2. *Contact force on the top of the tool*

Iz komponent sile F izračunamo nagibna kota glede na površino (sl. 2):

From the components of force F the inclination angles to the surface are calculated (Fig. 2):

$$\varphi_x = \arctan(\frac{F_x}{F_z}) \tag{5}$$

$$\varphi_y = \arctan(\frac{F_y}{F_z}) \tag{6}$$

Kadar tipalo drsi po površini, se v sili F izmeri tudi sila trenja, ki deluje v nasprotni smeri gibanja. Silo trenja je mogoče oceniti v primeru znanega koeficienta trenja in ravnih površin, kar pa v praksi ni najbolj pogosto. V primeru neupoštevanja sile trenja se pri drsenju pojavi določen kot napake pri nagibu orodja glede na normalo površine. To napako zmanjšamo z uporabo orodij z majhnim koeficientom trenja.

When the tool is sliding over the surface a frictional force in the opposite direction of the motion is present. The friction force can be calculated only if the friction coefficients are known and the surface is flat. As in practice this is usually not the case, the influence of the friction is neglected and consequently some error is introduced to the inclination angles. To minimize these errors we use tools with low friction coefficients.

1.3 Slikovno zaznavalo

Za sledenje na površini izrisane poti uporabimo na zapestje nameščenno slikovno zaznavalo (kamera). Zajeto sliko je treba obdelati. Da bi sistem omogočal kar najbolj robustno delovanje, je zajem slikovne informacije zastavljen na barvni kameri, v barvnem prostoru "barvni odtenek - nasičenost - vrednost" (HSV). Slika je razčlenjena na podlagi barvne sestavine H in S. V prvi fazi se v področju zanimanja, predstavljenem v pravokotniku s polno črto (sl. 3a), na podlagi barvne informacije določi področje slike, ki pripada orodju. Iz tega področja se izračuna koordinate vrha orodja P_t. Zaradi znane medsebojne lege orodja, glede na kamero, se pri analizi slike poišče le vrh podajnega orodja, katerega dolžina se v odvisnosti od sile, s katero deluje na podlago, lahko spreminja. Potek krivulje se poišče s Canny-evim postopkom iskanja robov na sestavini barvnega prostora H (sl. 3b).

Krivulja na sliki ima dva robova. Za točke krivulje so upoštevane zgolj točke srednjih vrednosti robov. Ob tem se preveri še, ali je odtenek barve med robovoma podoben barvi, ki je v fazi kalibracije določena kot barva krivulje. Na podlagi segmentiranih podatkov se po metodi najmanjših kvadratov približa potek krivulje s kvadratnim polinomom v smeri premika orodja (sl. 3c). V višini vrha orodja j se iz približne krivulje določi tangento in izračuna razdaljo med orodjem in tangento e_y (sl. 3d). Po tangenti se določi kot φ_z glede na smer i.

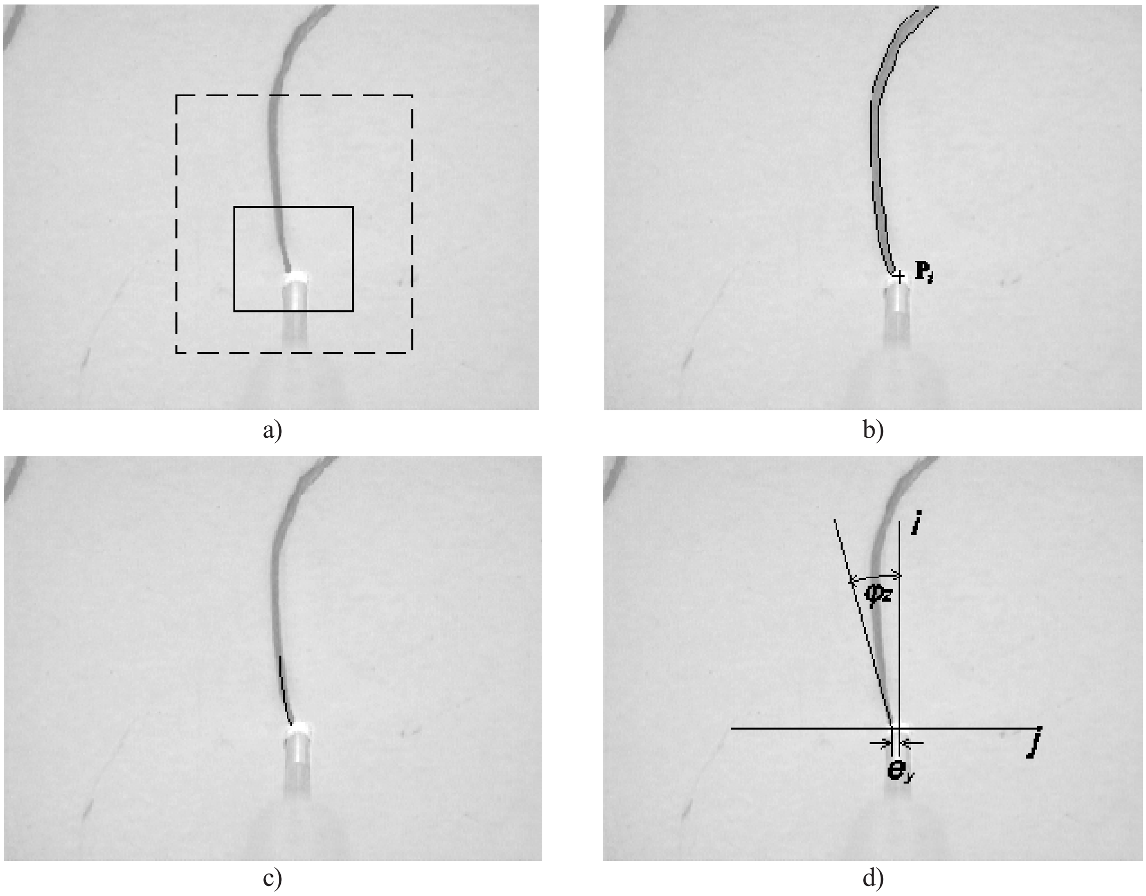
Za boljše spremljanje krivulje upoštevamo še njeno ukrivljenost (B). Ta postopek se izvaja na večji

1.3 Vision sensor

The information acquired from the wrist-mounted visual sensor (camera) is used for tracking the trajectory drawn on the surface. The captured images have to be analyzed. To achieve robust image segmentation a color camera was used. Data was processed in the "Hue-Saturation-Value" (HSV) space. The image was segmented into H and S color components. Based on color information the region of the image that belongs to the tool was identified. These data were used for a calculation of the coordinates of the top of the tool. Because of the known mutual position between the tool and the camera only the position of the top of the tool, which can change according to the compliant tool, has to be found. The curve is searched by the Canny edge detector of the H component in the color space (Fig. 3b). The color of the curve is determined in the calibration phase.

The curve is color coded and has two edges. The points of the curve are calculated as mean values in the region between the two edges. Based on the segmented image data the direction of the curve is approximated with a second-order polynomial calculated by the least-squares method (Fig. 3c). The tangent to the approximated curve at the position where the top of the tool is in contact with the curve gives the direction of the curve. The distance e_y between the tangent and the top of the tool is estimated and the angle φ_z is calculated from the tangent (Fig. 3d).

To define the optimal robot speed in the direction along the curve a bending factor *(B)* of the trajectory is calculated. This procedure is done in a wider region (Fig. 3a dashed rectangle) than the



Sl. 3. *Razgradnja slike: a) manjši pravokotnik pomeni območje za izračun tangente, črtkan pa za oceno ukrivljenosti z Wang-ovim detektorjem; b) določitev vrha orodja in točk krivulje; c) približek krivulje; d) vrednosti za slikovno sledenje*

Fig. 3. *Image segmentation: a) Smaller rectangle represents the region for the calculation of the tangent, the dashed rectangle is used for an estimation of curve bending; b) Determination of the top of the tool and the points of the tracked curve; c) Approximated curve; d) Values for the curve tracking*

dolžini krivulje (sl.3, črtkan pravokotnik), tako pridobimo boljšo informacijo o dinamiki spreminjanja krivulje. Ukrivljenosti krivulje (*B*) smo ocenili z Wang-ovim detektorjem [9].

1.4 Hibridno vodenje

Ker želimo voditi robot po legi in sili, smo uporabili hibridno vodenje, ki ga shematsko ponazarja slika 4. Vhodni primerjalni vrednosti sistema sta želena sila, s katero orodje deluje na površino, in največja hitrost gibanja po krivulji.

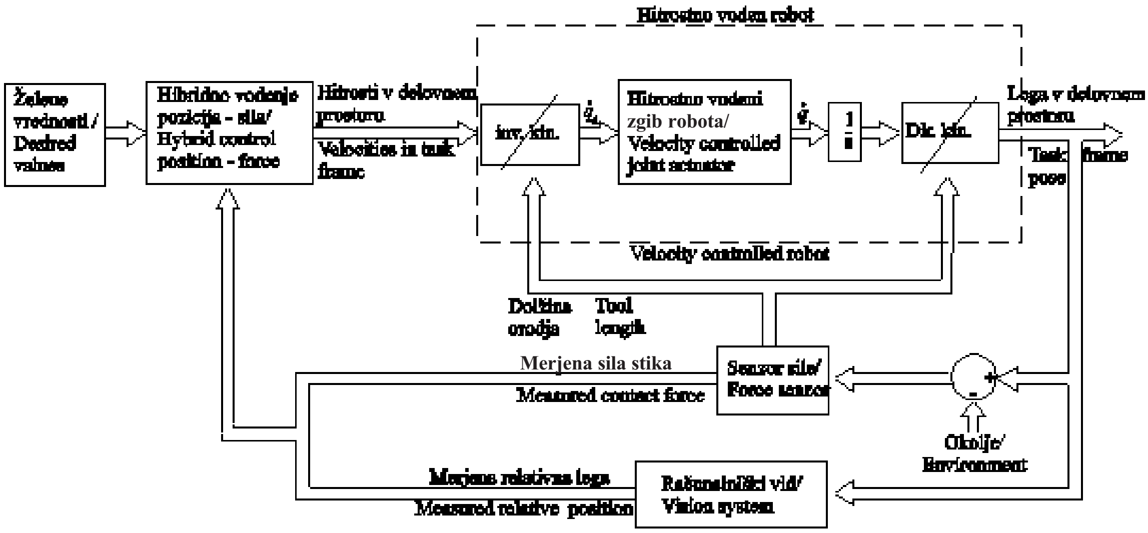
Hibridno vodenje združuje položajno vodenje in vodenje sile, izvedeno kot zunanja krmilna zanka okrog, zgibno krmiljenega, robota. Za preslikavo iz zgibnega prostora v delovni prostor uporabimo

estimation of the tangent and gives more global information about the curve dynamics. The bending factor of the curve is obtained by the Wang detector [9].

1.4 Hybrid control

The robot is based on a hybrid control, as schematically illustrated in Fig. 4. The desired force acting on the surface and the maximum speed along the tracked curve are the reference input values.

The hybrid control structure combines the sensor-based position and the force control, implemented as an outer control loop around the joint controlled robot. For the transformation from the joint space to the task space the robot kinematics



Sl. 4. *Shema hibridnega vodenja okrog hitrostno vodenega robota*
Fig. 4. *Hybrid control scheme around the velocity-controlled robot*

robotsko kinematiko. Po podatku o sili F_z izračunamo dolžino podajnega orodja z enačbo (3). Dolžina orodja vpliva na parametre inverzne in neposredne kinematike. V danem sistemu so smeri vodene s podatki o sili stika in relativne lege orodja. Glede na to, da obravnavamo hitrostno voden sistem, bodo v nadaljevanju podani postopki vodenja izraženi v hitrostnem prostoru.

is used. The length of the compliant tool affects the direct and inverse kinematics and the length of the compliant tool is calculated using the Equation (3). In the presented system all the directions are controlled according to the contact force or the relative position of the tool on the curve. Because the robot is velocity controlled, all the control actions are in the velocity space.

1.5 Vodenje sile

V smereh, vodenih s silo, je poglavitni namen vzdrževati zanesljiv stik orodja s podlago, tako da je sila nespremenjena in leži orodje pravokotno na podlago. Vodenje robota z želeno silo na podlago zagotavljamo s proporcionalnim krmilnikom:

1.5 Force control

In the directions controlled by the force the main goal is to maintain a constant contact with the surface so that the force is constant and the tool is perpendicular to surface. This is ensured by a proportional controller:

$$v_z = k(F_{dz} - F_z) \tag{7},$$

kjer so v_z zahtevana hitrost , F_{dz} in F_z želena in merjena sila v podani smeri ter k koeficient ojačanja.

Po podatkih o zaznani sili F na podlagi enačb (5) in (6) izračunamo nagibna kota orodja glede na normalo površine. Zaradi zahteve, da je orodje usmerjeno pravokotno na podlago, opravljamo zavrtitev okrog osi $_tx$ in $_ty$ s proporcionalnim krmiljenjem po enačbah:

where v_z is the control velocity, F_{dz} and F_z are the desired and the measured forces in a given direction, and k is amplifying the gain.

Force information is also used to determine the slant angles between the tool and the normal to the surface (5) and (6). To establish and maintain the orientation of the tool perpendicular to the surface the following angular velocities control is used.

$$\omega_x = -k_\omega \varphi_x \tag{8}$$

$$\omega_y = -k_\omega \varphi_y \tag{9}.$$

Usmeritev površine se izračuna iz usmeritve orodja in zavrtitvene matrike robota.

Knowing the tool orientation and the robot-orientation matrix means that the orientation of the surface can also be estimated.

1.6 Sledenje krivulji

1.6 Curve tracking

Sledenje krivulji je izvedeno z nekalibrirano kamero, kar pomeni, da vrednosti o absolutni vrednosti razdalj med koordinatnim sistemom kamere in orodja niso podane. Vidno vodenje je razbito na dve pravokotni smeri, kjer se v smeri y popravlja napaka e_y (sl. 3d) lege orodja pravokotno na os ${}_t x$:

The visual control is performed by an uncalibrated camera system. Hence, the absolute relation between the coordinate system of the camera and the top of the tool is not known. The visual tracking is divided into two orthogonal directions, where in the course of ${}_t y$ the error of e_y is corrected (Fig.3d).

$$v_y = -k_y e_y \quad (10).$$

Na osnovi informacije kota med tangento na krivuljo in osjo ${}_t x$ se izvede popravek zasuka orodja okrog osi ${}_t z$:

Based on information about the angle between the tangent on the curve and the axis, the rectification of the orientation of the tool around ${}_t z$ is made:

$$\omega_z = -k_{\omega z} \varphi_z \quad (11).$$

1.7 Hitrostno vodenje

1.7 Velocity control

V primeru, da bi bil opisani sistem namenjen sledenju po nezahtevnih krivuljah in ravnih površinah, bi vodenje robota lahko vedno izvajali s stalno hitrostjo robota v smeri osi ${}_t x$. Glede na to, da je naš cilj vodenje robota tudi po razgibanih površinah in po zelo ukrivljenih krivuljah, zarisanih na površini, je hitrost vodenja robota treba prilagoditi spremembam smeri sledene krivulje in razgibanosti površine. Zmanjševanje hitrosti zaradi ukrivljenosti krivulje je nujno zaradi zahteve po pravokotnosti med zaznanimi smermi v delovnem prostoru, kar zagotovi natančnejše izvajanje sledenja primerjalni krivulji v točkah ukrivljenosti.

Ob drsenju vrha orodja po površini se v primeru pomikov z velikimi hitrostmi ob razgibani površini dogaja, da vrh orodja na površino ne deluje z želeno silo, ali da na površino ni postavljeno popolnoma pravokotno. Da se zagotovi želeno sledenje je v tem primeru treba hitrost robota v smeri osi ${}_t x$ ustrezno zmanjšati.

Hitrostno vodenje robota v smeri pomika orodja je zato izraženo z enačbo

In the case when the proposed system is used for tracking a simple curve and almost flat surfaces robot control along direction ${}_t x$ with constant velocity. Our goal is also to track a curve on a more complex surface and curves with a more dynamic course; therefore, we have to adapt the velocity in a given direction according to the profile of the curve and to the shape of the surface. The bending of the curve could cause that axis ${}_t x$ not to be aligned with the tangent to the curve. In this case the system's ability to track a curve would be compromised.

At high velocity, sliding of the tool on the dynamic surface can occur, so that the top of the tool would not act on the surface with the desired force and the tool is not perpendicular to the surface. To ensure the desired tracking, the velocity ${}_t v_x$ in the direction ${}_t x$ has to be appropriately reduced.

The velocity control in direction ${}_t x$ can be expressed in following way

$$v_x = v_{x\max} - k_F \| \vec{F} - \vec{F}_d \| - k_B B \quad (12),$$

kjer je v_{xmax} največja dovoljena hitrost, $\| \vec{F} - \vec{F}_d \|$ je norma razlike med želeno in merjeno silo, B pa koeficient ukrivljenosti krivulje.

where v_{xmax} is the maximum-allowed velocity, ${}_t \vec{F}$ and ${}_t \vec{F}_d$ are the measured and the desired force on the top of the tool and B is the coefficient of curve bending.

Celotno vodenje v prostoru hitrosti zapišemo takole:

Combining all the partial velocity controls we obtain:

$$\begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} v_{x\,max} - k_F \,||\, \vec{F} - \vec{F}_d \,||\, - k_B B \\ -k_y e_y \\ k_z (F_{dz} - F_z) \\ -k_\omega \varphi_x \\ -k_\omega \varphi_y \\ -k_{\omega z} \varphi_z \end{bmatrix} \qquad (13).$$

2 PREIZKUSNI MODEL

Sistem sestavlja robot Mitsubishi PA-10 z zaznavalom sile JR3 in kamero Hitachi KP-D50 ločjivosti 640×480 na vrhu robota. Vodenje robota in zbiranje informacij z zaznavala sile poteka s frekvenco 700 Hz, medtem ko zbiranje in obdelava slik poteka s frekvenco 30Hz. Robot je hitrostno voden, kar pomeni, da so vhodi v krmilnik kotne hitrosti v sklepih robota.

2 EXPERIMENTAL MODEL

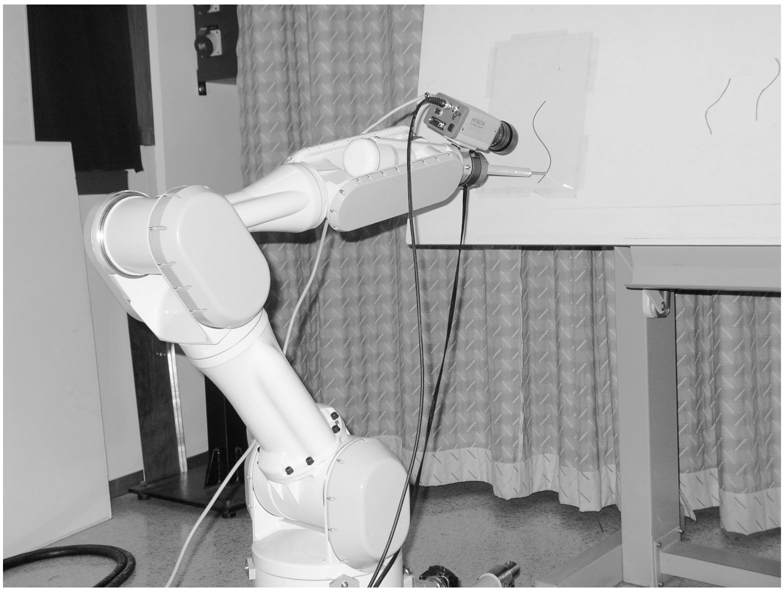
The system combines Mitsubishi Pa-10 robot with the JR3 force sensor and the wrist-mounted Hitachi KP-D50 color camera with a resolution of 640x480. The robot control and the force acquisition work at 700 Hz, meanwhile the camera capturing and the image analysis is maintained at a frequency of 30 Hz. The robot is velocity controlled, so the inputs to the controller are the angular velocities of the robot's joints.

3 PREIZKUSNI REZULTATI

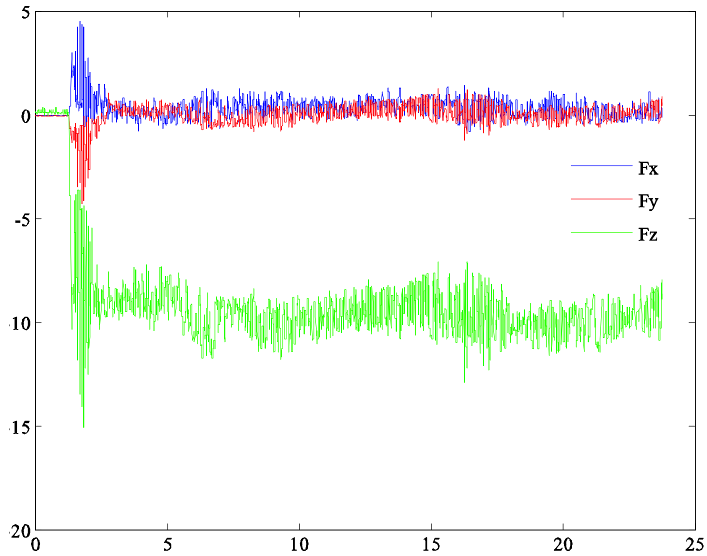
Predlagano metodo smo preizkusili na prej opisanem sistemu. Robot mora slediti krivulji na neznani togi površini. Delovna naloga je podana v delovnem prostoru robota. Znana trajektorija je načrtana na ravni obdelovani površini, po kateri

3 EXPERIMENTAL RESULTS

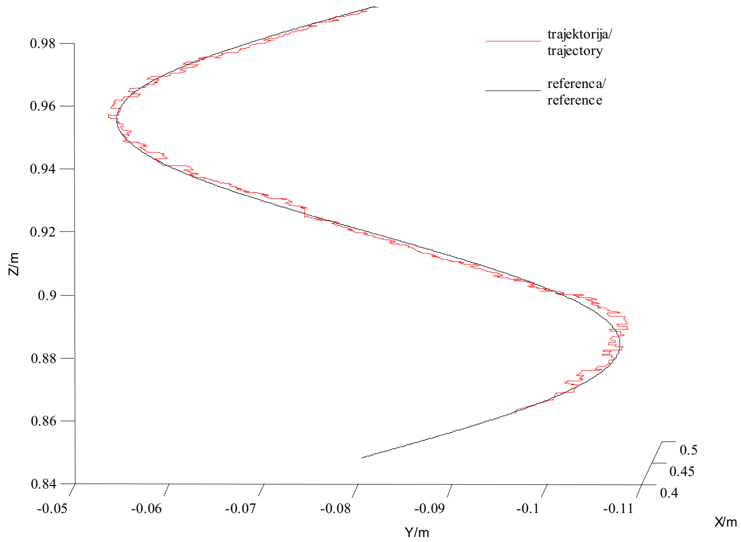
The proposed method was tested on the described system. The robot had to track a curve on an unknown stiff surface. A trajectory with a known shape was drawn on a plain surface. The curve had to be tracked with a maximum velocity of 0.01 ms^{-1}



Sl. 5. *Preizkusni model*
Fig. 5. *Experimental model*



Sl. 6. *Sile na vrhu orodja*
Fig. 6. *Forces on the top of the tool*



Sl. 7. *Dejanska pot vrha robota v referenčnem KS*
Fig. 7. *Actual trajectory of the end effector in the reference CS*

želimo drseti z največjo hitrostjo 0,01 ms^{-1} ob tem pa mora delovati na podlago s silo 10N .

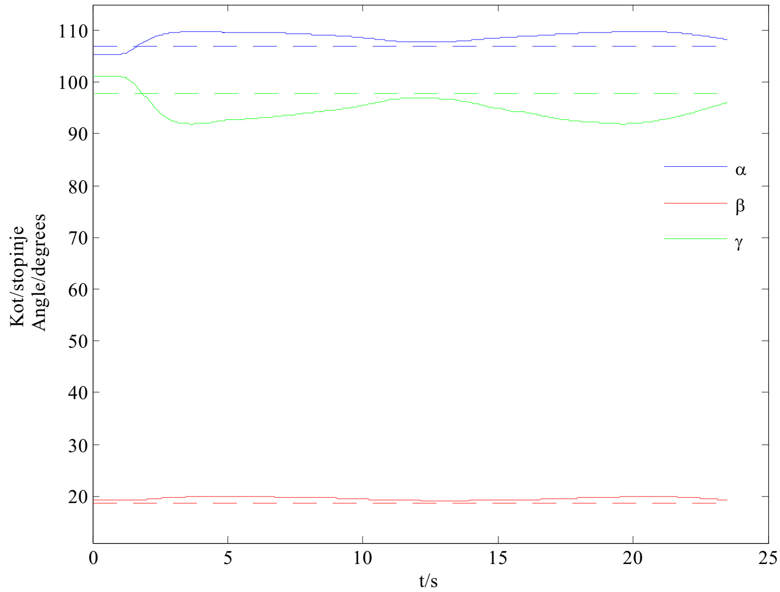
Rezultati preizkusov so predstavljeni na slikah 6 do 8. Merjeni podatki o silah vsebujejo informacijo o dotiku in tudi o vztrajnostnih silah, zato se v fazi vzpostavljanja sile pojavijo nihanja (sl. 6). Sistem po 0,5 s vzpostavi želeno silo pritiska F_z. Sili v preostalih smereh se stabilizirata 2 s.

S slike 7 je razvidno, da je sistem zmožen slediti želeni krivulji, vendar pa zaradi nenatančne informacije o dolžini orodja prihaja do premikov v

and tool had to maintain a constant contact force of 10 N.

The results of the test are presented in Figures 6–8. As the measured data also include information about the inertia forces, some oscillations appear in the transient phase (Fig. 6). The system is able to establish the desired force in the z_t direction in 0.5 s. Forces in other two directions stabilize in 2 s.

From Fig. 7 it is evident that the system is able to track the desired curve. Because of the inaccurate information about the tool length, there



Sl. 8. *Smerni koti $_tz$ v referenčnem KS. Črtkane premice pomenijo dejanske smerne kote normale površine.*
Fig. 8. *Directional angles of $_tz$ in the base CS. The dashed lines are real directional angles of the surface.*

smeri $_ty$ v delih krivulj z največjo ukrivljenostjo, ko os $_tx$ ni poravnana s krivuljo. Ti odmiki so tudi posledica izbire neoptimalnih parametrov vidnega vodenja.

Iz zavrtitvene matrike preslikave med baziènim in delovnim KS izračunamo smerne kote osi $_tz$ v primerjalnem KS robota. S slike 8 je razvidno, da se smer osi $_tz$ spreminja v območju 5° okrog želene vrednosti, kar je posledica dejstva, da smo zanemarili silo trenja in da sile v smeri osi $_tx$ in $_ty$ niso enake nič.

are some position errors in parts where the bending of the curve is large and the $_tx$ axis is not aligned with the curve. These errors can also be caused by non-optimal visual control parameters.

From the rotation matrix of the homogeneous transformation between the base CS and the $_t$CS direction the angles of the axis $_tz$ in the reference CS of robot were calculated. From Fig.8 it is evident that the direction of the axis $_tz$ is within a region of 5° around the desired value. The reason for this is that the frictional force is neglected and the forces in the direction of the $_tx$ and $_ty$ axes are not exactly zero.

4 SKLEP

Razvili smo sistem, ki je zmožen na temelju združevanja podatkov različnih zaznaval slediti neznani poti na neznani površini in ob tem vzdrževati stalen stik med površino in orodjem. Zaznavalo sile, nameščeno v zapestju robota, zagotovi informacijo o krajevni usmeritvi površine v točki dotika. Kamera v zapestju je uporabljena za sledenje neznane krivulje na površini. Predlagana metoda ne zahteva kalibracije kamere, zagotoviti je treba zgolj pravilno postavitev kamere glede na $_t$KS.

Sistem bi izboljšala uporaba merilne ure za merjenje L, namesto posrednega merjenja prek sile. Zaradi neznane natančne lege vrha orodja smo uporabili manjše vrednosti ojačanj za sledenje usmeritve površin, saj se zaradi nenatančne lege vrha

4 CONCLUSION

We have developed a system based on sensor fusion that is able to track an unknown trajectory on an unknown surface and to maintain a constant contact between the tool and the surface. A wrist-mounted force sensor provides local information about the surface orientation at the point of contact, while the camera is used for tracking the unknown curve on the surface. The proposed method does not require camera calibration, only proper placing of the camera in the $_t$CS has to be ensured.

The system could be improved by a direct measurement of the compliant tool length. The unknown exact position of the top of the tool forced us to use smaller values of gains for the tracking-surface orientation. The inaccurate direct kinematics cause namesto čiste zavrtitve pojavijo še premiki v delovnem prostoru. Dodatna izboljšava bi bila tudi uporaba nekalibriranega prostorskega vida, saj bi s tem pridobili bolj celovito informacijo o razgibanosti površine, kakor jo omogoča zaznavalo sile.

translation in the task space when only the orientation is supposed to be done. Another improvement to the proposed system would be the use of an uncalibrated stereo vision system. In this case more global information about the surface dynamics could be acquired.

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Nove knjige - New Books

Gary B. Tatterson: Process Scaleup and Design

Založba: Gary B. Tatterson,
1. izdaja, november 2002.
Obseg: format 21 × 28 cm, 204 strani, 41 slik, 10 citatov.
Cena: 30,57 $

Načrtovanje postopka in njegov prenos iz laboratorijske naprave na dejansko tj. industrijsko napravo je pomembno področje dejavnosti pri praktično vseh vejah industrije, s katerim se predvsem srečujejo razvojne skupine novih izdelkov. Knjiga podaja koristne informacije različnim profilom znotraj razvojnih skupin, kakor so menedžerji, inženirji, znanstveniki in tehnično osebje, tako iz teoretičnih osnov kakor tudi iz bogatih praktičnih izkušenj avtorja med dolgoletnim delovanjem v industriji. Z obsežnimi primeri iz industrijske prakse avtor podaja številne praktične rešitve skozi širok spekter industrije (splošna in specialna kemijska proizvodnja, petrokemijska, biokemijska, agrokemijska, farmacevtska in živilska proizvodnja), ki opozarjajo na možne probleme pri povečavi postopka in usmerjajo k pravilni rešitvi. Zaradi različnih nepredvidljivosti obstaja namreč tudi možnost nastanka slabega izdelka pri prenosu na industrijsko napravo.

Vsebina knjige je tematsko razdeljena na naslednja poglavja: (i) povečava in načrtovanje postopka, ki obsega raven načrtovanja postopka, izbiro opreme, ponovljivost načrtovanja, itn. (ii) smotrna metoda povečevanja s poudarkom na razumevanju postopka, (iii) težave pri povečevanju z vidika kemijskih in fizikalnih osnov postopka, geometrijske podobnosti itn., (iv) robni pogoji postopka in nepredvidljivost, (v) možne smeri razvoja postopka ob začetnih zahtevah, nadaljnji optimizaciji postopka s posebnostmi in (vi) uporaba pilotske naprave, ekonomija postopka, zgodovinski oris in varnost.

Knjiga v celoti podaja nove informacije in gradivo, kako izvesti postopek povečave in načrtovanja in je primerna tako za industrijsko prakso kakor pomoč študentom pri njihovem študiju.

doc.dr. Andrej Bombač

Osebne vesti - Personal Events

Prof.dr. Anton Kuhelj ml. - sedemdesetletnik
Prof. Anton Kuhelj jr. - 70th Anniversary

Pred časom je 70. rojstni dan praznoval upokojeni profesor dr. Anton Kuhelj ml., dolgoletni visokošolski učitelj na Fakulteti za strojništvo Univerze v Ljubljani. Rojen je bil 9.8.1934 v Ljubljani in tu tudi maturiral kot najboljši maturant generacije gimnazijcev, ki se je učila tako latinščine kakor tudi grščine. Diplomiral je na Fakulteti za strojništvo 1960 leta. Po diplomi je deloval dve leti na Inštitutu Jožef Štefan, nato pa je skoraj dve leti preživel v Švici, kjer se je spoznaval s praktičnimi vidiki dinamike strojev na Centrali za dinamiko podjetja Gebrüder Sulzer AG v Winterthuru. Po vrnitvi v domovino se je zaposlil na Fakulteti za strojništvo, kjer je bil 1964 izvoljen za asistenta za predmete mehanike. Leta 1969 je magistriral ter leta 1972 doktoriral pri prof.dr. Ervinu Prelogu. V učiteljski naziv docenta je bil izvoljen leta 1973, v naziv izrednega profesorja leta 1978 ter v naziv rednega profesorja leta 1984.

Na FS je poučeval predmete mehanike, na začetku na visokošolski in na višješolski stopnji, kasneje pa na univerzitetni stopnji vse do svoje upokojitve decembra 1997. Med predmeti, pri razvoju katerih je pustil neizbrisljiv pečat, so predmeti s področja dinamike, ki so med njegovo aktivno dobo na FS nosili različna imena od Mehanike II do Dinamike in nihanj, danes pa predmet nosi ime Dinamika. Zasnoval je tudi predmet Dinamika strojev, v sklopu katerega je poučeval poglobljene teoretične osnove, ki so bile tako včeraj kakor tudi danes še kako potrebne sodobnemu inženirju strojništva. Nekaj let je poučeval tudi predmet Dinamika strojev na Visoki tehniški šoli v Mariboru in tudi predmet Elastodinamika na Strojni fakulteti v Sarajevu, na oddelku v Banjaluki. Za potrebe dodiplomskega študija je napisal visokošolska učbenika iz Kinematike ter Dinamike. Na podiplomskem študiju FS je bil nosilec oz. sonosilec predmetov Dinamika in vibracije, Lomna mehanika ter Akustična emisija in hrup. Med njegovim aktivnim učiteljskim obdobjem je pod njegovim mentorstvom končalo študij večje število študentov, tako na diplomski kakor tudi na magistrski ter doktorski stopnji.

Ustanovil in do upokojitve tudi vodil je Laboratorij za dinamiko strojev in konstrukcij, znotraj katerega se je pod njegovim vodstvom začelo ter razmahnilo tako teoretično-raziskovalno in tudi, predvsem za potrebe slovenske industrije, uporabno-razvojno delo na področju, ki ga označuje že samo ime laboratorija. Dejavnosti njegovega laboratorija so združevale teoretsko-analitično delo na področju dinamike z eksperimentalnim delom. Pri slednjem je začel praktično iz nič ter je v letih vodenja laboratorija pridobil osnovno eksperimentalno opremo, ki je omogočala primerjavo izračunanih ter izmerjenih spremenljivk v dinamiki. Dejaven je bil na področju dinamike rotorjev, modeliranja dinamičnega obnašanja dejanskih tehničnih sistemov, utrujanja kovin, zmanjševanja hrupa, če poudarim le najpomembnejše smeri strokovnega delovanja. Kot zanimivost naj izpostavim npr. preračun dinamike pralnika med zagonom ter ožemanjem, pri katerem je njegova skupina že pred skoraj 20 leti svoje modele približala dejanskem stanju nekako od 10 do 15%. Še sedaj se spominjam predstavnika podjetja, ki je na naš predlog, da bi poskusili gibanje pralnika analitično-numerično ovrednotiti, izjavil, da se to vendar ne da.

Na FS je prof. Kuhelj opravljal vrsto nalog skupnega pomena, od katerih je bilo pomembno delo prodekana za znanstveno-raziskovalno delo ter nato njegovo vodenje fakultete v vlogi dekana v letih 1987/88. Vodil je tudi usmerjene raziskovalne programe, kjer je omogočil pridobitev javnih sredstev večjemu številu mlajših raziskovalcev na FS, za kar so mu še danes hvaležni. Bil je dejaven tudi zunaj fakultete, in sicer v okviru tako Univerze v Ljubljani kakor tudi raziskovalne skupnosti. Zelo cenim njegov prispevek, ko sva s skupnimi močmi sredi 90. let zavrtela kolesje pred tem ustanovljenega Likarjevega sklada, ki podpira študij študentov Univerze v Ljubljani na Tehniški Univerzi v Münchnu. Posvetovalnemu odboru tega sklada je predsedoval 10 let in v tem času omogočil finančno podporo prek 20 študentom.

Prof. Kuhelj je v vlogi učitelja in vodje laboratorija pokazal širino in nesebičnost pri svojih odločitvah. Spominjam se njegovega kratkega stavka v zimskem vrtu na FS decembra 1997, ko je odhajal v pokoj in ko se je fakulteta poslavljala od dejavnega delovanja treh rednih profesorjev. Prof. Kuhelj se je zahvalil navzočim z besedami, ki so tako značilno opisale njegov način razmišljanja. Dejal je, da je pri svojem delovanju vedno gledal na širše koristi.

Prof. Kuhelj ni samo odličen pedagog in strokovnjak, pač pa ga poznam tudi kot človeka v najboljšem pomenu te besede. Če bi moral s čim manj izrazi opredeliti njegove glavne poteze, bi izpostavil prav njegovo širino ter preudarnost. Širino mu je dala njegova družina, klasična izobrazba, znanje več tujih jezikov in ne nazadnje tudi bivanje in pridobivanje strokovnih izkušenj v tujini. Pred vsako odločitvijo je rajši premišljeval malo dlje, da si kasneje ni premislil. In čas je pokazal, da so bile njegove odločitve vedno pravilne.

S prof. Kuhljem sem sodeloval dolgo vrsto let, saj me je že takoj po opravljenem izpitu v drugem letniku povabil k sodelovanju kot demonstratorja. Pozneje se je iz tega sodelovanja razvilo moje dolgoletno delo v vlogi asistenta pri njegovih predmetih, zlasti na področju dinamike. Po njem sem se zgledoval pri pedagoškem in raziskovalnem delu, skupaj pa sva tudi reševala praktične probleme iz vibracij slovenske industrije. Ko se je odločil, da bo odšel v pokoj in vodenje vsega, kar je v dolgih letih ustvaril, prepustil mlajšim, mi ni bilo težko slediti poti, ki jo je že začrtal. Vsi člani Laboratorija za dinamiko strojev in konstrukcij nadaljujemo njegovo delo, ga še dalje razvijamo in nadgrajujemo.

Tone, spomenika si večinoma nihče ne postavi sam, pač pa mu ga postavijo njegovi učenci ter nasledniki. Upam, da si ponosen na nas, svoje učence. Mi smo ponosni nate.

prof. dr. Miha Boltežar

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 *17. oktobra 2005*: **mag. Matevž Dular**, z naslovom: "Razvoj metode napovedi kavitacijske erozije";

dne *20. oktobra 2005*: **mag. Janko Slavič**, z naslovom: "Nelinearna in nezvezna dinamika sistema diskretno definiranih togih teles z enostranskimi kontakti";

dne *27. oktobra 2005*: **mag. Aleš Brezovar**, z naslovom: "Procesno orientirana organizacija proizvodnje v virtualni skupini podjetij".

S tem so navedeni kandidati dosegli akademsko stopnjo doktorja znanosti.

MAGISTERIJI

Na Fakulteti za strojništvo Univerze v Ljubljani sta z uspehom zagovarjala svoji magistrski deli:

dne 6. oktobra 2005: **Iztok Jelen**, z naslovom: "Optimizacija nosilnih varjenih konstrukcij v procesu snovanja hidromehanske opreme";

dne 13. oktobra 2005: **Urban Žargi**, z naslovom: "Model računalniško podprtega načrtovanja in razporejanja operacij".

Na Fakulteti za strojništvo Univerze v Mariboru so z uspehom zagovarjali svoja magistrska dela:

dne 6. oktobra 2005: **Oton Mlakar**, z naslovom: "Model gospodarjenja z bolnišničnimi odpadki";

dne 12. oktobra 2005: **Vlasta Ojsteršek**, z naslovom: "Primerjava tehnoloških in ekonomskih značilnosti ločevanja težkih in lahkih deležev komunalnih odpadkov";

dne 14. oktobra 2005: **Zorko Terpin**, z naslovom: "Načrtovanje in integriranje informacijskega sistema za proizvodnjo";.

S tem so navedeni kandidati dosegli akademsko stopnjo magistra znanosti.

DIPLOMIRALI SO

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

dne *3. oktobra 2005*: Matjaž BEVC, Peter ŠIMNIC, Aleš ŠOLAR, Jože TOMEC;

dne *26. oktobra 2005*: David BOMBAČ, Anton MARC, Boštjan NOTAR.

Na Fakulteti za strojništvo Univerze v Mariboru je pridobil naziv univerzitetni diplomirani inženir strojništva:

dne *27. oktobra 2005*: Aleš RAJŠP.

*

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

dne *13. oktobra 2005*: Dejan GOVEDNIK, Marko MIŠIČ, Marko UDOVČ;

dne *14. oktobra 2005*: Matjaž AVSEC, Nejc BRVAR, Andrej DOLENC, Sašo DOLENC;

dne *17. oktobra 2005*: Božo BENEDEJČIČ, Janez ČERVEK, Peter IFKO, Jani KENDA.

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

dne *27. oktobra 2005*: Bogdan LUKMAN, Tilen STROPNIK, Bojan URŠEJ.

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.

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].

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

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.

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].

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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