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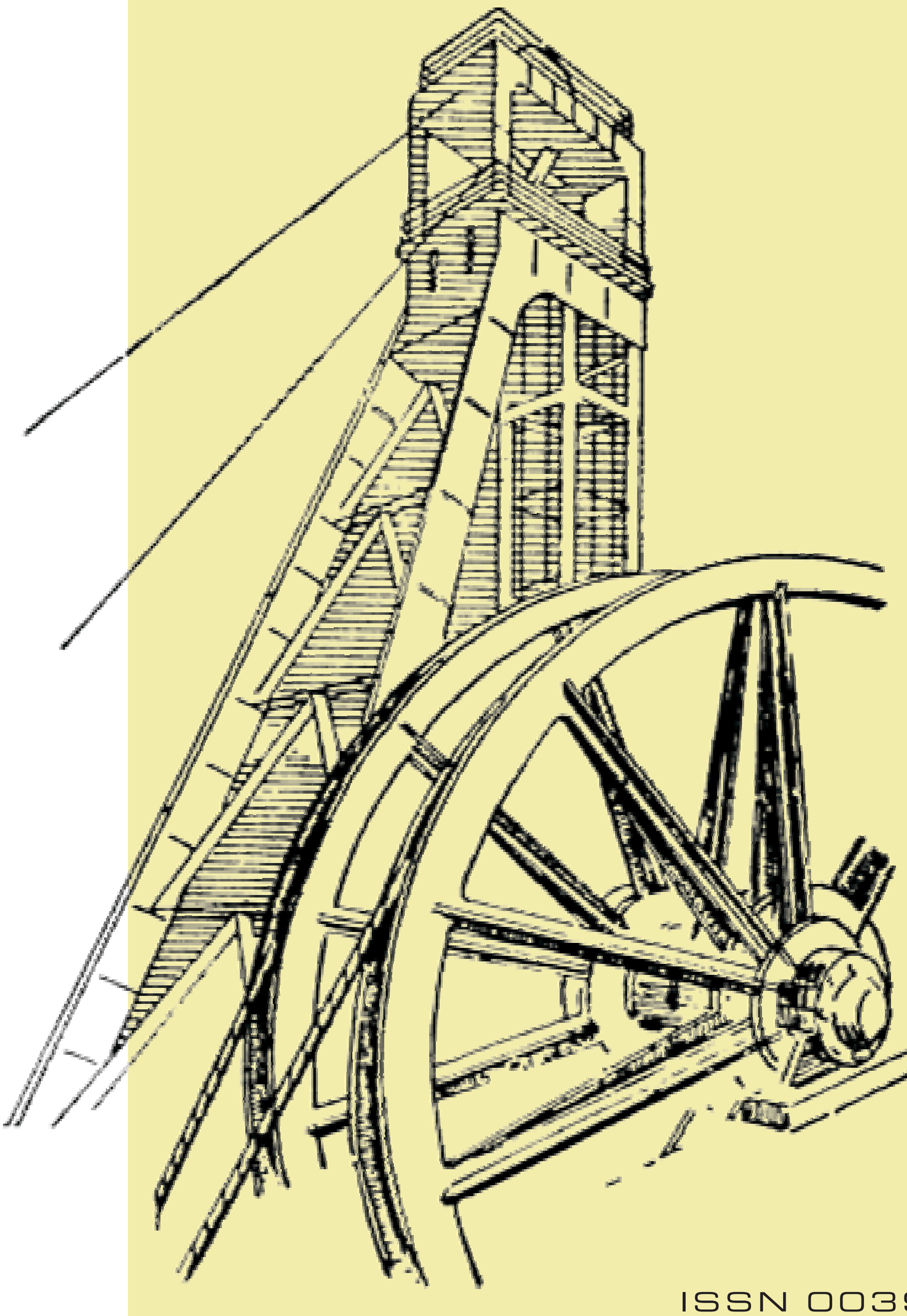

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Analiza tokovnih struktur v vstopnem sistemu motorjev - primerjava rezultatov meritev in numerične simulacije

Analysis of the In-Cylinder Flow Structures Generated by the Engine Induction System – a Comparison of Experimental and Simulated Data

Samuel Rodman Oprešnik - Sašo Prijatelj - Tomaž Katrašnik - Ferdinand Trenc - Frančišek Bizjan

V prispevku so prikazani rezultati numerične analize - simulacij na osnovi računalniške dinamike tekočin (RDT) in meritev hitrostnega polja v vstopnem sistemu motorja z notranjim zgorevanjem z uporabo laserskega Dopplerjevega anemometra (LDA). V ta namen je bil izdelan stekleni osmerokotni model valja, ki je po geometrijski obliki podoben valju resničnega motorja. Premičen bat je tokovne razmere na modelu še bolj približal resničnim razmeram pri pravem motorju. Ugotovljeno je dobro ujemanje izračunanih in izmerjenih rezultatov pri določitvi tokovnih struktur, hitrostnega polja v valju in pri določitvi pretočnega koeficienta v vstopnem ventilu motorja. Raziskava je tudi pokazala, da je mogoče z numerično analizo RDT-jem razmeroma dobro napovedati dogajanje v valju motorja in izboljšati razumevanje pojavov, ki spremljajo polnjenje valja motorja.

(Ključne besede: motorji ZNZ, računalniška dinamika tekočin, CFD, polja hitrostna, anemometri Dopplerjevi laserski)

A comparison and analysis of laser Doppler anemometry (LDA) measurements and a computed fluid dynamics (CFD) simulation of the in-cylinder flow structures generated by an engine induction system is presented in this paper. An octagonal glass model with a moving piston complementary to a real engine cylinder was applied in the analysis. Good agreement between the measured and simulated patterns of the flow structures and the inlet-valve discharge coefficients was obtained. In general, this study shows that in-cylinder CFD predictions yield reasonably accurate results that help to improve the knowledge of the air-flow characteristics during the intake stroke. CFD therefore represents an effective design tool for developing less-polluting and more efficient internal combustion engines.

(Keywords: internal combustion engine, computational fluid dynamics, CFD, air flow characteristics, laser Doppler anemometry)

0 UVOD

Kakovost zgorevanja v valju ottovega in dizelskega motorja z notranjim zgorevanjem močno vpliva na nastanek škodljivih emisij v ostankih zgorevanja, zato je dobro poznavanje tokovnih razmer v valju motorja z notranjim zgorevanjem neobhodno. Strukture turbulentnega toka v valju motorja so pomembne tako za začetek kakor tudi za celotno obdobje trajanja zgorevanja in njegovo učinkovitost [1]. Velikostni red turbulentnih struktur je različen: od največjega, ki ga omejuje geometrijska oblika zgorevalnega prostora, pa vse do najmanjših, pri katerih prevladuje molekulska difuzija. Vrtinčni tok zgorevalne zmesi, ki ima poudarjen vrtinec v obodni in/ali vzdolžni

0 INTRODUCTION

In order to reduce harmful exhaust emissions and increase the efficiency of internal combustion engines, fundamental knowledge of in-cylinder fluid motion is required, since it significantly affects the combustion process in both SI and CI engines. It is well known that the structure of the turbulent flow field of the fresh charge is a determining factor in the initiation, the rate of propagation, and the efficiency of the combustion process in an internal combustion engine [1]. The turbulent length scales range from the largest, which are limited by the physical constraints of the combustion chamber, to the smallest, which are governed by molecular diffusion. A smeri valja je stabilnejši, razpada počasneje in zato koristno pomaga pri učinkovitem mešanju goriva in zraka ter zgorevanja tudi v kasnejših obdobjih zgorevanja ([2] in [3]). Zato je za razvoj sodobnih motorjev, še posebno glede zmanjšanja škodljivih emisij v izpušnih plinih, izredno pomembno dobro razumevanje časovnega in krajevnega razvoja tokovnih struktur med vtekanjem in stiskanjem delovne snovi v valju [4].

Pri določanju oblike toka v valju, ki je predvsem posledica oblike vstopnega kanala in pogojev delovanja motorja, so bili do sedaj največkrat uporabljeni rezultati preizkusov na mirujočem valju oziroma modelu valja (npr. v objavah [5] in [6]). Kasneje so bili osnovnim podatkom dodani še dodatni parametri, ki so bolje opisovali integralni tok v valju [7]. Z rezultati eksperimentalnega dela, ki je bilo podprto s preprostimi fenomenološkimi modeli, podobne sta razvila za potrebe svojih raziskav Davis in soavtorji [8] in Murakami in soavtorji [9], je bilo mogoče določiti osnovne parametre, ki določajo tokovno polje v valju motorja. Pomembno prednost omenjenega načina kombiniranega reševanja odlikuje enostavnost in majhna poraba raziskovalnega časa, medtem ko pomeni manjša podrobnost opisa tokovnih struktur večjo pomanjkljivost, ki nas lahko pripelje tudi do napačnih rezultatov in sklepov. Velik korak pri natančnem preizkusnem določanju hitrostnega polja v mirujočem valju pomeni uvedba laserske Dopplerjeve anemometrije (v nadaljevanju LDA) ([10] in [11]). Rezultati so bistveno natančnejši od rezulatov, ki so bili izmerjeni s starejšimi ustaljenimi preizkusnimi metodami. Vpogled v tokovno dogajanje v valju omogočijo tudi sodobne 3D numerične simulacije (v nadaljevanju modeli RDT), s katerimi lahko rešimo ustrezne tokovne enačbe in izračunamo podrobne vrednosti povprečnih hitrosti toka in značilnosti turbulentnega hitrostnega polja. Pri uporabi modelov RDT moramo upoštevati posebnosti nestalnega toka, vpliv visokega Reynoldsovega števila toka in izjemno zamotane oblike trdnin - sten pretočnih kanalov, ventilov in valja.

V zadnjem času lahko v strokovni literaturi za potrebe določitve tokovnega polja v valju (tudi delujočega motorja) zasledimo (npr. [12] in [13]) tudi pogosto uporabo metode določanja hitrosti delcev toka z analizo optičnih posnetkov - DHD (PIV). Njena prednost je, v primerjavi z drugimi preizkusnimi metodami, v trenutnem in ne samo časovno povprečenem prikazu celotnega tokovnega stanja v valju. Ima pa metoda DHD tudi pomanjkljivosti: zahteva velike moči laserjev, sorazmerno velike dodatne delce za sipanje svetlobe, ki zaradi svoje

well-defined swirl and/or tumble flow structure is more stable than other large-scale in-cylinder flows and, therefore, it can break up later during the cycle, giving higher turbulence during combustion ([2] and [3]). Therefore, a good understanding of the evolution process of fluid motion in internal combustion engines is critical when the development of advanced engines with the most attractive operating and emission characteristics is concerned [4].

Simple experimental tests in steady-state flow rigs have been widely used to determine the flow motion generated by induction systems (see, for example, [5] and [6]). Some supplementary parameters to evaluate the bulk motion of in-cylinder flow were defined more recently [7]. In conjunction with simple phenomenological models, such as those developed by Davis et al [8] and Murakami et al [9], these experimental procedures helped to determine several fundamental variables that define the flow inside the cylinder. Simplicity and a moderate consumption of time are the advantages of this type of approach. However, the information provided is not detailed enough, and the assumptions made can lead to inaccurate results. A more accurate experimental technique is the measurement of the velocity field in a steady-flow test rig using laser Doppler velocimetry (LDV) ([10] and [11]). This method provides high-quality results and more information than other conventional methods. Another approach for getting an insight into the in-cylinder flow is the application of three-dimensional numerical simulation codes (CFD models), that are efficient in solving the governing flow equations, and thus provide a detailed description of the mean velocity and the turbulent velocity fields. When applied to internal combustion engines, the CFD models have to consider the specific problems linked to the unsteady flows, the high Reynolds numbers involved, and the highly complex geometry of the solid boundaries.

Many authors (see, for example, [12] and [13]) have applied the PIV (Particle Image Velocimetry) method to determine the flow patterns in cylinders, since it produces whole field data relating to a particular instant of the observed time rather than a phase-average. However, high laser-power levels and relatively large seeding particles are required to achieve satisfactory results; on the other hand, large particles introduce measurement errors due to inertial effects [14].

The aim of this study was to validate the accuracy of the CFD simulations of the in-cylinder vztrajnosti ne sledijo toku in tako vnašajo večjo merilno negotovost [14].

Namen predstavljenega dela je, da ovrednotimo natančnost uporabljene simulacije RDT in raziščemo njeno uporabnost ter omejitve pri določitvi tokovnega polja v valju motorja z uporabo preizkusne metode LDA. Zahtevnost in različnost oblike vstopnega sistema za različne motorje onemogoča preprost prenos ekstrapolacije dobljenih rezultatov opravljenih preizkusov na druge motorje [15], pač pa je zelo primeren in pogosto uporabljan pri optimizaciji oblike vstopnega, izpušnega sistema in zgorevalnega prostora opazovanega motorja. Zato je bil izdelani model steklenega valja motorja ustrezno obdelan in pripravljen za uporabo v simulacijski kodi CFX [16]. Opravljena in prikazana analiza ima dva cilja: 1) da preveri uporabnost in natančnost izračunanega pretočnega koeficienta in 2) da preveri uporabnost rezultatov računske simulacije RDT tokovnih struktur v valju motoja.

Pretočni koeficient vstopnega ventila motorja pomembno vpliva na količino v valj motorja vnesene sveže snovi in s tem tudi na moč in emisijo škodljivih snovi v izpušnih plinih. Obenem je tudi pomemben vstopni podatek pri računanju z nič in enorazsežnimi simulacijskimi modeli. Žal je njegova računska določitev praktično nemogoča zaradi izredne zapletenosti toka skozi ventil.

1 PREGLED UPORABLJENIH PREIZKUSNIH METOD

1.1 Opis preizkusne naprave

Merilna naprava, katere posnetek je prikazan na sliki 1 in s katero so bili opravljeni vsi predstavljeni preizkusi, sestoji iz pet pomembnejših sestavnih delov:

- sistema LDA za merjenje hitrosti v modelu valja,
- računalniško vodenega položajnega sistema za uporabljeno merilno lečo LDA,
- sistema merilnikov diferenčnega tlaka v modelu valja,
- enote sesalnika za prah z elektronsko nastavljivo frekvenco vrtenja - nastavljivim tokom zraka in nastavljivim poljubnim tlačnim padcem v vstopnem ventilu,
- kovinske - izvirne glave primerjalnega motorja, ki je bila pritrjena na stekleni model valja; omogočena je poljubna nastavitev pretočne špranje v ventilu.

Za potrebe raziskav je bil iz optičnega stekla izdelan osmerostrani model valja dizelskega tlačno polnjenega motorja MAN D0926 LOH15 z delovno

flows with laser Doppler anemometry (LDA) measurements and explore the applicability and the limitations of the CFD representation of the in-cylinder flow pattern. The complexity of the fluid motion in IC engines makes it difficult to extrapolate experimental results from one engine geometry to another [15]; therefore, validated and calibrated CFD simulation codes are gaining popularity when the optimization of the combustion-chamber geometry, the induction and exhaust system geometry, etc., is concerned. Therefore, a cylinder model with optical access was built, and its geometry was simultaneously implemented into the CFX (AEA Technology) simulation code [16]. The presented analysis has two goals: 1) to analyze the accuracy and applicability of the simulated intake-valve discharge coefficient and 2) to analyze and explore the applicability of the CFD simulations to predict the in-cylinder flow structures.

The intake-valve discharge coefficient is a fundamental variable that substantially influences the quantity of fresh air in the cylinder, and therefore the engine performance and the emission of pollutants. It is also an important input parameter for all zero- and one-dimensional engine-simulation models. An analytical determination of the flow coefficients is not possible due to the complexity of the fluid flow.

1 EXPERIMENTAL METHODS

1.1 Experimental equipment

The measurement equipment used for all the experiments is presented in Fig.1; it consists of five general components:

- an LDA system for in-cylinder velocity measurements
- a computer-controlled positioning system for an applied optical probe
- a gauge-pressure measurement system
- a vacuum-cleaner suction unit to set the appropriate air flows and pressure drops across the cylinder and cylinder head
- a real engine cylinder head attached to the glass model of the cylinder; the setting of an arbitrary intake-valve clearance and any piston-crown position is possible.

An octagonal model cylinder made of optical glass (similar to the cylinder of the four-stroke 6.871 l turbocharged and aftercooled MAN D0826 LOH15 prostornino 6,871 dm^3. Podrobnosti lahko najdemo v magistrskem delu Prijatelja [17]. Natančna računalniško vodena položajna naprava s koračnimi motorji (natančnost ± 0,01 mm) je omogočala natančno nastavitev, ponovljivost lege izbranih merilnih točk in meritev tretje komponente prostorskega vektorja hitrosti. Trorazsežno hitrostno polje je bilo določeno v 165 izbranih točkah notranjosti modela valja za različne nastavitve odprtja vstopnega ventila. Z uporabo elektronsko krmiljenega ventilatorja sesalnega stroja je bilo mogoče nastaviti različne pretočne količine zraka pri izbranem tlačnem padcu v vstopnem ventilu in tako umetno ustvariti razmere, kakršne so pri dejanskem motorju. Za merjenje hitrosti toka je bil uporabljen dvožarkovni LDA za sočasno merjenje dveh komponent hitrosti izdelovalca TSI z imensko močjo 4 W, ki pa je deloval dejansko z 1 W. S pomočjo položajne naprave in zavrtitvijo optične leče za 90° je bilo mogoče določiti tudi tretjo komponento hitrosti v isti merilni točki. Dodatno sipanje svetlobe in obravnavo večjega vzorca podatkov v vsaki merilni točki je zagotavljalo dodajanje drobnih kapljic glicerina v vstopni zračni tok. Natančnost LDA je bila preverjena pri ustaljenem načinu delovanja z vrtljivo ploščo; pri hitrosti 25 m/s je bil odstopek manjši od 0,2 %. Razporeditev merilnih mest v opazovanih vodoravnih prereznih ravninah modela valja bo prikazana v poglavju 3.

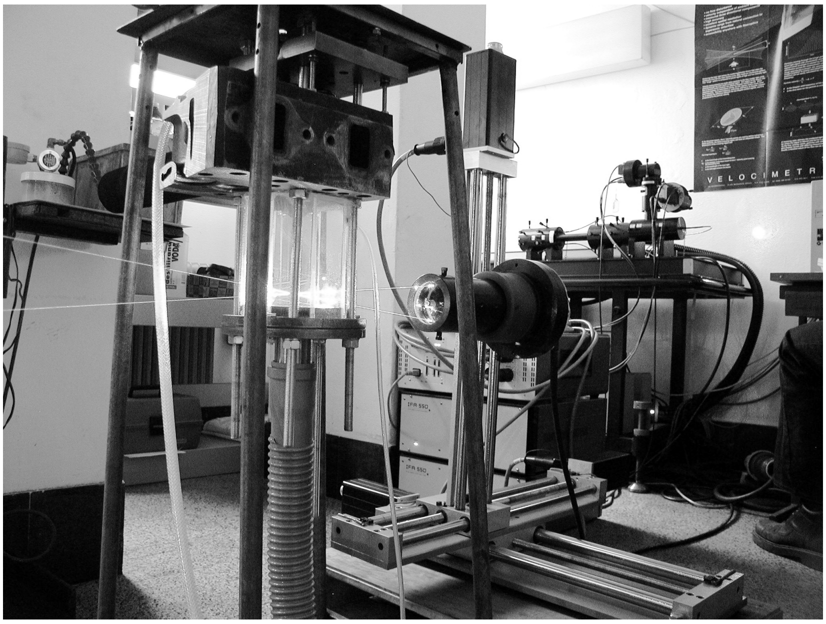
Payri in soavtorji [18] so ugotovili, da oblika čela bata, oziroma oblika zgorevalnega prostora v batu, nimata pomembnega vpliva na obliko toka v času celotnega sesalnega in vsaj v začetku takta stiskanja. O podobnih ugotovitvah poročajo tudi Zhu in soavtorji [19], ki poleg omenjenega tudi ugotavljajo, da je vpliv oblike kotanje v batu pri hitrotekočih dizelskih motorjih pomemben šele v zadnji fazi postopka stiskanja delovnega zraka, ko se pojavi prečno iztiskanje zraka iz čela bata v notranjost zgorevalne kotanje v batu. Tudi Arcoumanis in soavtorji [20] ter Wakisaka in soavtorji [21] ugotavljajo, da oblika zgorevalnega prostora nima vpliva na obliko tokovnega polja pri polnjenju valja motorja. Tako lahko ugotovimo, da zaradi poenostavitve oblike čela bata (ravna površina) pri opravljenih preizkusih ni trpela kakovost dobljenih rezultatov numerične simulacije RDT niti rezultati preizkusnih raziskav v modelu valja.

V tem prispevku je bil pretočni koeficient polnilnega ventila izmerjen v pogojih ustaljenega toka in mirujočega bata. Podobni način so uporabili

diesel engine) with a moving piston and with an attached real metal cylinder head was applied for the experimental analysis. Details of the design and the experimental procedure can be found in the work of Prijatelj [17]. An accurate (accuracy ± 0.01 mm) positioning system controlled by a PC with stepper motors ensured the repeatability of the selected measurement points and the measurement of the third flow-velocity component. The velocity field in the whole cylinder was determined for selected intake-valve lifts. The speed-controlled fan of a vacuum cleaner made possible settings of the pressure drop in the inlet valve as well as air mass-flows that corresponded to realistic engine operation under diverse running conditions. A two-component laser Doppler anemometer (LDA) for simultaneous measurement of two velocity components (blue and green beams), manufactured by TSI with a rated power of 4 W, but operating at approximately 1 W, was applied for the experiments. The third velocity component was measured by a simple turning of the optical probe by 90 degrees. Glycerin drops were introduced in the air-flow as seeding particles to ensure an appropriate number of sampled data to determine the flow-velocity components. The accuracy of the applied LDA was previously tested with a rotating disc: at a velocity of 25 m/s the error was smaller than 0.2 %. The determination of the observed horizontal measurement planes in the cylinder and the position of the measurement points will be given in the 3. section.

According to Payri et al [18], the piston-crown geometry (facing the combustion chamber) has little influence on the in-cylinder flow during the entire intake stroke and during the first part of the compression stroke; this conclusion also corresponds to the results published by Zhu et al [19], who reported that the effects of the geometry of the piston bowl pip for a high-speed direct-injection diesel engine become more pronounced late in the compression stroke due to the squish. Furthermore, Arcoumanis et al [20] and Wakisaka et al [21] reported that the geometry of the combustion chamber is not significant when the air flow inside the cylinder during the intake stroke is analyzed. Hence, it can be concluded that the quality of the results obtained with the simplified geometrical model of the piston (flat piston crown) applied for CFD and experimental analyses are not affected by this simplification.

The results of the measurements and computations of the steady-flow discharge coefficient are presented in the second part of the presented



Sl. 1. *Preizkusna naprava za meritev hitrostnega polja v modelu valja*
Fig.1. *Experimental setup for in-cylinder velocity measurements*

tudi drugi avtorji ([22] do [24]), medtem ko sta Fukutani in Watanabe [25] potrdila dobro ujemanje med statičnimi in dinamičnimi vrednostmi pretočnega koeficienta.

2 NUMERIČNE SIMULACIJE VTOKA V VALJ

Natančnost izračunanih rezultatov je močno odvisna od geometrijske podobnosti modela pretočnih kanalov, ventila in valja, ki so bili uporabljeni pri računskem modelu. Z uporabo Microscribe 3 D kopirne roke in programom računalniško podprtega načrtovanja (RPN) so bili obrisi pretočnih površin notranjosti valjeve glave označeni in kasneje s programom za 3 D modeliranje Mechanical Desktop ponovno spremenjeni v dejansko obliko pretočnih kanalov motorja. ki je bila primerna za obravnavo v programskem paketu RDT. Ta omogoča ob upoštevanju predpisanih robnih pogojev rešitev gibalnih enačb in izračun značilnosti dinamike zračnega toka (RDT). Natančnost izračunanih rezultatov je odvisna od gostote računske mreže in izbranega turbulentnega modela. Primer izbrane oblike in gostote računske mreže v izbranem vzdolžnem prerezu modela vtočnega kanala in valja, je prikazan na sliki 2. Payri in soavtorji [18] so na podlagi preizkusnega dela ugotovili, da predpostavka izotropne turbulence v običajnem

study. A similar experimental procedure was also proposed by other authors ([22] to [24]), while Fukutani and Watanabe [25] confirmed good agreement between the static and dynamic discharge coefficient.

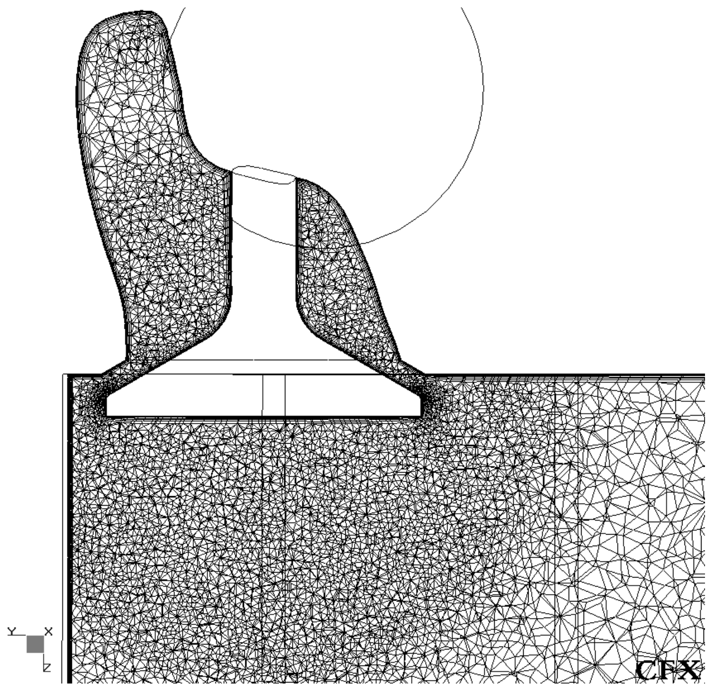
2 NUMERICAL SIMULATIONS OF THE INTAKE FLOW

The quality of the computed results strongly depends on the applied geometry of the engine intake channel and the cylinder. An appropriate geometry of the engine intake channel was therefore transferred to the 3D model, applying the CAD code. A 3D contour of the real engine system was precisely copied by the measurement arm Microscribe 3D and then transformed into a realistic engine geometry by applying a computer program for 3D modeling - Mechanical Desktop. The channel, cylinder, valve etc., geometry model was finally transferred into the CFX program package applied for the numerical evaluation of the flow dynamics (CFD) by solving momentum equations and by considering the prescribed boundary conditions. The accuracy of the computed results mostly depends on the density of the computational mesh and on the suitability of the applied turbulent model. The details of the applied mesh configuration in one longitudinal section of the observed inlet channel and cylinder are presented in Fig.2. The standard $k–\varepsilon$ turbulence modelu k–ε ne prinaša večjih napak pri izračunu tokovnih razmer v valju motorja – posebno primerna je za modeliranje toka v zgorevalnih prostorih brez poudarjenega vrtinčnega toka oziroma brez izrazite prečne komponente hitrosti. S tem je bila potrjena tudi upravičenost uporabe turbulentnega modela k–ε tudi v obravnavanem primeru pri reševanju diskretiziranih Navier-Stokesovih enačb.

Tudi izbira robnih pogojev je bila v prikazanem primeru podobna ustrezni izbiri drugih avtorjev (npr. Payri [18]): robni pogoj nespremenljivega tlaka je bil predpisan na vstopu in izstopu zračnega toka v model valja, medtem ko sta bila za stene valja in vstopnih kanalov predpisana adiabatni in robni pogoj brez zdrsa (obodna hitrost tekočine ob steni je enaka 0). Poleg tega je bila predpisana tudi stalna vrednost temperature zraka na vstopu in predpostavka nestisljivega sredstva. Ta predpostavka ni vnesla v izračun gostote zraka pomembnejše napake, ker so bile tudi ustrezne spremembe tlaka (podatek) v pretočnem prerezu ventila zelo majhne (tlačno razmerje v ventilu znaša 0,97 do 0,99). Običajni turbulentni model k–ε je bil uporabljen tudi pri izračunu (modeliranju) pretočnega koeficienta. Vrednosti za turbulentno kinetično energijo k in raztrosno hitrost kinetične energije ε je

model was applied to solve the discretized Navier-Stokes equations, since Payri et al [18] experimentally verified that the isotropic turbulence assumption of the standard k–ε model is reasonably accurate for calculations of the in-cylinder flow, particularly in quiescent combustion chambers where there is no strong interaction between swirl and squish and, more generally, in zones of the cylinder where the radial flow does not dominate the flow pattern.

In accordance with other publications (see also [18]), constant pressure boundaries were assigned to the flow inlet and outlet, whereas no-slip and adiabatic boundary conditions were applied on solid boundaries. The measured temperature was assigned to the intake-flow boundary condition, and the non-compressible flow was assumed during the computation procedure due to a very small air density change being the consequence of very small pressure fluctuations in the intake valve (the pressure ratio in the inlet valve was 0.97 to 0.99). The values for the turbulent kinetic energy k and the velocity dissipation of the kinetic energy ε should also be prescribed at the flow inlet boundary condition. The option "default intensity and autocompute length scale" was assumed for the performed computations due



Sl. 2. *Primer uporabljene računske mreže v vzdolžnem prerezu modela vstopnega kanala in valja*
Fig.2. *Details of the computational mesh in the longitudinal section of the inlet channel and cylinder*

bilo treba določiti na vstopnem robnem pogoju. Zaradi nepoznavanja teh vrednosti je bila privzeta intenziteta in izračunana dolžinska skala, kar pa na srečo ni imelo bistvenega vpliva na izračunano strukturo toka.

3 PRIKAZ IN OBRAVNAVA REZULTATOV

3.1 Tokovno polje in potek hitrosti v valju motorja

V sklopu preizkusnih raziskav so bili na 33 različnih merilnih mestih v petih vodoravnih – prečnih ravninah osmerostranega valja (torej skupno v 165 točkah) izmerjene po tri komponente vektorja hitrosti toka. Več točk v vsaki ravnini ni bilo mogoče izmeriti zaradi poševne postavitve steklenih sten modela. Na sliki 3 je prikazan potek oziroma primerjava izmerjenih in izračunanih hitrosti v prečni ravnini $x-y$, ki je oddaljena 120 mm od vrha valja. Iz diagrama lahko povzamemo, da:

- se lega središča izračunanega vrtinca le malo razlikuje od lege središča vrtinca toka, ki je bil izmerjen z meritvami LDA,
- se absolutna velikost izračunanih in izmerjenih vrednosti vektorjev hitrosti v opazovani ravnini precrej dobro ujema z vrednostmi meritev.

Obodno gibanje (kroženje v prečnih ravninah) sveže polnitve v valju je zelo pomembno za pravilno

to a lack of any appropriate information. Fortunately, their choice has little effect on the flow structure for the observed case. The standard turbulent k–ε model was also applied to compute the flow-discharge coefficient.

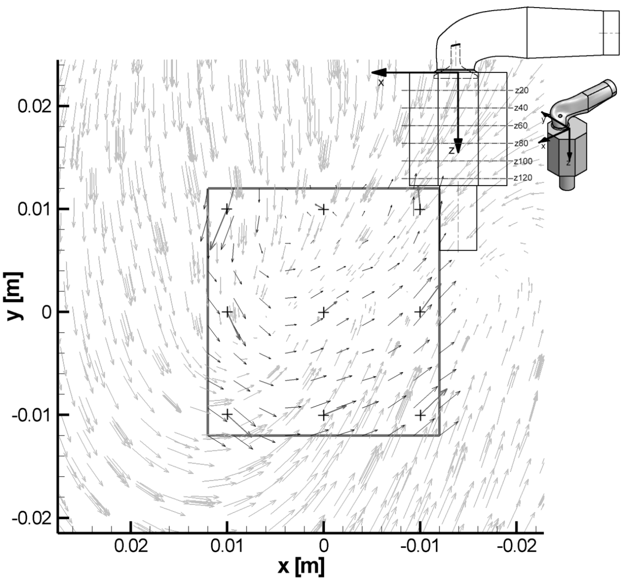
3 RESULTS AND DISCUSSION

3.1 Flow pattern and velocity field within the cylinder

Three components of the velocity vectors were measured in the octagonal glass cylinder model at 33 different measurement points and in 5 different cylinder transverse planes (altogether at 165 locations). Fig. 3 represents the computed and measured velocity vectors in the x-y plane, 120 mm from the cylinder top (z – axis). It can be concluded from this diagram that:

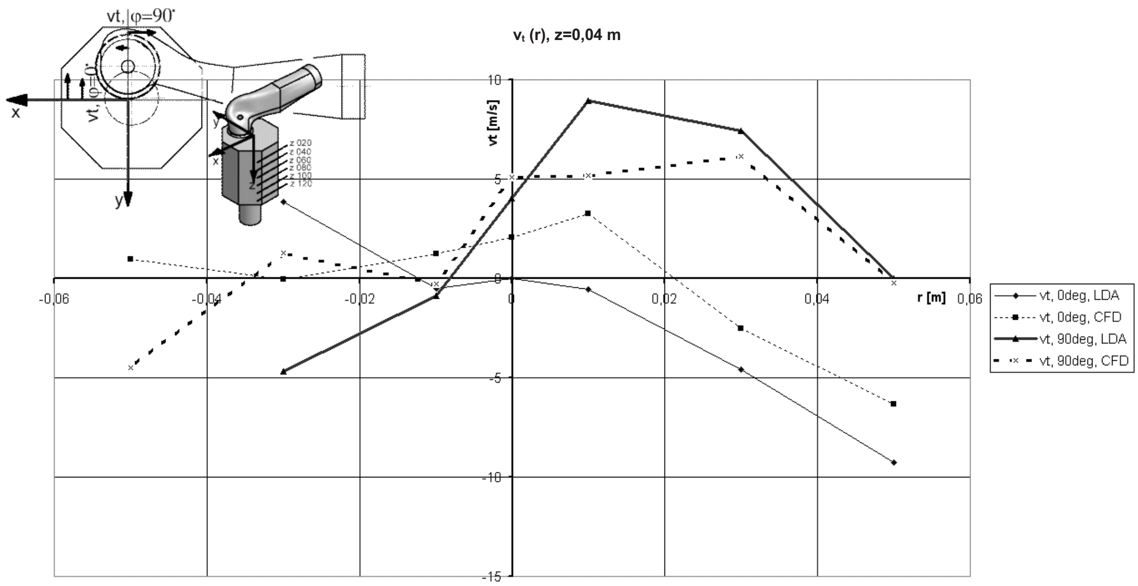
- the positions of the calculated and measured vortex center nearly coincide
- the size of the computed and measured velocity vectors (length of particular indicated velocity vector) are similar within the observed plane

Tangential motion (in the transverse cylinder planes) of the fresh charge is very important for appropriate air-fuel mixing, and therefore for effective combustion. Thus, the swirl ratio or the swirl



Sl. 3. *Primerjava izmerjenih in izračunanih vektorjev hitrosti v prečni ravnini valja 120 mm od vrha (smer z); temnejše puščice – meritev, svetlejše puščice – računska simulacija*

Fig. 3. *Comparison of measured and computed velocity vectors in the cylinder transverse section 120 mm from the top (direction z); black arrows – experiment, light arrows – numerical simulations*



Sl. 4. *Primerjava izmerjenih in izračunanih obodnih hitrosti v dveh izbranih legah v prečni ravnini valja 40 mm od vrha (smer z)*

Fig. 4. *Comparison of the measured and computed tangential velocity components in the cylinder transverse section 40 mm from the top (direction* z*)*

mešanje zgorevalnega zraka z gorivom in posledično za čim popolnejše zgorevanje. Velikost in porazdelitev obodne hitrosti toka v valju močno vplivata na vrtinčno število toka v valju, ugotavljajo Payri in soavtorji [18]. Zato je na sliki 4 prikazana tudi primerjava poteka in velikosti obodne komponente vektorja hitrosti v prečni ravnini valja $x-y$ 40 mm od vrha valja. Potek in smer opazovanih hitrosti sta podobna za oba primera. Velikost izračunanih vrednosti, posebno blizu stene valja (ni prikazano na tej sliki) in v prečnih ravninah na polovici višine valja, je večja od izmerjenih vrednosti. Vzrok tiči verjetno v naslednjih pomanjkljivostih: 1) neupoštevanju spremembe lastnosti toka pri pretakanju ob steni osmerostranega modela valja in 2) zaradi nenatančnih meritev padca tlaka med opazovanim vstopnim in izstopnim robom toka zraka, ki je rabil tudi kot robni pogoj pri numeričnem modeliranju.

3.2 Pretočni koeficient vstopnega ventila

3.2.1 Določitev pretočnega koeficienta z meritvami in računsko simulacijo

Najprej je bil pretočni koeficient določen z uporabo rezultatov meritev. Potem je bila izvedena računska simulacija masnega toka zraka skozi vstopni

number is strongly affected by the size and the distribution of the tangential velocity, F.Payri et al [18]. The distribution of the calculated and measured tangential velocity component in the transverse plane 40 mm from the cylinder top (z = 40 mm), which is perpendicular to the x and y axes is presented in Fig. 4. It can be concluded that the orientation of the tangential velocities is similar for both cases. The calculated values are larger in comparison with the measured ones, especially in the transverse planes half-way from the cylinder top and in the vicinity of the cylinder wall (not presented in this figure). The reason for this can be found in: 1) a probably incorrect consideration of the flow characteristic when the computation of the flow along the octagonal cylinder wall is considered, and 2) incorrect measurement of the pressure drop, which represents the boundary condition for the performed computations.

3.2 Discharge coefficient

3.2.1 Experimental and numerical determination of the discharge coefficient

The discharge coefficient was first determined experimentally, i.e., it was calculated from the measured in-cylinder mass-flow data by applying ventil, izračunani ustrezni pretočni koeficienti in rezultati primerjani z rezultati preizkusov. Pretočni koeficient μ je bil določen z enačbo:

$$\mu = \frac{A_{eff}}{A_g} \quad (1),$$

kjer pomeni A_g najmanjšo geometrijsko pretočno površino vstopnega ventila, A_{eff} pa dejanski pretočni prerez v vstopnem ventilu:

A_{eff} je bil potem izračunan z enačbo (2), ki opredeljuje masni tok (podrobnosti najdemo v viru [17]) stisljivega medija skozi zaslonko pri znanih podatkih: tlačnem razmerju v ventilu p_2/p_1=0,97, ter temperaturi in tlaku okolice T_1 = 295K in p_1 = 100 kPa:

$$A_{eff} = \dot{m} \cdot \left(\cdot \frac{p_1}{\sqrt{T_1}} \cdot \sqrt{\frac{2\kappa}{\kappa\text{-}1} \cdot \frac{1}{R} \cdot \left(\left(\frac{p_2}{p_1}\right)^{\frac{2}{\kappa}} - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa+1}{\kappa}} \right)} \right)^{-1} \quad (2).$$

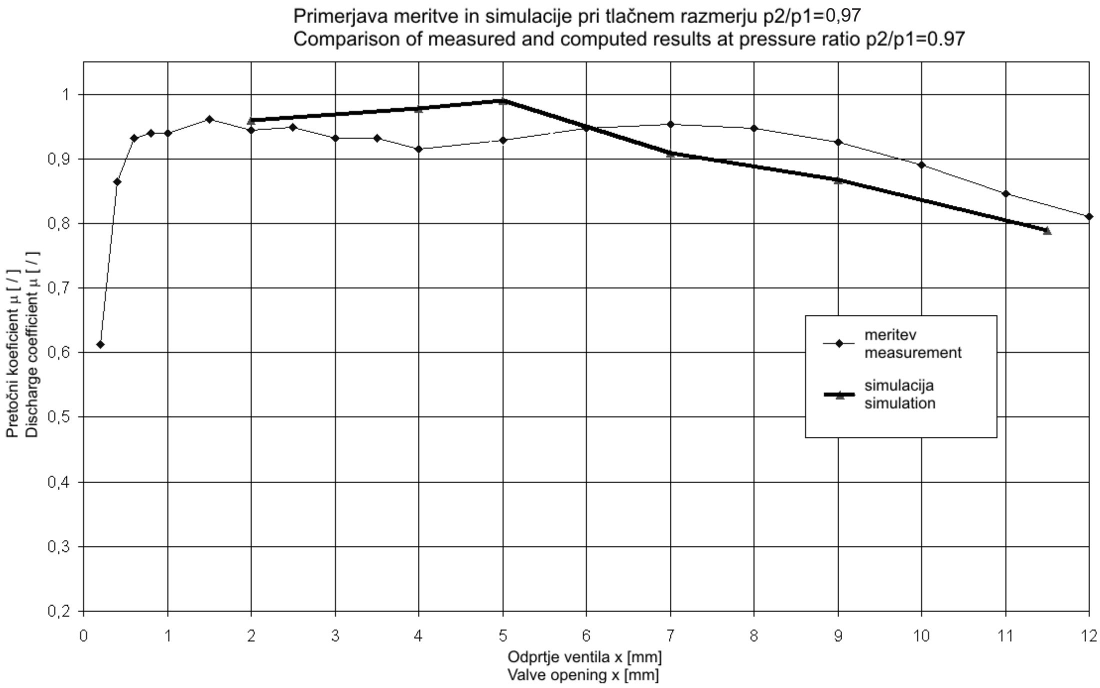
Primerjava izmerjenih in izračunanih vrednosti koeficienta μ je prikazana na sliki 5. Rezultati se zelo dobro ujemajo pri odprtju ventila za 2 mm. Potem je opazno hitrejše večanje in manjšanje (odmik) izračunanih vrednosti koeficienta μ. V celoti se vrednosti meritev in izračunov sorazmerno dobro ujemajo. Tudi oblika spremembe poteka izmerjene kriulje μ s spremembo odprtja vstopnega ventila se ujema z napovedmi drugih avtorjev ([22] do [24]) in je potrjena s spremembami toka v špranji ventila. Pri majhnih odprtjih ventila, pri katerih ne prihaja do odcepitev toka od trdne stene, vpliv mejne plasti pa je tudi zanemarljiv, smer toka sledi obliki ventilne glave in sedeža ventila. Z večanjem odprtja ventila se zato v prvi fazi odpiranja ventila intenzivno povečuje tudi vrednost μ. Pri nekoliko večjih tokovih, večjih odprtjih ventila, se najprej pojavi odcepitev toka od vodilne površine ventilne glave; dejanska pretočna površina se zmanjša in z njo tudi vrednost μ. Z nadaljnjim povečevanjem odprtja ventila opazimo odcepitev toka tudi na strani sedeža ventila, kar vpliva na nadaljnje zmanjšanje vrednosti μ. Potem se usmeritev zmanjševanja vrednosti μ nekoliko umiri zaradi ponovnega prilepljenja toka ob vodilno površino ventilne glave in s tem nekoliko povečanega dejanskega pretočnega prereza ventila. Pri velikih vrednostih odprtja ventila opazimo nadaljnje, vendar zmerno zmanjševanje pretočnega koeficienta.

the equation of compressible flow through the nozzle, see also [17]. The discharge coefficient is determined by the equation:

where A_{eff} denotes the effective cross-section through the inlet valve and A_g the minimum geometrical cross-section of the inlet valve.

A_{eff} was then calculated from Equation (2) by applying the results of the simulation for the mass-flow $\dot{m}$, from the known pressure ratio across the valve p_2/p_1=0.97 and from the ambient parameters T_1 = 295K and p_1 = 100 kPa:

The results of the numerical simulations of the discharge coefficient in the inlet valve were compared to those obtained by experiments. The results of the comparisons are presented in Fig. 5. The results coincide very well for a 2-mm valve lift, whereas it can be seen that the numerical simulation predicts a gradual increasing and a subsequent decreasing of the discharge coefficient earlier than the experimental data for approximately 2 mm of the valve lift. Overall, the measured and computed results are in relatively good agreement. The shape of the discharge coefficient curve also coincides well with the results reported by other authors ([22] to [24]). From the analysis of the flow structure it can be seen that at very small valve openings the air flow follows the shape of the valve seat and the valve head – no flow separation occurs and due to the negligible effects of the boundary layer the discharge coefficient increases with increasing valve lift. At larger airflows the boundary layer breaks away from the valve head, reduces the effective flow area and thus reduces the discharge coefficient. Further opening of the valve gives rise to the flow separation, even at the side of the valve seat, and substantially decreases the discharge coefficient. The decrease of the discharge coefficient is less pronounced with still further opening of the valve, due to the re-attachment of the flow to the valve head – the effective flow area is, therefore, relatively larger. The discharge coefficient then continues to decrease at the largest valve openings, but at a lower rate.



Sl. 5. *Potek pretočnega koeficienta v odvisnosti od odprtja ventila*
Fig.5. *Discharge coefficient for the intake valve, depending on the valve lift*

3.2.2 Ocena merilne negotovosti pri določitvi pretočnega koeficienta

Pri oceni skupne merilne negotovosti za pretočni koeficient ě, so bili v skladu z enačbama 1 in 2 in ob upoštevanju ustrezne literature [26] upoštevane naslednje merilne negotovosti:

- ocenjena merilna negotovost izmerjenih statičnih tlakov $u_r(p1) = \pm 1\%$
- merilna negotovost izmerjene temperature $u_r(T) = \pm 0{,}17\%$
- merilna negotovost izmerjenega masnega toka zraka $u_r(\dot{m}) = \pm 0{,}8\ \%$
- merilna negotovost izmerjenega masnega toka zraka $u_r() = \pm 0{,}8\ \%$
- pri določitvi merilne negotovosti geometrijskega pretočnega preseka A_g so bile ocenjeni merilni pogreški: pri določitvi premera ventila ± 1 mm in pri dvigu ventila ± 0,05 mm; ocenjena merilna negotovost $u_r(A_g)$ je torej znašala ±2,5%.
- Izračunana je bila tudi merilna negotovost dejanske - efektivne pretočne površine ventila $u_r(A_{eff})$ v merilnem območju masnih tokov zraka (= 0,1 kg/s), ki ne presega ± 1,38%

Končno je bila izračunana še skupna merilna negotovost pretočnega koeficienta:

3.2.2 Assessment of the measurement uncertainty for the determination of the discharge coefficient

Taking into account measurement parameters in Equations 1 and 2 and in corresponding literature [26] when determining the total collective measurement uncertainty the following individual uncertainties were considered:

- Of the measured absolute pressures $u_r(p1) = \pm 1\%$
- Of the measured temperatures $u_r(T) = \pm 0.17\%$
- Measurement uncertainty of the measured air mass-flow $u_r(\dot{m}) = \pm 0.8\ \%$
- The following measurement errors were estimated when assessing the measurement uncertainty of the geometrical valve flow area A_g: ± 1 mm for the valve diameter and ± 0.05 mm for the valve lift; the assessed measurement uncertainty $u_r(A_g)$ was therefore ±2.5%.
- The measurement uncertainty of the valve effective flow area $u_r(A_{eff})$ was then determined for the observed mass-flow range of 0.1 kg/s and amounted to ±1.38%.

Finaly the total measurement uncertainty of the discharge coefficient was determined for the observed air mass-flow applying the formula:

$$u_r(\mu) = \sqrt{(u_r^2(A_{eff}) + u_r^2(A_g)} = \sqrt{0{,}0138^2 + 0{,}0253^2} = \pm 0{,}029 = 2{,}9\% \quad (3),$$

ki v opazovanem merilnem območju masnih tokov zraka okrog 0,1 kg/s ne presega ±2,9%

that never exceeded ±2.9%.

4 SKLEPI

Iz predstavljenih rezultatov raziskave lahko povzamemo, da je uporaba metode RDT primerna in da zagotavlja prepričljive rezultate, ki izboljšujejo razumevanje tokovnih pojavov, ki spremljajo vtok medija v valj motorja. RDT je torej učinkovito orodje pri snovanju sodobnih motorjev. Omogoča dobro napoved pojava, mesta in velikosti vrtinčnih struktur v valju. Primerjava med izmerjenimi in izračunanimi vrednostmi obodnih komponent hitrosti toka v valju modela motorja je pokazala, da so izračunane vrednosti večje predvsem v bližini stene valja in v prečnih ravninah, ki ležijo v področju polovice višine valja. Na to so verjetno vplivali: netočni izmerjeni podatki padca tlaka v ventilu, ki so obenem pomenili tudi predpisani robni pogoj pri opravljenih računskih simulacijah in nepoznavanje tokovnih razmer pri kroženju zraka ob osmerostranih stenah modela valja.

Dobro ujemanje med izmerjenimi in izračunanimi vrednostmi lahko opazimo tudi pri rezultatih pretočnega koeficienta v vstopnem ventilu. Iz rezultatov izračunov izhaja, da je izračun zanesljivejši pri večjih odprtjih ventila, ko je vpliv mejne plasti na tok zraka v špranji med glavo in sedežem ventila manjši. Gostota računske mreže je lahko zaradi tega pri večjih odprtjih ventila ustrezno manjša, s tem pa se ustrezno izboljša tudi razmerje med kakovostjo rezultatov in zmanjšano potrebno porabo računalniškega časa. Analiza dobljenih rezultatov in primerjava z ustreznimi rezultati drugih avtorjev je tudi pokazala, da je vpliv oblike čela bata (oziroma oblike zgorevalnega prostora v batu) in lege bata v valju na velikost in potek pretočnega koeficienta majhna.

4 CONCLUSIONS

The presented study shows that in-cylinder CFD predictions ensure credible results that help improve the knowledge of the air-flow characteristics during the intake stroke. CFD therefore represents an efficient design tool for developing less-polluting and more efficient internal combustion engines. Good prediction of the vortex center, direction and even the size of the flow field was made possible by applying the described numerical method. A comparison between the measured and computed tangential in-cylinder velocities showed that the relatively larger computed values – especially close to the cylinder wall – were probably affected by the incorrect measurement of the pressure drop across the intake valve; it was applied as a prescribed boundary condition for the performed computations. On the other hand, it is also difficult to precisely determine the flow field close to the octagonal walls of the model cylinder.

Good agreement between the measured and calculated inlet-valve discharge coefficients was obtained. It can be concluded from the performed computations that it is was relatively convenient to calculate the discharge coefficients at larger inlet valve openings, since the boundary layer has a smaller influence on the air-flow within the restricted area between the valve head and the valve seat. A good compromise between the quality of the results and the computational times could also be achieved for larger valve openings, since accurate results could be obtained with a reasonable computation-mesh density. The analysis and comparisons with the appropriate results of other authors showed that that the piston position in the model cylinder has little effect on the size of the discharge coefficient.

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5 LITERATURE

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Model za učinkovito upravljanje podatkov iz uporabe – primer proizvodnje izdelkov bele tehnike

A Model of Effective Data Management From Exploitation – A Case of Domestic-Appliance Production

Peter Meža - Andrej Polajnar - Srečko Glodež

Podjetje, ki želi ostati konkurenčno, mora stalno spremljati kakovost izdelkov na trgu in odpravljati napake na kritičnih izdelkih. V ta namen potrebujejo proizvajalci glede na svojo velikost in dejavnost specifičen model informacijske integracije podatkov iz faze uporabe. Strukturirani podatki iz uporabe izboljšajo kakovost dela in vključevanje izkušenj iz preteklih krogov izdelkov pri razvoju oz. izboljšavah sedanjih izdelkov.

Za potrebe menedžmenta kakovosti je bila povratna zveza dopolnjena z inženirskim modelom delovnega naloga, ki vključuje popis mehanizmov okvar. Na primeru proizvodnega podjetja so prikazani informacijski tokovi med izvajalci popravil na terenu in podjetjem. Specifikacija podatkovnega modela, ki temelji na predstavitvi napake, predstavlja znanje o mehanizmih in vzrokih okvar. Uporabljen je bil model kodifikacije okvar, ki pokriva celotni nabor stanj in vzrokov v strukturirani obliki, ki podjetju omogoča preprosto zbiranje podatkov ter urejeno znanje na osnovi tipiziranih okvar, ki se pojavljajo v dobi trajanja izdelka. Na enem mestu dostopne informacije o popravilih na izdelku omogočajo neposredno preoblikovanje podatkov v povratno zvezo podjetja. V prispevku predstavljen postopek ponuja podporo metodam menedžmenta kakovosti ter podlago za izvedbo izboljševalnih ukrepov v proizvodnem podjetju. V modelu delovnega naloga sestavljeni podatki omogočajo navigacijo v omrežjih stanj izdelkov.

(Ključne besede: kakovost izdelkov, zanesljivost, garancije, analize podatkov, tehnični servisi)

A company that wants to stay competitive has to keep up to date with the quality of products on the market, and constantly has to remove all the defects from its critical products. For this reason companies, depending on their size and type of activity, need a specific data-information integration model for the exploitation phase. Structured exploitation data increases the level of work quality and incorporates experience from former lines of products in the process of development or improving current products.

For the needs of management quality the recurrent feedback loop was supplemented with the engineer model of service order, which includes an inventory of defect mechanisms. The information flow between fieldwork repairers and the company is illustrated in the case of a production company. The specification of the data model, which is based on defect presentation, presents the knowledge of defect mechanisms and causes. We used the model of the codification of defects. It covers the total area of states and causes in the structured form, which enables the company to easily acquire data as well as organized knowledge on the basis of typified defects that occur in the product lifecycle. Product-repair data available in one place enables a direct data transformation back to the feedback loop of the company. The model presented in this paper offers support to the TQM methods as well as the basis for carrying out correction measures in the production company. The structured data in the service-order model make it possible to navigate in the product-failure net.

(Keywords: product quality, reliability, warranty analysis, technical services)

0 UVOD

V zvezi z naraščajočimi zahtevami glede izdelkov od zakonodajalcev se proizvodna podjetja vse bolj spoprijemajo z vedno večjimi pričakovanji v zvezi s kakovostjo svojih izdelkov. Upravljanje kakovosti skozi celotno dobo trajanja izdelka, še posebej na področjih, ki so na zunanjih mejah področja proizvodnega menedžmenta, postaja vse bolj pomembno področje raziskav, tudi na področju faze uporabe izdelkov.

Obvladovanje kakovosti izdelkov v uporabi pomeni razvijati zamisli, s katerimi je v danem primeru mogoče modelirati informacijske tokove in modele, ki pomembno prispevajo k obvladovanju povratnih zvez kakovosti in metod menedžmenta kakovosti.

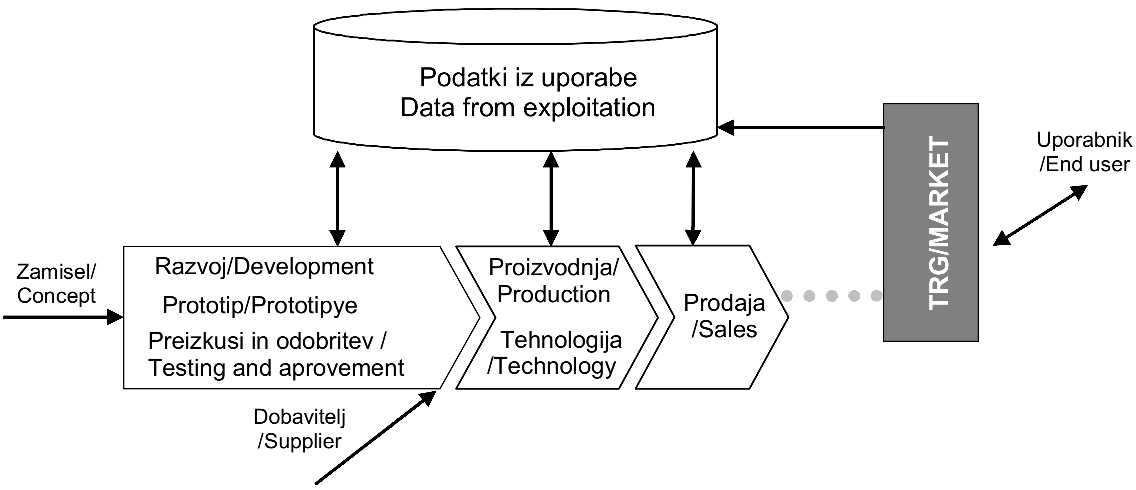
Prispevek obravnava kakovost izdelkov v uporabi. Glavni namen je, da se v okviru razvoja izdelkov uporabljajo informacije, ki se pridobivajo med samo uporabo izdelka, se pravi tiste, ki kažejo obnašanje izdelka in nastajanje napak med njegovo uporabo. To je smiselno, saj leži ključna točka dejavnosti razvoja v prilagajanju in izboljšanju že znanih izdelkov. Z vidika menedžmenta kakovosti, kakor tudi z vidika stroškov in časa, je ta enostranska naravnanost tokov informacij zelo vprašljiva. Še posebej velja izpostaviti informacije o posledicah odločitev s področij načrtovanja, ki se na primer pokažejo kot napake in šibke točke v uporabi izdelka. V smislu povratne zveze se lahko tako ustvarjajo krmilne zanke kakovosti [1]. Za to se morajo v predhodnih fazah uporabljati podatki iz uporab, ki pomenijo obnašanje izdelkov v uporabi (sl. 1).

0 INTRODUCTION

Due to the increasing number of legal requirements regarding products, manufacturers are faced with higher expectations connected with the quality of their products. Quality management in the product lifecycle, especially in the areas bordering on production management, has become an essential element of a product's exploitation-phase research.

Quality management in product exploitation stands for the development of concepts that can be used for modelling information flows and the models necessary to command the managing of quality feedback loops and quality-management methods.

This paper deals with the product quality in exploitation. The main goal is to use the information acquired during product application in the process of product development. It aims to use the information that reflects a product's behaviour and the faults emerging during the application. That is reasonable because the key point of the development activity lies in adapting and improving existing products. From the point of view of management quality, like from the point of view of expenses and time, this one-way orientation can be very problematic. In particular, one has to expose the information on the consequences of decisions regarding the area of planning, which can turn out to be wrong or to be weak points in the exploitation of the product. In the sense of feedback, controlled quality loops can emerge [1]. That is why exploitation data representing product behaviour in exploitation have to be used in the preliminary phases (Fig. 1).



Sl. 1. *Uporaba podatkov iz uporab med dobo trajanja izdelka*
Fig. 1. *Use of exploitation data during the product lifecycle*

1 VZPOSTAVITEV KROGA KAKOVOSTI S KRMILJENJEM POVRATNIH INFORMACIJ IZ UPORABE IZDELKA

Podjetje, ki se zaveda, da je kakovost usmerjena k potrebam in zahtevam trga, oblikuje integralni sistem kakovosti. Glede na dejavnosti v proizvodnem podjetju je treba postaviti tok informacij, v katerem so udeleženi ustvarjalci v vrednostni verigi.

Zamisli za podporo preventivnega menedžmenta kakovosti na podlagi povratnih podatkov iz uporabe temeljijo na pridobivanju podatkov o zanesljivosti. Uporaba podatkov iz uporabe prek skupne baze podatkov ali standardizirani vmesniki še ne obstajajo [5]. Kljub temu, da ima menedžment kakovosti v podjetju že dalj časa vlogo presečne funkcije, so na tem področju opažena prizadevanja za gradnjo enotnih podatkovnih formatov. V okviru celotnega menedžmenta kakovosti (CMK) so podana izhodišča za spremljanje podatkov iz uporabe. Ko proizvodno podjetje skušamo nadzorovati in usklajevati kakovost izdelkov na trgu, hkrati urejamo tudi zanesljivost izdelkov. V proizvodnem podjetju je treba nenehno spremljati elemente zanesljivosti in kakovosti na trgu za potrebe metod in orodij menedžmenta kakovosti.

Zanesljivost in kakovost v uporabi obsega stanje o okvarah na izdelkih na trgu [4]. Gre za ocenjevanje mehanizmov okvar, ki jih povežemo z viri. To je ocenjevanje stanja in učinkov na posameznih programih od vrha navzdol, pri čemer se lahko poizveduje na generični ali specifični ravni izdelka.

Prizadevanja za prepoznavanje tveganja zaradi slabe kakovosti na trgu lahko obsegajo tudi dejavnosti, ki pomagajo pri določitvi pogostosti okvar (zanesljivosti) ali posledic elementa tveganja (stroški zaradi slabe kakovosti na trgu) [3]. Kritična tveganja, ki se kažejo v slabi kakovosti na trgu, je treba zapisati, kakor zahteva CMK. Tako se kakovost na trgu obvladuje in se sproti nadzira oziroma ureja skozi dobe trajanja izdelkov. Stanja na trgu je treba preudarno pripraviti, da bi preprečili ključne posledice dejavnosti in da se posamezna dejanska stanja ne bi "izmuznila" iz analiz. Namena prepoznavanja stanja izdelkov v uporabi sta določanje in izbira vzrokov na podlagi opazovanj stanja okvar na izdelkih. To terja temeljito poznavanje trga, organizacije podjetja, izdelkov in mehanizmov okvar. Na podlagi postopkov ocenjevanja z

1 QUALITY-LOOP ESTABLISHMENT BASED ON THE REGULATION OF FEEDBACK DATA FROM PRODUCT EXPLOITATION

The company, which realized that quality is directed to market demands, implemented an integral quality system. Due to activities in manufacturing the company needs to make information flow, and there should be participation from all parties in the value chain.

The preventive quality-management control concepts based on feedback exploitation data (i.e., data on the product-exploitation phase) rely on obtaining reliable data. However, the possibility to use the exploitation data over a common database or standardized interfaces does not exist yet [5]. Although quality management has had a cross-section function in the company for a long time, there have been efforts in this field to set up unified data formats. Within total quality management (TQM), the starting points have been defined for monitoring the exploitation data. By trying to control the manufacturing company (enterprise) and the quality of products in the market, product reliability is controlled at the same time. In a manufacturing enterprise, constant monitoring of the reliability and quality elements in the market is necessary to meet the requirements of the methods and quality-management tools.

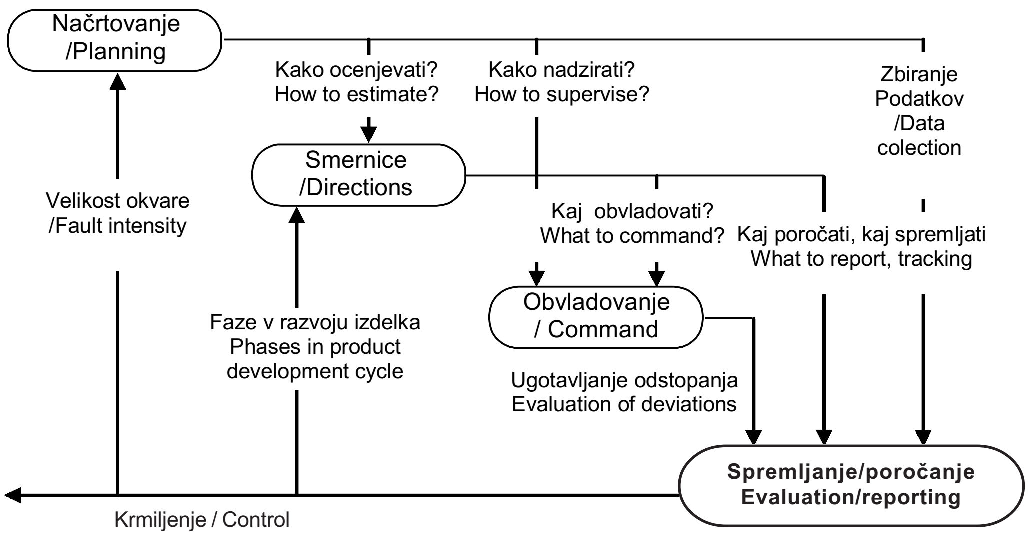
Reliability and quality in the product-exploitation phase involves the faults status of products in the market [4]. The issue at hand is evaluating the fault mechanisms, which are then linked to their respective sources. This includes evaluating the situation and effects in respective programs from the top down, where a query on a generic or a specific product level can be carried out.

The efforts to identify the risks due to poor quality in the market can also comprise activities to aid the recognition of fault frequency (reliability) or the consequences of the risk element (costs due to poor quality in the market) [3]. Critical risks that are evident in poor quality in the market have to be documented as required by TQM. In this way, the quality in the market is managed and controlled for "along the way" (i.e., simultaneously), or it is controlled through the product lifecycles. Market conditions/situations data should be carefully prepared to avoid overlooking the key activities and particular actual conditions in the analysis. The purpose of recognizing the product conditions in the exploitation period is identifying and selecting the causes based on observations of the product fault status. On the basis dopolnjevanjem opisov dejanskih stanj z izločitvijo vzroka, je treba ugotoviti, katere podatke potrebujejo skupine strokovnjakov.

Temeljna izhodišča postopka menedžmenta napak je preprečevanje ponavljanja napak v proizvodnem podjetju ("Učiti se iz napak") z ustreznimi metodami in programskimi orodji. Upoštevati je treba celotno verigo izdelka, to pomeni postopke od razvoja izdelka do prodaje končnemu uporabniku (notranje upravljanje napak), kakor tudi uporabo izdelka od uporabnika izdelka (zunanje upravljanje napak) [7]. Pri razvoju takšne osnove za rešitev je zelo pomembno vključevanje znanih informacijsko tehničnih podsestav posameznih podjetij in širjenje načela preprečevanja ponavljanja napak v krogu kakovosti. Za gradnjo računalniško podprtih krogov kakovosti, ki izboljšujejo postopek razvoja izdelka na podlagi analize napak, se morajo vzpostaviti sistemi povratnih informacij o mehanizmih okvar [4]. Napak, ki se ne dajo prikazati številčno, z matematično-statističnimi metodami ni mogoče zgostiti in pripraviti do stopnje, ki bi omogočala izpeljavo neposrednih nastavnih vrednosti za neko uredbo, npr. krogih na področjih izdelave, ki se urejajo na podlagi primerjave rezultatov meritev z idealno vrednostjo strojnih parametrov [6]. Za kakovostno opisane napake je za krmiljenje kakovosti razvoja izdelka potrebna metoda, s katero se omogoči postopek optimizacije (sl. 2).

of evaluation procedures that complement the actual state descriptions by isolating the cause, data sets required by expert teams should be identified.

The basic starting point of the fault-management approach is the support of repeated fault prevention in a manufacturing enterprise, i.e., to learn from one's own mistakes, by applying suitable methods and program tools. The entire product chain should be considered, i.e., the processes from the product development to the end-user sale (internal fault management), as well as the application of the product by the end-user (external fault management) [7]. When developing such a solution base, it is essential to include the existing informational-technical infrastructures of individual companies and extend the principle of repeated fault prevention within the quality loop. To set up computer-aided quality loops that improve the product-development process based on fault analysis, systems of feedback information about the fault mechanisms have to be established [4]. Faults that cannot be quantified by mathematical-statistical methods cannot be compressed and prepared to a level that would enable the derivation of direct setup values for a certain layout, as, for example, with loops in the field of manufacturing, which are regulated based on comparisons of measurements results with an ideal value of engineering parameters [6]. For qualitatively described faults, the control of the product development quality requires a method that would enable an optimization process (Fig. 2).



Sl. 2. *Uporaba podatkov iz uporabe v krogu kakovosti*
Fig. 2. *Use of data from exploitation in the quality circle*

Na podlagi poizvedb v bazi primerov se uporabniku v obravnavanem osnutku ponudijo različne možnosti za podporo, s čimer je omogočena uporaba pri različnih nalogah. V pomoč je tudi zagotovitev celotnega poteka nastanka izdelka, ki je potreben za analizo napak, vzrokov in izpeljavo ustreznih ukrepov. Zgodovina izdelka mora (predvsem pri zahtevnih izdelkih) obsegati naslednje točke:

- seznam vseh okvar in njihovih mehanizmov,
- dokumentacijo vseh dejavnosti popravil, vključno s seznamom vseh zamenjanih elementov, z navedbo časa popravila in
- podatke o izdelkih (serijska številka, datum nakupa, pogoji uporabe itn.).

Nadaljnja pomembna točka v zvezi s sistemsko tehnično podporo izvajalcev popravil je zagotovitev mehanizmov za analizo vzrokov in razpoznavo primernih ukrepov. V proizvodnem podjetju se pojavlja zahteva po sistemu, ki temelji na načelu sklepanja iz primerov; to je natančen opis napak in stanja izdelka, ki je odpovedal na trgu. Na tej podlagi se lahko iz baze pomembnih podatkov pridobijo podobni primeri, za katere so že zapisani uspešni ukrepi. Tako pridobljene ukrepe je nato treba še oceniti in jih prilagoditi prisotnemu problemu.

2 ZASNOVA PODATKOVNEGA MODELA ZA OBVLADOVANJE PODATKOV IZ UPORABE

Pred sistematično obravnavo pretoka informacij pri izvajanju popravil tehničnega servisa na izdelkih v uporabi je treba celovito poznati dogajanje in potrebe v proizvodnem podjetju. Primer izvedbe popravil izdelkov bele tehnike je izbran za podrobnejšo obravnavo zaradi svoje razširjenosti. Analizirali smo informacijske tokove, ki se pojavljajo pri izvajanju popravil v garanciji s poudarkom na izhodnih tokovih. Glede na ugotovitve je podana izhodna struktura podatkov iz uporabe v delovnem nalogu kot zbirniku vseh pomembnih informacij. Podane niso podrobnosti trenutnega stanja znane organizacije, poudarek je na predlogih, ki temeljijo na tehničnem in poslovnem informacijskem sistemu in predstavitvi metod analize. Razmerja izvajanja popravil z drugimi funkcijami v proizvodnem podjetju z vidika informacijskih in materialnih tokov so prikazane na sliki 3.

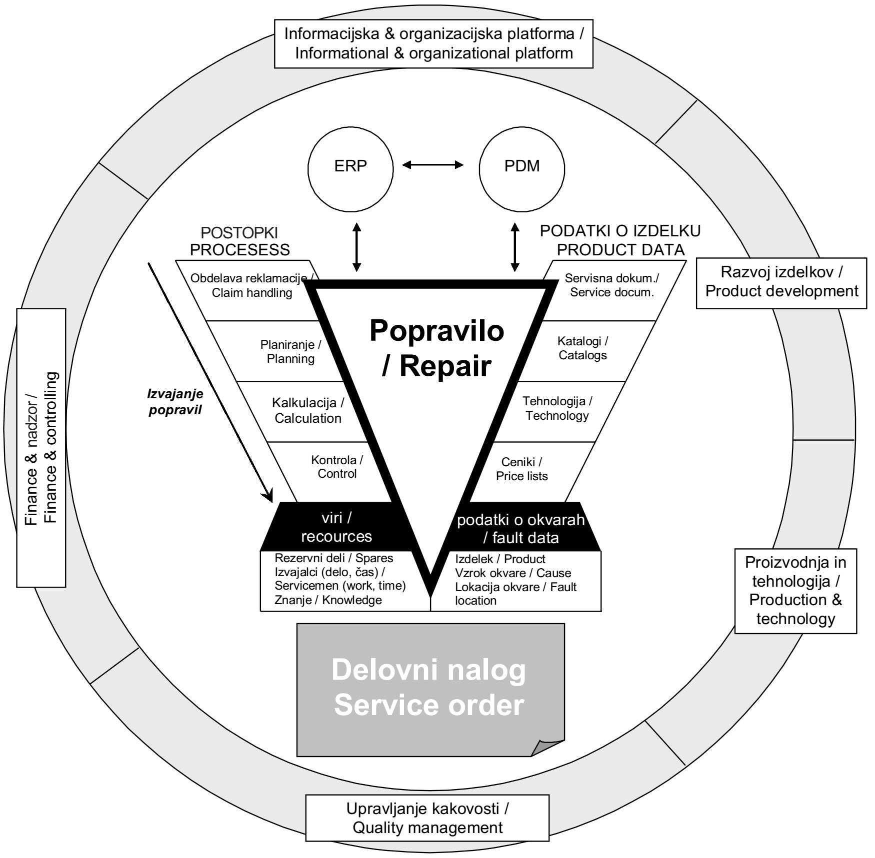
Based on queries in the examples database, the user is offered several support options for the concept considered. This also enables application in different tasks. Another aid for the process is the provision of the entire product history, which is required for the analysis of faults, causes, as well as the derivation of appropriate measures. The product history has to (especially with complex products) involve the following elements:

- A list of all faults and their mechanisms,
- documentation on all repair activities, including the list of all the substituted elements, stating the time of repair,
- the product information (serial number, date of purchase, conditions of use, etc.).

A further important point regarding the system technical support by the repair personnel is the provision of mechanisms for cause analysis and the identification of suitable measures. A manufacturing company is faced with the requirement for a system that is based on the principle of drawing conclusions from individual sets of examples (induction). The foundation for such a system is an exact description of the faults and the condition of the product that failed in the market. Based on this, similar examples can be obtained from the relevant database, for which successful measures have already been defined. Measures that were arrived at in this way only have to be evaluated and adjusted to the current problem.

2 OUTLINE OF A DATA MODEL FOR EXPLOITATION DATA MANAGEMENT

Before any systematic consideration can be made of the information flow about the performance of technical service repairs on products in service, the activities and requirements in a manufacturing company should be thoroughly and wholly recognized. An example of white-goods product repair has been chosen for detailed consideration because of its frequent occurrence. We have analyzed the information flows that take place when performing repairs in the warranty period, with an emphasis on the outgoing flows. Considering the findings and conclusions, the outgoing exploitation data structure has been defined in the work order as a collecting point for all the relevant information. Details from the current condition of a particular organization have not been stated, the emphasis lies on suggestions based on technical and business-information systems, as well as on the presentation of the analysis method. The relations of repair performance with other functions in a manufacturing company from the information and material-flows viewpoint are shown in Figure 3.



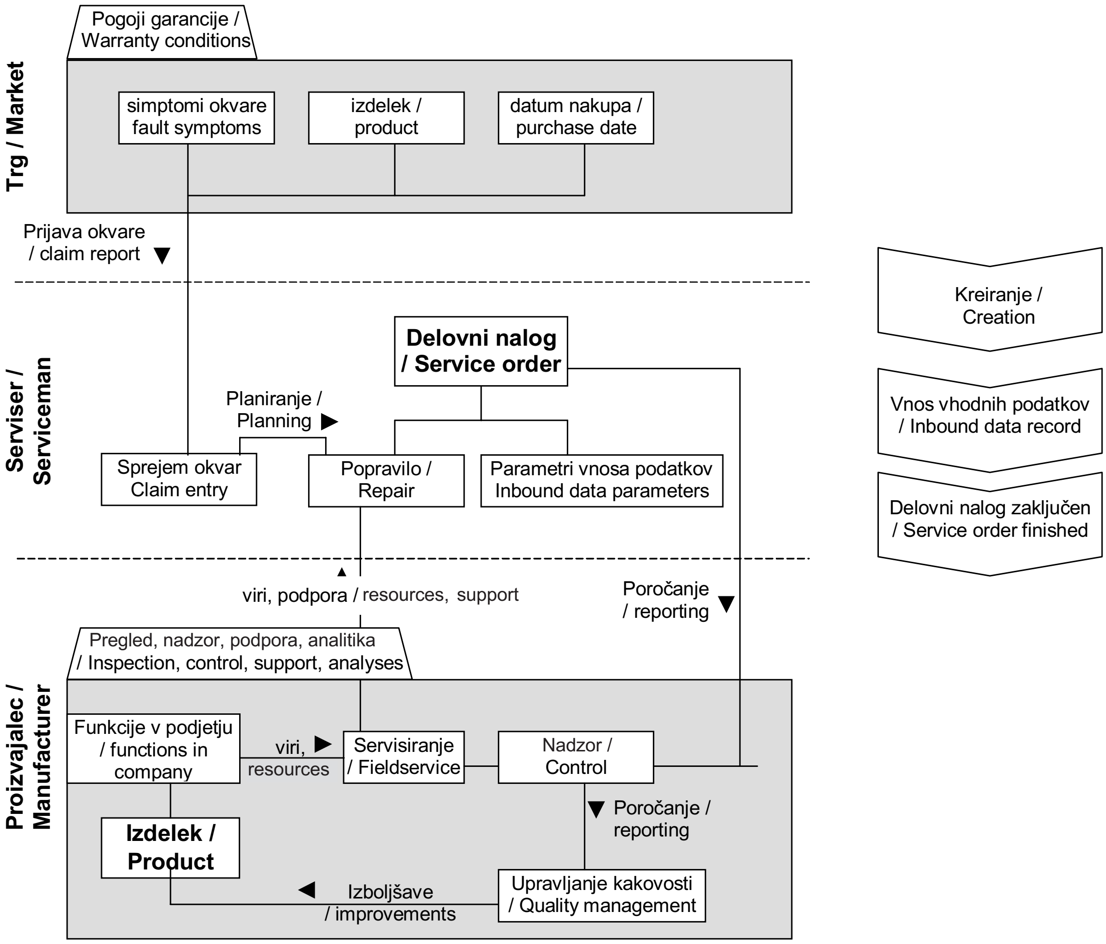
Sl. 3. *Informacijski in materialni tokovi v postopku popravila*
Fig. 3. *Information and material flow in the repair process*

Zahtevnost izdelkov in stopnja posplošitve okvare zmanjšujejo preglednost informacij o stanju izdelka. Izvajalci del so specializirani za izvedbo del (znanje, tehnologija), ki je pri izdelku uporabljena. Dinamika razvoja izdelkov (število izvedenk), prodane količine, zanesljivost izdelkov in razpoložljivost rezervnih delov pomembno vplivajo na izvajanje popravil [8]. Izdelki znotraj posameznih skupin izdelkov se razlikujejo v izmerah, funkcijah in pripadajočih rezervnih delih, medtem ko v sami funkciji in delovanju ni velikega odstopanja. Visoka stopnja standardizacije in poenotenja rezervnih delov zmanjšuje zapletenost poslovanja z rezervnimi deli in poenostavi izvajanje popravil.

Znani so poizkusi informacijske podpore tehničnega servisa izdelkov v uporabi [2], vendar na tržišču ni komercialnih programov, ki bi bili preprosti za uporabo in dovolj prilagodljivi za dinamiko dela pri izvajanju popravil na terenu. Temeljni postopki, ki se pojavijo v uporabi, so za potrebe gradnje končnega modela predstavljeni na sliki 4.

Product complexity and fault abstraction level obscure the transparency of the product condition information. The personnel are specialized for particular tasks (knowledge, technology) that are applied during the product manufacturing. The product-development dynamics (number of versions), quantity sold, product reliability and spare-part availability influence significantly the repair performance [8]. The products within particular product groups differ in dimensions, functions and relevant spare parts, while the variance of function and operation itself is not large. A high standardization and unification level of spare parts reduces the complexity of spare-part management and simplifies the repair procedures.

There have been attempts to establish information support for the technical service of products in use [2], but there are no commercial programs (software) available in the market that would be easy to use and flexible enough for the dynamics of field repairs. Figure 4 presents the basic processes that take place in the exploitation, for the purpose of setting up the final model.



Sl. 4. *Model razvoja delovnega naloga*
Fig. 4. *Model of service-order evaluation*

Prepoznavanje dejanskih stanj izdelkov je zelo pomembno, saj prisili organizacijo, da upošteva povezave med vsemi dejavniki kakovosti na trgu in lahko tako določi mogoča problematična področja, ki bi jih sicer lahko spregledali. Ena najmočnejših prednosti formalnega trajnega postopka upravljanja podatkov iz uporabe je dejavno prizadevanje, da bi ugotovili vzroke za okvare in jih pripravili za izboljšave v krogu kakovosti.

Razvojne skupine potrebujejo pri izvajanju konstrukcijskih izboljšav, ki za svoja izhodišča uporablja podatke iz uporabe, sestavljene informacije s podrobnimi opisi. Težko in najverjetneje nemogoče je oceniti vsako mogoče napako v prihodnosti.

3 REZULTATI IN RAZPRAVA

Strnimo osnovne predpostavke, s katerimi je s preglednostjo povratnih informacij s trgov mogoče

Identifying the actual product conditions is very important, since it forces the organization to account for the connections between all the quality factors in the market, thus being able to define the potential problematic fields, which could otherwise be overlooked. One of the strongest advantages on a formal permanent exploitation data management process is a proactive effort to identify the fault causes and prepare them for the purpose of improvements in the quality loop.

Development teams that are performing the construction improvements using the exploitation data as their starting points need structured information with detailed descriptions. It is very difficult – if not impossible – to evaluate every potential fault in the future.

3 RESULTS AND DISCUSSION

Let us sum up the basic assumptions that, together with the transparency of feedback informadose๠i, da se razvojni timi osredotočijo na tista kritična področja – izdelke, kjer obstajajo možnosti izboljšav. V ta namen je treba zagotoviti sisteme poročanja in dokumentiranja ter pripraviti zahteve in merila spremljanja podatkov iz uporabe.

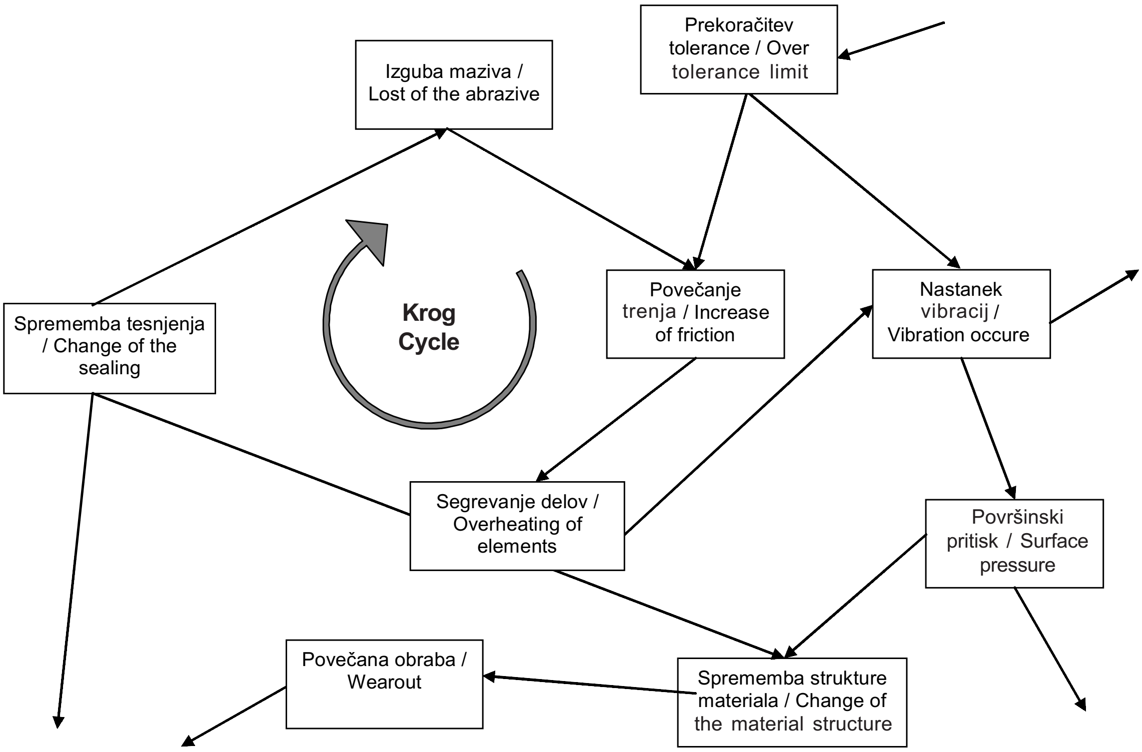
Prvi pogoj, ki je potreben za zagotavljanje sistemsko-tehnične podpore upravljanju napak, je ustrezna predstavitev napak. Dodelitev napak izdelkom, sklopom ali posameznim delom je sicer za izvajanje ukrepov nujno potrebna, vendar velikokrat nezadostna. Prav tako je tekstovni opis napake in spremljevalnih okoliščin treba razširiti za ciljno iskanje ali sklepanje na podlagi primerov. Jasno morajo biti predstavljene vzročno-posledične povezave med posameznimi napakami, da bi se lahko upodobile povezave vzroka in učinka. Na temelju teh povezav se mora ustvariti možnost, da se napake ne dodelijo samo drevesnim sestavom temveč tudi mrežnim sestavom. Tako so znotraj teh mrežnih sestavov mogoče tudi krožne povezave, ki upodabljajo vzajemno delovanje napak in njihovih posledic. Ustrezen primer je predstavljen na sliki 5.

Podpora zbiranja podatkov iz uporab od izvajalcev popravil/servisa je pomembna predvsem

tion from the markets, enable the development teams to focus on the critical fields, i.e., products, where the improvement potentials exist. To do this, it is essential to provide the reporting and documentation systems, as well as the preparation of requirements and the metrics of exploitation data monitoring.

A precondition for providing a system technical support of fault management is an appropriate fault presentation. Attributing faults to products, sets or individual parts is required for performing the measures, but this is often insufficient. A textual description of the fault and pertaining conditions should also be extended for targeted searching or drawing conclusions based on sets of examples. Causal-consequential relationships between particular faults/errors should be clearly presented to enable the visualization of the relationship between cause and effect. Based on these relations a capacity/possibility has to be established to prevent attributing the faults solely to tree-structures, but also to network structures. This would enable identifying cyclical relations within these network structures, showing the simultaneous occurrence of faults and their consequences. An appropriate example is shown in Figure 5.

Exploitation data acquisition support by the repair/service personnel is important, especially from



Sl. 5. *Krog v mreži napak*
Fig. 5. *Cycle in fault net*

z vidika neposredne povezave izvajalcev popravil z izdelki in uporabniki. Zbirajo se številne pomembne informacije – informacije, ki se zapisujejo skozi postopke izvajanja popravil in so, poleg zapisov o porabljenih virih (stroški, material itn.) ter mehanizmih okvar, potrebne za potrdilo o opravljenem delu, oziroma so na delovnih nalogih o opravljenih popravilih. Sem spadajo na primer:

- napake in vzroki zanje,
- mogoči viri napak,
- načrtovani in izpeljani ukrepi,
- zamenjani (rezervni) deli,
- informacije o uporabi in podatki o stroju.

Po natančni preučitvi informacijskih tokov v uporabi in potreb proizvodnega podjetja pri zmanjševanju stroškov zaradi slabe kakovosti na trgu smo želeli ugotoviti, kako zbirati podatke o odpovedih izdelkov za potrebe optimizacije skupinam v konstrukciji.

Zaradi velikega števila izdelkov, njihove zapletenosti in načrtne delitve trgov je težišče raziskave na zbiranju in opisu stanj izdelkov na trgu. Delovni nalog o opravljenem popravilu ponuja stvarno možnost za zbiranje pomembnih informacij. Za doseganje ciljev raziskave je treba delovni nalog razširiti z vključenjem vseh izrazitih značilnosti ali posebnosti izdelka, ne da bi jih bilo treba neposredno povezati z neko motnjo. Na ta način se lahko na primer dokumentirajo izrecno ali posredno podane informacije o zanesljivosti izdelkov na trgu.

Subjektivnosti zbiranja podatkov o okvarah, ki načelno obstajajo, če so bili kakovostni podatki zbrani od izvajalcev del, ni mogoče izključiti, vendar je mogoče s primerno definicijo stavka okvare doseči podroben popis stanja. Pomanjkljivostim, kakor so različna uporaba pojmov posameznih oseb, se je mogoče izogniti tako, da se zagotovi običajni sistem zbiranja. V tem pogledu mora biti zagotovljen mehanizem, ki omogoča logično jasno dodelitev različnih pojmov k vsakokratnemu pomenu.

Na podlagi naših ugotovitev smo zgradili model primerjalnega sistema kodifikacije okvar, ki lahko vsakemu logičnemu objektu dodelijo zadostno število pojmov. Zapis stavka okvare se uporablja tudi za omogočanje večjezičnosti informacijskih sistemov. Ta model omogoča popis in nadaljnjo analizo stanj preteklih dogodkov, ki so strukturirani v pomembnih bazah podjetja. Rezultati so podlaga za večino predlogov in dejanj pri optimizaciji konstrukcij izdelkov.

the viewpoint of a direct interaction of repair personnel and end-users. A lot of important information is gathered – information that is documented through the processes of repair performance – which is, apart from the documentation on resources used (costs, material etc.), required for a receipt of the work preformed or is listed in repair work orders. The information includes:

- errors and their causes,
- potential error sources,
- planned and actually applied measures,
- substituted (spare) parts,
- information about the use/application and machine information.

Following a detailed study of information flows in the exploitation and of the requirements of a manufacturing company for reducing the costs due to poor market quality, we wanted to find how to acquire data about product faults for the optimization purposes of construction teams.

Due to a large number of products, their complexity and market allocation, the research was focused on acquiring and describing the product conditions in the market. A repair work order offers a real possibility to acquire relevant information. To achieve the research goals, the work order has to be extended by including all the significant characteristics or specific properties of a product, without having to link them to a particular fault or error. In this way it is possible to document the explicitly or implicitly stated information regarding the reliability of products in the market.

The subjectivity of fault data acquisition (capturing) in the cases where quality data have been provided by repair personnel cannot be eliminated; it is, however, possible to attain a detailed description of the situation by an appropriate definition of the error string. The shortcomings, such as different use of terms by different persons, can be avoided by providing a standard data-acquisition system. In this respect a mechanism has to be provided that will enable a logically clear attribution of different terms to a particular meaning.

Based on our findings we have established a model of a reference fault codification system that can attribute a sufficient number of terms to every logical object. The formation of a fault/error string is also used to enable multilingual information systems. This model enables listing and the further analysis of previous event conditions, which are structured in relevant company bases. The results represent a foundation for the majority of suggestions and actions regarding the optimization of product constructions.

Prepoznavanje šibkih mest se prične z zbiranjem in obdelavo pomembnih podatkov s trga – informacije o opravljenih popravilih v servisih. V prvi fazi se zbira informacije s trga. V nadaljevanju je treba preučiti in razpoznati podatke, kar izvedemo z omejitvijo na podrobnejšo raven, ki omogoča podjetju prepozanavnje tveganj, razvojnim skupinam pa razumevanje stanj vplivnih dejavnikov in razlago mehanizmov okvar. To je zelo učinkovit način razčlenitve v mreži napak.

Šibka mesta na izdelkih v uporabi so tisti dogodki/stanja na izdelkih, ki pomenijo za podjetje škodljive učinke. Menedžment v proizvodnem podjetju na podlagi poročil o stanju kakovosti na trgu ugotavlja tveganje in z dejavnostmi upravlja zvezo kakovosti. Na podlagi sestavljenih podatkov iz uporabe potekajo dejavnosti:

- izdelava tehnične osnove zbiranja podatkov,
- določanje dejavnosti in informacije s tehničnega in stroškovnega področja,
- priprava poročil in presoj,
- predlog popravnih dejavnosti,
- nadzor,
- zapisovanje časovnega načrta in vrednotenje učinkov.

Iskanje informacij pomeni pomemben delež v delovnem času zaposlenih. Analiza pretoka informacij v proizvodnem podjetju je pokazala, da strokovne službe intenzivno uporabljajo podatke iz sistemov za upravljanje podatkov iz uporabe, pridobljenih od izvajalcev popravil. Sestavljeni podatki iz uporabe sicer ne morejo zagotoviti dokončanega izdelka in nadomestiti nadarjenega konstrukterja. Lahko pa izboljšata kakovost dela in vključevanje izkušenj iz preteklih krogov izdelkov pri razvoju oziroma izboljšavah sedanjih izdelkov. Z ustrezno podporo se lahko pomembno pospeši faza razvoja in izboljša komunikacija med prodajo in razvojem izdelkov.

Znanje in izkušnje iz uporabe smo uredili v pregledno drevesno sestavo, ki uporabnikom omogoča prehajanje med različnimi stopnjami posplošitve izdelkov, od tehničnih načel do določene izvedbe. Za dopolnitev je predstavljen razširjeni inženirski model predstavitve/zbiranja napake (sl. 6), ki združuje servisno dokumentacijo, pri kateri so mehanizmi okvar sestavljeni za potrebe proizvodnega podjetja, vključno z uporabljenimi viri in organizacijskimi podatki.

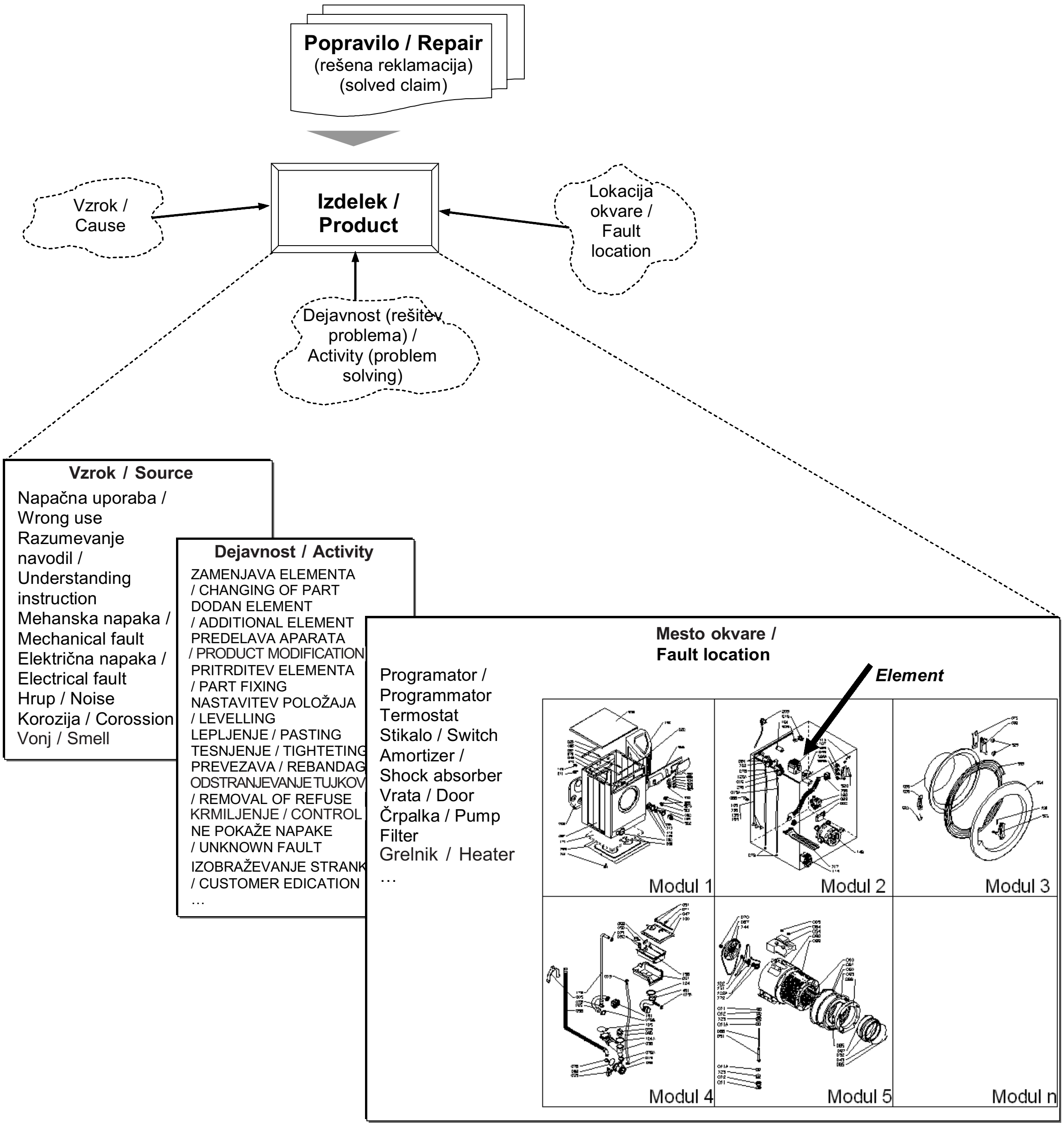
Identifying the weak points starts by collecting and processing the relevant market data – information about the repairs performed by service workshops. In the first phase the market information is acquired. After this, the data has to be studied and identified, which is performed by a reduction to a more detailed level that enables the company to recognize the risks, and enables the development teams to understand the conditions – influential factors and interpretation of the fault mechanisms. This is a very efficient way of segmentation in a fault/error network.

The weak points in the products in exploitation are those product events/conditions that imply negative or harmful effects for the company. Based on reports about the quality situation in the market, the management determines the risks and regulates the quality loop by appropriate activities. Based on structured exploitation data the activities take place:

- providing technical foundations of data acquisition,
- determining activities and information in the technical and cost field,
- preparing reports and judgments,
- suggesting corrective activities,
- control,
- documenting the schedule and evaluating the results/effects.

Searching for information represents an important fraction of the working hours of he personnel. An analysis of information flows in a manufacturing company has shown that professional departments intensively use the data from exploitation data management systems, which are acquired by repair personnel. Structured exploitation data cannot provide for an elaborate or perfect product or replace a talented designer/constructor. It can, however, improve the quality of work performed and include the experience from previous product cycles in the development or improvement process of new products. Appropriate control can significantly accelerate the development phase and improve the communication between after-sales and product development.

Knowledge and experience from the exploitation phase have been sorted into a transparent tree structure that enables the users to switch between different levels of product abstraction – from technical principles to particular applications. To complement this, an extended engineering model of fault presentation/data acquisition is presented (Figure 6), joining the service documentation where the fault mechanisms are structured to meet the requirements of a manufacturing company, including the used resources and the organization data.



Sl.6. *Model zapisa stavka okvare*
Fig. 6. *Model of fault sentence description*

Pri postavljanju osnutka smo upoštevali faze in informacijske potrebe v proizvodnem podjetju. Znano je, da sistemi ERP podpirajo predvsem materialne in finančne tokove in so omejeni predvsem na postopke v primarni vrednostni veri proizvodnega podjetja. Naš cilj je podpreti in razširiti informacijske tokove iz uporabe z vključevanjem in zbiranjem informacij o mehanizmih okvar.

Delovni nalog o opravljenih popravilih mora vključevati pomembne podatke, ne samo z vidika

When establishing the concept, the phases and informational requirements in a manufacturing company are accounted for. It is commonly known that ERP systems support mainly material and financial flows and are limited to processes in the primary value chain of a manufacturing company. Our goal is to support and extend the information flows from the exploitation phase by including and acquiring (capturing) the information about fault mechanisms.

A work order about repairs performed must comprise all the relevant data, not only from the view-potreb izvajalcev popravil, temveč tudi za druge oddelke v proizvodnem podjetju (računovodstvo, kakovost, razvoj itn.). Npr. pri vnosu podatkov o opravljenih delih v delovni nalog potrebujejo izvajalci popravil poleg potrebnih informacij in virov tudi specifikacijo podatkov za vnose. Za vzdrževanje izdelkov splošne rabe je značilen velik obseg dela, zato so pomembna orodja, ki avtomatizirajo vsakdanja opravila. Pri obliki podpore je potrebno upoštevanje ravni dela. Trdimo lahko, da imamo opravka s ponavljajočimi se dejavnostmi, pri katerih imamo opravka s ponavljajočimi se izdelki, okvarami in potrebnimi viri. Serviser poleg svojega znanja o razpoznavanju uporablja preverjene tehnične rešitve in vire in je sposoben prepoznati vzroke in mehanizme okvar. Zato v tem primeru izvajalci popravil ne potrebujejo podpore z delovnimi načeli ali razčlenitve funkcijske strukture. Dobrodošli pa so različni pripomočki, ki omogočajo čim bolj učinkovito delo, npr. knjižnice tipiziranih tehničnih objektov in specifikacije za vnose mehanizmov okvar.

Pri obvladovanju kakovosti na trgu je ključnega pomena spremljanje stroškov popravil in mehanizmov okvar. Zaradi tega je potrebno stalno spremljanje kakovosti na trgu in odpravljanje napak na kritičnih izdelkih. Količina podatkov pri izdelkih splošne rabe je bistveno širša kakor pri posamičnem vzdrževanju tehničnih objektov investicijske narave. Temu primerna morata biti tudi ustrezen vhodni in izhodni tok informacij, npr. podatki o različnih materialih, izdelkih ter pregled in nabor napak in lokacij, ki dajejo pregledni okvir povratnim informacijam. Pomemben izziv pri oblikovanju sestave povratnih informacij iz uporabe je oblikovanje formata, ki bo omogočal hitro in učinkovito zbiranje podatkov ter hkrati zadoščal potrebam menedžmenta kakovosti. Tukaj je cilj odkriti doslej neznana načela, ki pa seveda morajo biti skladna s prakso v proizvodnem podjetju.

Pri poizvedbah vzrokov za reklamacije obstajajo številne možnosti. Da se ohrani pregled nad izvajanjem popravil ter analiza mehanizmov okvar, je uporabljen opis okvare v štirih skupinah. Običajno so trg, izdelek/proizvodni program ter kritični elementi izhodišče za nadaljnje poizvedbe. V naslednjih korakih se določi topologijo oz. kodifikacijo virov. Opisana struktura ni obvezujoča. Kriteriji opisa okvare so uporabljeni kot vir navdiha za izboljšave ali pa kot kazalo o stanju kakovosti/zanesljivosti izdelkov. Kot zelo primerna se je pokazala drevesna sestava.

point of repair personnel, but also for other departments in a manufacturing company (accounting, quality management, development, etc.). For instance, when entering the data about work performed into the work order, the repair personnel need the data specification for the entries, in addition to the required information and sources. The maintenance of the products for general use involves a large amount of work, which makes the tools for the automatic performing of routine tasks even more important. When considering the form of support, the work levels have to be considered. It can be claimed that since we are dealing with repeated activities, we are also dealing with repeating products, faults and required resources. Apart from the diagnostics knowledge, the serviceman also employs established technical solutions and sources and is capable of identifying the fault causes and mechanisms. Thus, in this case the repair personnel do not require support by working principles or by analyzing the functional structure. However, various accessories that enable more efficient work are welcome, such as libraries of typified technical objects and specifications for entering the fault mechanisms.

When dealing with market quality management, monitoring the repair costs and fault mechanisms is of key importance. This requires the constant monitoring of market quality and eliminating the critical product errors. The quantity of data with the general use products is significantly more extensive than with the individual maintenance of technical investment-character objects. Therefore, the in - and outgoing information flows have to be adjusted accordingly, e.g., the data on different materials and products, an overview and an array of errors and locations providing a transparent framework for feedback information, etc. An important challenge when designing the exploitation feedback information structure is designing a format that will enable quick and efficient data acquisition (capturing), meeting at the same time the requirements of the quality management. Here, the goal is to discover some hitherto unknown principles, which should, however, comply with the manufacturing company practice.

Regarding the queries about the warranty claim causes, there are several possibilities. To maintain the overview of the repair performance and the fault mechanism analysis, a fault description in four groups is employed. Usually, the market, the product/product line and the critical elements are the starting point for further queries. In the following steps the topology or the codification of sources is defined. The described structure is not default (or mandatory). The fault description criteria are used as a source of inspiration for improvements or as an index table about the product quality/reliability. The tree structure has proven to be very appropriate.

Pri popravilu izdelkov se uporabljene dejavnosti in viri (material, delo, čas, stroški) vpišejo v delovni nalog. Jedro je dokument, tj. delovni nalog z vnesenimi podatki po sistemu kodifikacije okvar. Vsak material/rezervni del nosi podatke, ki podrobneje določajo mehanizme okvar. Pri tem je prepoznavanje elementov, ki so nosilo okvar, ključnega pomena za obvladovanje vzročno-posledičnih verig. Na delovnih nalogih so navedeni organizacijski parametri, ki razširijo mogoče analize in poizvedbe. Navedene so vse mogoče različice in tudi pravila, ki osnovnim odločitvam priredijo ustrezne gradnike. Tako se lahko hitro izdela analizo za določen trg oziroma izdelek.

V razširjenem inženirskem modelu delovnega naloga so definirani vnosi podatkov. Podatki o kupcu in izdelek so predstavljeni ločeno od mehanizmov okvar. Za boljše razumevanje mehanizmov okvar se navaja okvaro kot kodiran stavek "Vzrok/Dejavnost/ Lokacija", kar je prikazano na sliki 6.

4 SKLEPI

Poglavitni namen prispevka je bil predstaviti model zbiranja podakov iz uporabe. Predstavljeni osnutki sledijo uporabi detajliranih podatkov iz uporabe izdelkov, ki so specifični za določen izdelek. Sestavni element obvladovanja kakovosti v proizvodnem podjetju je ustrezen popis stanj izdelka v uporabi. Za zbiranje in obdelavo se upoštevajo predvsem zahteve glede izdelka kakor tudi dejanska stanja, povezana z izdelkom, to so na primer napake, pozitivna stanja in njihove vzročno-posledične povezave v obliki verige vzroka in učinka.

Za doseganje ciljev je bila potrebna definicija podatkovnega modela zapisa okvare, ki omogoča zbiranje podatkov v zahtevani obliki in poenostavlja izmenjavo podatkov. V prispevku predstavljen model kodifikacije okvar vsebuje definicijo popravila izdelka na delovnem nalogu. Kodifikacija okvar pokriva celotni nabor stanj in vzrokov v sestavni obliki, ki podjetju omogoča preprosto zbiranje podatkov ter urejeno znanje na podlagi tipiziranih okvar, ki se pojavljajo v dobi trajanja izdelka. Na enem mestu so dostopne vse informacije o popravilih na izdelku. S tem se izognemo dolgim zapisnikom o opravljenih popravilih. Omogočeno je neposredno preoblikovanje podatkov o opravljenih popravilih v informacijske baze.

The activities performed and the resources used during the repairs (material, work, time, costs) are entered into the work order. The core document is the work order with entered data, following the system of fault. Every material/spare part contains information that can further specify the fault mechanisms. The recognition of elements that act as potential fault causes is of key importance for controlling the cause-and-effect chains. Organizational parameters are stated on the work orders, extending the analysis and query possibilities. All possible variants and rules that attribute appropriate construction elements to the basic decisions are stated. This way, analysis for a particular market or product can be performed quite quickly.

In the expanded engineering model of work order, the data entries are pre-defined. The data about the customer and the product are presented separately from the fault mechanisms. For a better understanding of fault mechanisms every fault is stated as a codified string "cause/activity/location", as shown in Figure 6.

4 CONCLUSIONS

The main purpose of this paper was to present a model of exploitation data acquisition (capturing). The concepts presented follow the application of detailed data from the product exploitation, which are specific to a particular product. The elements of quality control in a manufacturing company are stated on an appropriate list of product conditions during its exploitation phase. When capturing (or acquiring) and processing the data, the requirements regarding the product are considered, as well as the actual conditions connected with the product, such as errors/ faults, positive conditions and their causal relations in the form of cause-and-effect chains.

To attain the goals set ahead, it was necessary to define the data model of the fault record, thus enabling the acquisition (capturing) of data in the required form and simplifying the data exchange. The fault codification model that is presented in the article contains the definition of product repair in the work order. Fault codification covers the entire array of conditions and causes in a structured form that enables the company to have a simple data acquisition (capturing), and organizing the accumulated knowledge on the basis of typified faults that occur during the product lifecycle. All information about the product repairs is accessible at one location. In this way, lengthy textual records of the repairs performed are avoided. Thus, a direct real time transformation of the repair data into the information databases is enabled.

5 LITERATURA
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Razvoj proizvodnih zmogljivosti v industrijskih grozdih – primer Slovenski avtomobilski grozd

The Process of Manufacturing-Capability Development in Industrial Clusters – A Case Study of the Automotive Cluster of Slovenia

Tatjana Fulder - Iztok Palčič - Andrej Polajnar - Petja Pižmoht

Industrijski grozdi so sodobna zamisel mrežnega povezovanja, ki je uveljavljen tudi v slovenskem gospodarskem prostoru, hkrati pa pomenijo tudi nove izzive za raziskovanje na področju opravilnega in proizvodnega menedžmenta. Raziskani so že vzroki in namen nastanka industrijskih grozdov, zelo malo pa je raziskav, ki bi pojasnjevale strateške posledice povezovanja. Zato prispevek obravnava postopek razvoja proizvodnih zmogljivosti, ki smo ga preučevali v industrijskih grozdih z uporabo metodologije študije primerov.

(Ključne besede: grozdi industrijski, viri proizvodni, zmogljivosti proizvodne, študije CASE)

Industrial clusters are interesting concepts of network collaboration that are also well established in the Slovenian business environment. They represent a new challenge for research in the field of production and operations management. The reasons for cluster formation have been explored for many years, but there is little research that explores the strategic consequences of this type of collaboration. This paper deals with the manufacturing-capability development process and with the research conducted in the industrial clusters. The research is based on a case-study methodology.

(Keywords: industrial clusters, resource-based view, manufacturing capability, CASE study)

0 UVOD

Industrijski grozdi so nastali kot odgovor na globalizacijo in hiter tehnološki razvoj ter s tem zadostili potrebi po pospešenem razvijanju globalne konkurenčne zmogljivosti gospodarstva v okviru posameznih držav in regij [1]. Industrijski grozdi so zaradi priložnosti, ki jih podjetjem ponujajo, sodobna zamisel povezovanja, ki je razširjena v svetovnem gospodarskem prostoru in tudi v Sloveniji, zaradi tega pa zanimiva tudi za znanstveno preučevanje. Zato ne preseneča dejstvo, da se raziskovanje na področju opravilnega in proizvodnega menedžmenta na eni strani vse bolj usmerja na raziskovanje industrijskih grozdov, po drugi strani pa tudi v raziskovanje proizvodnih zmogljivosti z vidika teorije proizvodnih virov, v pomenu pojasnjevanja doseganja konkurenčnih prednosti tovrstnih mrežnih organizacij.

0 INTRODUCTION

Industrial clusters are the answer to processes like globalisation and rapid technological development, and they can satisfy the need for faster development of global competitive capabilities of the business environment in a single country and region [1]. Industrial clusters are, because of the opportunities they offer, an interesting concept of collaboration, worldwide and in Slovenia. It is a very interesting concept for scientific research as well. It is not surprising that the research in the field of production and operations management is orientated in two directions: first, to study this phenomenon, and second, to explore manufacturing-capability development from the RBV (Resource-Based View) perspective in an attempt to explain how this type of network organisation achieves a competitive advantage.

Večina raziskav na področju teorije proizvodnih virov se ukvarja predvsem s samim definiranjem ter prepoznavanjem zmogljivosti ter njihovim vplivom na specifične vire podjetja, v primerjavi s tem pa najdemo zelo malo raziskav, ki bi obravnavale, zakaj se zmogljivosti oziroma najboljše prakse dejansko razvijajo, kako se razvijajo in vzroke za njihov razvoj. Zaradi intenzivne rasti najrazličnejših oblik mrežnih organizacij pa zasledimo že nekaj poskusov uporabe teorije proizvodnih virov pri preučevanju mrežnih organizacij, pri čemer se le-ta uporablja predvsem za razumevanje oblikovanja in upravljanja mrežnih organizacij.

Neraziskano ostaja tako vprašanje, kako se proizvodne zmogljivosti razvijajo v mrežnih organizacijah, oziroma kako le-te vplivajo na njihov razvoj. Na to vprašanje smo poskušali odgovoriti z raziskavo, predstavljeno v tem prispevku.

Prispevek obravnava postopek razvoja proizvodnih zmogljivosti, ki smo ga raziskovali na primeru industrijskih grozdov, ki so kot oblika mrežne organizacije v poslovnem svetu poznani predvsem kot pomembna nosila gospodarskega razvoja. Tako smo v raziskavi izhajali iz naslednjih teoretičnih predpostavk:

- *V industrijskih grozdih gre za dinamično povezavo med različnimi vrstami zmogljivosti.*
- *Zmogljivosti lahko razvrstimo glede na perspektivo, s katere opazujemo industrijski grozd, in koristi, ki jih imajo vključena podjetja.*
- *Dinamika razvoja industrijskega grozda narekuje razvoj zmogljivosti grozda.*

1 TEORIJA PROIZVODNIH VIROV IN POSTOPEK RAZVOJA ZMOGLJIVOSTI

Teorija proizvodnih virov je vplivno teoretično ogrodje za razumevanje, kako se doseže konkurenčna prednost znotraj podjetja ter kako se le-ta vzdržuje oziroma ohranja ([2] in [3]). Bistvo teorije proizvodnih virov se kaže v trditvi, da je konkurenčni položaj podjetja definiran s skupkom edinstvenih virov in zmogljivosti ter odnosov med njimi [4]. Podjetja, ki so zmožna razviti vire in zmogljivosti, ki so vredni, nezamenljivi in težko posnemljivi, bodo dosegla konkurenčno prednost v primerjavi s konkurenčnimi podjetji ([2] in [5]). Spremembo na področju teorije proizvodnih virov pa pomeni postopek dinamičnih zmogljivosti, pri katerih gre za premik iz statičnih specifičnih virov podjetja v postopek razvoja zmogljivosti [6]. V literaturi

Most of the research in the field of RBV has studied questions like, what are the capabilities, how they can be recognised, and how they influence firm-specific resources? But there is little research that explains why the capabilities and best practices are developing, how they develop and what is the reason for their development. Because of the intensive growth of different types of network organisations, we have noticed some attempts to use the logic of RBV in the research of network organisations, but more in a way to understand their formation and management.

There is still an open research question, how the manufacturing capabilities develop in the network organisation and how network organisation influences their development? We have tried to find the answer with the research presented in this paper.

The paper deals with the process of manufacturing-capability development in industrial clusters as one of the types of network organisations, known as the important tools for economic development. The research is based on three theoretical assumptions:

- *Industrial clusters are about a dynamic connection between different types of capabilities.*
- *Capabilities can be classified with regard to the perspective from which the cluster is viewed and the benefits its members enjoy.*
- *The dynamics of functioning within a cluster dictates the need for the development of cluster capability.*

1 THE RESOURCE-BASED VIEW AND THE PROCESS OF CAPABILITY DEVELOPMENT

The resource-based view represents the influential theoretical framework that explains how the firm achieves and sustains its competitive advantage ([2] and [3]). The essentials of the resource-based view lie in the assertion that the competitive position of an organisation is determined by the sum of its unique resources and capabilities, and the relationships between them [4]. The firms that are able to accumulate resources and capabilities that are valuable, non-substitutable and difficult to imitate will achieve a competitive advantage over competing firms ([2] and [5]). The change in the field of the resource-based view represents the dynamic capability approach, which shifts the emphasis from static firm-specific assets to the dynamic process of dezasledimo malo raziskav, ki bi pojasnjevale logiko in dinamiko postopka razvoja zmogljivosti. V splošnem namreč velja, da podjetja ''že nekako'' razvijajo zmogljivosti skozi čas. Nedavno pa so se raziskave že nekoliko preusmerile v raziskovanje, kako zmogljivosti nastanejo, se razvijajo in spreminjajo skozi čas [7]. Tako se prihodnost raziskovanja na področju teorije proizvodnih virov vse bolj usmerja na vprašanje, kako podjetja razvijajo in zbirajo zmogljivosti v razvojnem postopku.

Teorija proizvodnih virov običajno obravnava posamezno podjetje kot enoto analize. V zadnjem času pa se na tem področju kažejo že nekateri zanimivi poskusi uporabe teorije proizvodnih virov pri obravnavanju različnih oblik mrežnih organizacij. Nekateri avtorji menijo, da je teorija proizvodnih virov ena izmed ključnih področij strateškega raziskovanja, v katerem so velike možnosti tudi za mrežne organizacije [8], pri čemer to utemeljujejo z dejstvom, da so mrežne organizacije nekaj posebnega in da so nastale skozi zaporedje določenih postopkov ter jih lahko obravnavamo kot vir neposnemljivih in nenadomestljivih vrednosti [9].

Vzroki za oblikovanje mrežnih organizacij so že zelo raziskani, kar pa ne moremo trditi za raziskovanje strateških posledic oblikovanja mrežnih organizacij. Zelo malo je raziskav, ki obravnavajo vpliv mrežnih organizacij na razvoj zmogljivosti. Večina študij mrežnih organizacij uporablja teorijo proizvodnih virov z namenom poudariti izmenjavo že znanih zmogljivosti in virov ter raziskati pomen učenja ter zbiranja izkušenj pri upravljanju le-teh. Podjetja si skozi povezovanje pridobijo dostop do virov, ki ustvarjajo nove vrednosti, ter do zmogljivosti, ki terjajo čas, da se razvijejo. Ahuja [10] trdi, da je število partnerjev, ki so se pripravljeni povezovati, odvisno od pristojnosti podjetja, proizvodnih zmogljivosti, prodajne mreže in od števila drugih povezav, ki jih je podjetje vzpostavilo kot socialni kapital. Hkrati zasledimo definicijo virov mrežne organizacije, ki pravi, da so viri kakor povezave med podjetji, ki poskrbijo za koristne informacije [11]. Gulati tudi dokazuje, da na pripravljenost podjetij za vstop v novo zvezo vpliva obseg virov mrežne organizacije, ki jim je na voljo [12]. Nekateri avtorji dokazujejo, da se podjetja učijo upravljati mrežno organizacijo na osnovi pridobljenih izkušenj [13]. Z drugimi besedami lahko rečemo, da je uspeh mrežne organizacije odvisen od izkušenj, ki si jih podjetje pridobi skozi povezovanja z drugimi podjetji. Večina takšnih raziskav tako obravnava

veloping capabilities [6]. In RBV literature, very little effort has been made to explain the logic and dynamic structure of the process of developing capabilities. It has been generally assumed that firms somehow develop such capabilities over time. More recently, research has turned to exploring the ways in which firm capabilities emerge, develop, and change over time [7]. The future research in the field of the resource-based view will be oriented more towards addressing the question of how firms develop and accumulate the capabilities in the evolutionary process.

The RBV perspective traditionally adopts an individual firm as a unit of analysis. Recently, this field witnessed some interesting attempts to extend the RBV perspective to different forms of networks. Some authors suggest that the RBV perspective represents one of the key areas of strategy research in which there is a potential for incorporating network organisations [8]. The argument is that a firm's network is idiosyncratic and created through a path-dependent process and can therefore be understood as an origin of inimitable and non-substitutable value [9].

The reasons for the formation of networks are already well known, but quite opposite is the case when it comes to research on the strategic consequences of network formation. There was little research that explored how networks influence the development of capabilities. Most studies of networks use the RBV perspective to emphasise the sharing of already existent capabilities and resources and to explore the importance of learning and accumulating the experience in managing networks. Through the networks firms can obtain access to resources that create value and to capabilities that require time to build up. Ahuja claims that the number of potential partners that are willing to link with a firm is dependent on the firm's competence, manufacturing capabilities, distribution network and the number of ties formed by a firm to its social capital [10]. According to one definition, network resources are like ties among firms that provide informational advantage [11]. Gulati argues that the willingness of firms to enter new alliances is influenced by the amount of network resources available to them [12]. Some authors argue that firms learn to manage interfirm networks as experiences accumulate [13]. In other words, the success of the network is dependent on the number of the firm's ties. The majority of such studies explore the relations between the razmerje med obsegom povezovanj in uspehom podjetja, po drugi strani pa postopek, skozi katerega podjetja dejansko razvijajo svoje zmogljivosti v mrežnih organizacijah, še ni bil ustrezno raziskan.

Poleg tega pa se zmogljivosti še zmeraj obravnavajo znotraj okvira posameznega podjetja. Tako nekateri avtorji trdijo, da povezovanje v mrežne organizacije predstavlja osnovno zmogljivost podjetja [14]. A večina literature se še zmeraj osredotoča na interno zmogljivost podjetja, na osnovi katere se ustvarjajo koristi povezovanja v mrežne organizacije in ki je pomembna za upravljanje teh povezovanj. Zmogljivosti se namreč še zmeraj obravnavajo kot nekaj, kar je specifično za vsako podjetje. Tako pojem *zmogljivost mrežne organizacije* spreminja to splošno razumevanje.

Zmogljivost mrežne organizacije se razume kot zmogljivost, ki ni značilna oziroma vezana na eno podjetje v mreži, ampak pomeni skupni prispevek h koordiniranju in učenju [15]. Zmogljivost mrežne organizacije se razlaga tudi glede na različne koristi, ki jih imajo sodelujoči v mrežni organizaciji, kar pomeni posamične in skupne koristi [16]. Zmogljivost mrežne organizacije namreč omogoča povezanim podjetjem, da skupaj uporabljajo lastne zmogljivosti z namenom ustvariti nekaj, od česar imajo koristi vsi sodelujoči. Literatura s področja dobaviteljskih verig, ki je preučevala proizvodne postopke v Toyoti, predstavi zmogljivost mrežne organizacije kot take, ki je ne najdemo v nobenem podjetju, ampak je bila izoblikovana skozi prenos pristojnosti in pomembnih izkušenj od osrednjega podjetja do njegovih dobaviteljev ([17] do [19]). V tem primeru zmogljivost mrežne organizacije izhaja iz zmožnosti centralnega podjetja, da usklajuje podjetja, ki sestavljajo dobavno verigo.

Motivi za raziskavo, predstavljeno v tem prispevku, so izhajali iz želje, pojasniti, kako se proizvodne zmogljivosti razvijajo v industrijskih grozdih, ki so kot oblika mrežne organizacije zelo pomembni tako za ljudi iz poslovnega okolja kakor za raziskovalce s področja proizvodnega menedžmenta.

2 INDUSTRIJSKI GROZDI – TEORETIČNA IZHODIŠČA

Gospodarski temelj za obstoj industrijskih grozdov in lokalnih industrij je raziskovalo mnogo avtorjev, pri čemer se kot začetnika omenjata Marshall ter Weber ([20] in [21]). Marshall je izpostavil tri bistvene razlage o nastanku grozdov. Prvič, podjetja se geografsko tesno združujejo iz razloga, ker jim to omogoča razvoj specializirane delovne sile, ki je

number of contracts and performance. On the other hand, the process by which firms actually develop capabilities in networks has not yet been adequately explored.

In addition to that, capabilities are still dealt with merely within the framework of the individual firm. Some authors argue that making an alliance represents a firm’s generic capability [14]. Most of the literature still focuses on the firm’s internal capability to create value through networks and to manage alliances. In the research work the competitive environment is treated as a network. However, the capability is still understood as something firm-specific. The notion of *network capability* changes this general understanding.

The network capability is like a capability that is not specific or isolated to a single firm in network, but represents joint gains to coordination and learning [15]. Network capability can be explained by using different kinds of benefits available to participants in networks, i.e., private benefits and common benefits [16]. Network capability enables the firms in the network to collectively use their capabilities to produce something that is beneficial to them all. Supply-chain literature studying the Toyota Production System presents such a network capability, where capability did not reside in any given firm, but was created by the transfer of competence and best practices from the central firm to its subcontractors. In this case, the network capability arises from the ability of the central firm to coordinate among firms that constitute the supply chain ([17] to [19]).

The motives for the research presented in this paper result from the context to explain the process of capability development in industrial clusters that are, like a form of network organisations, very interesting for the business environment and also for the researcher from the field of production management.

2 INDUSTRIAL CLUSTERS – THEORETICAL BACKGROUND

The economic basis for the existence of industrial clusters in local industries has been explored by many authors, beginning with Marshall and Weber ([20] and [21]). Marshall highlighted three key explanations. First, firms get close together geographically because this allows them to develop a pool of specialised labour that is highly skilled for the specific needs of an specializirana za specifične namene industrije. Tako imajo podjetja hiter dostop do tega znanja. Nadalje, ta podjetja lahko zaradi geografske bližine uporabljajo ekonomijo obsega pri razvoju novih ali uporabi znanih tehnologij, ali uporabljajo že znano infrastrukturo. Kot tretje pa lahko rečemo, da geografska bližina podjetij omogoči učinkoviti pretok informacij, znanja in idej. Še več literature o industrijskih grozdih poudarja, da nameravajo podjetja znotraj regije dati na voljo podobne vire, stroškovne strukture, miselne modele in konkurenčno obnašanje [22]. Ta tok raziskav predpostavlja, da so podjetja znotraj takšnih regij homogena ter dosegajo podobne ravni učinkovitosti.

Druge raziskave tudi kažejo, da nekaterim podjetjem uspe razviti in ohraniti zmogljivosti, ki jim omogočijo konkurenčnost, po drugi strani pa pešajo podjetja zaradi zastarelega znanja in izkušenj [23]. Enright [24] trdi, da ima mnogo industrijskih grozdov svoj vir v nekaterih specifičnih lokalnih dejavnikih, lokalnih zahtevah ali sorodnih industrijah. Isti avtor prav tako razpravlja o tem, da sta rast in vztrajnost industrijskih grozdov posledica razvoja pritiska, spodbud in zmogljivosti po inovacijski dejavnosti, ki jih ustvarja krajevno okolje. Pečat na področju preučevanja industrijskih grozdov pa je zagotovo pustil Porter [25], ki je s svojim delom opozoril na industrijske grozde kot na močne spodbujevalnike gospodarskega razvoja. Isti avtor trdi, da so: …grozdi geografske koncentracije medsebojno povezanih podjetij, specializiranih dobaviteljev, storitvenih organizacij, podjetij v sorodnih industrijah in institucij (univerz, agencij, trgovskih zvez) na določenem področju, ki hkrati tekmujejo in sodelujejo.

Kakor lahko razberemo, je zamisel grozdov postala zelo zanimiva za raziskovanje na več področjih znanosti. Pomembnost raziskovanja tovrstnih področij potrjujejo tudi najrazličnejši izsledki v literaturi, zato lahko z gotovostjo trdimo, da bo prihodnje raziskovanje na področju proizvodnega menedžmenta temeljilo med drugim na vključevanju teorije proizvodnih virov v raziskovanje industrijskih grozdov. Eden izmed ciljev takšnega raziskovanja je razvoj temeljnega modela razvoja proizvodnih zmogljivosti v industrijskih grozdih, s katerim bi lahko prepoznavali pomembne spremenljivke ter njihova medsebojna vplivanja.

3 METODOLOGIJA RAZISKOVANJA

Raziskava temelji na metodologiji študije primerov. Razvojna narava postopka razvoja

industry and relatively easy for the firms in need of these skills to access them. Second, these firms can experience economies of scale in developing and using common technologies or a particular capital infrastructure, because they localize themselves in close geographic proximity. Third, firms that join together geographically can generate a maximum flow of information, knowledge and ideas. More literature on geographical clusters argues that firms within a region tend to exhibit similar resources, cost structures, mental models and competitive behaviour [22]. This stream of research assumes that firms in these regions are homogeneous and achieve similar levels of performance.

Other research suggests that whereas some firms manage to acquire and maintain the capabilities to successfully compete, others languish with obsolete skills and routines [23]. Enright affirms that many industrial clusters had their origins in some specific local factor condition, local demand or related industry [24]. The same author also argues that the growth and persistence of industrial clusters results from the development of pressures, incentives and capabilities to innovate, provided by the local environment. But the industrial clusters have become a major consideration in international research circles with the work of Porter, who pointed out that industrial clusters are the promoters of economic development [25]. The same author claims that industrial clusters are geographic concentrations of interconnected companies, specialized suppliers, service providers, firms in related industries, and associated institutions (e.g., universities, R&D institutions, trade associations) in a particular field that compete but also cooperate.

We can say that the concept of industrial clusters became very interesting in many fields of science. The importance of industrial clusters as a subject of research is confirmed through the many scientific publications. For this reason we claim that the future research in the field of production management will be oriented on the research of industrial clusters. One specific direction of such research would be to develop the basic model of capability development in industrial clusters. Such a model should aim to identify the relevant variables and the interactions among them.

3 RESEARCH METHODOLOGY

A case study methodology was used to conduct the research. The evolutionary nature of the zmogljivosti v industrijskih grozdih terja vzdolžni postopek raziskovanja. Ena izmed najtežjih in hkrati najpomembnejših stvari v raziskavi je prepoznati razmerja med vzrokom in učinkom, zato je pomembno, v kakšnem časovnem obdobju jih preučujemo. Raziskava sledi razvoju postopka v zadnjih štirih letih, kar se seveda ujema s pričetkom razvoja grozdov v Sloveniji. Leonard-Barton [26] zagotavlja, da poglobljena vzdolžna študija primera zagotavlja notranjo veljavnost raziskav. Model, ki je bil razvit v okviru raziskave, temelji na podatkih, ki smo jih zbrali v dejanskem poslovnem okolju posameznih proizvodnih podjetij in drugih organizacij v grozdu. Model se je razvijal med raziskavo s stalno povezavo, analizo in zbiranjem podatkov. Takšen raziskovalni postopek je skušal zmanjšati razkol med razvitim modelom in poslovno stvarnostjo. Izbrani so bili trije primeri – industrijski grozdi, ki so bili namenjeni za pridobivanje podatkov.

Ti primeri niso bili izbrani naključno, ampak zaradi teoretičnih razlogov. Izbrani so tako, da omogočajo kar najboljše možnosti za obravnavanje predmeta raziskave. Osrednjo študijo primera predstavlja SAG – Slovenski avtomobilski grozd, ki predstavlja primarno in najbolj poglobljeno študijo primera. Druga podporna študija je bil štajerski avtomobilski grozd Styria iz sosednje Avstrije, tretji primer pa je bil Slovenski orodjarski grozd. Zaradi obsežnosti izvedene raziskave, prispevek obravnava samo Slovenski avtomobilski grozd.

Enoto analize predstavlja razvoj proizvodnih zmogljivosti. Za ta postopek so značilne zahtevnost, slaba strukturiranost, posebnost in dinamična historična odvisnost. Ker je postopek razvoja zmogljivosti specifičen za vsako podjetje, je preučevanje tega pojava še toliko zapletenejše na ravni grozda, ki s tega vidika pomeni skupek nekih specifičnih zmogljivosti. Izbrana metodologija zaradi svoje poglobljenosti tako omogoča učinkovito obravnavanje zapletenosti postopka.

Pogovori, poslovna dokumentacija in opazovanja so metode zbiranja podatkov, uporabljenih pri raziskavi. Pogovori s ključnimi osebami v podjetjih so trajali v povprečju uro in pol. Vsi pogovori so bili posneti. Poslovna dokumentacija in arhivski dokumenti so ob pogovorih drugi vir podatkov. Uporaba več različnih virov izboljša notranjo veljavnost raziskave. Za raziskavo je bila pomembna vsa poslovna dokumentacija, ki je omogočala spoznavanje zahtevne poslovne stvarnosti, in tista, ki tako po kakovosti kakor tudi po kolikosti podpira

process of capability development in industrial clusters requires the longitudinal research approach. One of the most difficult and also the most important part in this type of research is to recognize the linkage between cause and effect. Because of this it is very important in which time period the phenomenon is explored. The research followed the last four years of the research problem, which is also the starting point of clustering initiatives in Slovenia. Leonard-Barton argues that a detailed longitudinal case-study research provides internal validity of the research [26]. The model developed through the research is based on data, gathered in the real business environment of production companies and other organisations in the cluster. The model is developed through research, and continuous interaction, analysis and data gathering. This research approach tries to reduce the gap between the developed model and business reality.

Three case studies have been selected (industrial clusters) that serve as a source for data gathering. The case studies were not selected randomly, but carefully selected from theoretical reasons. They were selected in such a way that they provide the best possibility to explore the subject of the research. The most important is the Automotive Cluster of Slovenia, which is the most detailed case study. The other two case studies are the Automotive cluster of Styria and the Toolmakers Cluster of Slovenia.

The unit of analysis is the process of manufacturing-capability development. This process is characterised by complexity, bad structure, idiosyncrasy and path-dependency. It is also firm-specific, and for this reason the exploring on a cluster level is more complex because the process represents the bundle of specific capabilities.

The applied case-study methodology is a very appropriate tool to deal with the complexity of a studied process.

Interviews, business documentation and observations were all methods for gathering the necessary data for the research. Interviews with key people in the organisation lasted for 1.5 hours, on average. All the interviews were recorded. Besides interviews, business documentation and archival documents were also used as a source of data. The use of different sources enhanced the internal validity of the research. For the research, all the business documents that led to an understanding of business reality were important, as were those which supported the data obtained during interviews, eipodatke, pridobljene z razgovori. Kolikostni podatki so predvsem tisti, ki lahko z meritvami dokažejo, da so razpoznane zmogljivosti res tiste, na katerih temelji konkurenčna prednost podjetja, in prikazujejo dinamiko razvoja zmogljivosti v proučevanem obdobju. V raziskavi so se kot viri uporabljali opisi in rezultati projektov, notranji časopisi, časopisni članki in drugi pomembni poslovni dokumenti. Analiziranje informacij pomeni bistvo raziskovalnega postopka induktivnega oblikovanja teorije. Ne gre samo za najtežji del raziskave, ampak tudi za njen najbolj ustvarjalen del. Ključni problem pri analizi podatkov je spopad z veliko količino podatkov. Analiza znotraj študije lahko pomaga pri tej poplavi podatkov. Naš namen je, da dobro razumemo vsak primer kot samostojno enoto.

Preden predstavimo rezultate raziskave, si nekoliko poglejmo Slovenski avtomobilski grozd.

Zgodba Slovenskega avtomobilskega grozda se je začela odvijati leta 2000, ko je Ministrstvo za gospodarstvo objavilo prvi razpis za izbiro pilotskih projektov za razvoj grozdov v Sloveniji, pri čemer je šlo za enega izmed ukrepov politike podjetništva in konkurenčnosti. Avtomobilski grozd je bil eden izmed treh pilotskih projektov, ki so bili med šestimi prijavljenimi predlogi izbrani na razpisu. Nosilno podjetje, ki je sklenilo pogodbeno razmerje z Ministrstvom za gospodarstvo, je bil poslovni sistem CIMOS. Na razpisu je podjetje s partnerji opravilo obsežna usklajevanja o prednostnih projektih za razvoj zahtevnejših izdelkov in infrastrukture ter obravnavalo formalnopravne in organizacijske rešitve. SAG je tako gospodarsko interesno združenje mehanske in kovinske industrije, električne in elektronske, kemijske, tekstilne in industrije transportnih sredstev ter razvojno-raziskovalnih organizacij in drugih storitvenih podjetij v dobaviteljski verigi, ki ustvarjajo in prodajajo izdelke in storitve za avtomobilsko industrijo. Na začetku je bilo v projekt vključenih devet podjetij in tri razvojne raziskovalne organizacije. Prva srečanja so potekala v duhu oblikovanja strategije ter poslanstva grozda, pri čemer so glede analiz zunanjega in notranjega okolja definirali tudi svojo vizijo: *slovenski avtomobilski grozd bo s svojimi člani postal razvojno intenzivna in zanesljiva mreža dobaviteljev za globalne proizvajalce vozil na izbranih segmentih, z izdelki višje stopnje sestavljenosti in dodane vrednosti.*

Danes članstvo Slovenskega avtomobilskega grozda sestavlja 43 industrijskih družb in 7 raziskovalno-razvojnih organizacij, od tega dva

ther qualitatively or quantitatively. Quantitative data are those which can measurably prove that the identified capabilities are the basis for the competitive advantage of companies, and they indicate the dynamics of the capability development in a specific time period. As quantitative data sources we used different descriptions and project results, internal articles and other important business documents. Data analysing presents the essence of the research process for inductive theory building. It is not only the largest part of the research, but also the most creative part. The key problem with data analysing is the conflict with the vast amount of data. The analysis inside the study can help to deal with overflow of data. Its goal is that we understand a single case as an autonomous entity.

Before introducing the research results, we have to describe some basic data about the Automotive Cluster of Slovenia.

The story about GIZ ACS began in 2000, when the Ministry of the Economy announced the first call for pilot projects cluster development in Slovenia. This was one of the measures for promoting entrepreneurship and increasing competitiveness. The Automotive cluster of Slovenia was one of the three pilot projects that was selected from among six registered initiatives. The leading company, which signed the contract with the Ministry of the Economy, was the CIMOS Group. This company made extensive adjustments with its partners about preferential projects for the development of more complex products and infrastructure. They also discussed the formal legal and organisational solutions. GIZ ACS is the Business Interest Association of the mechanical and metal industry, the electric and electronic industry, the chemical industry, the textile industry and the industry of transportation, R&D institutions and other service providers in the supply chain, which produces and sells the products for the automotive industry. At first, nine companies and three R&D institutions were affiliated to the cluster. The first meetings were about defining the strategy and the mission of the cluster, and they also defined the cluster vision: *The Automotive Cluster of Slovenia will become the research and development, intensive and reliable supplier network for global automotive manufacturers on selected segments, providing products with higher added value and complexity.*

There are 43 members in the ACS today from industry and 7 members from different R&D institusamostojna inštituta in pet fakultet. Svojo prihodnost vidijo v razvoju ključnih zmogljivosti grozda, v močnem podpornem okolju in v zanesljivih nosilcih razvoja grozda. Prav tako lahko prve uspehe vrednotijo tudi v številkah. Celotna slovenska avtomobilska dobaviteljska industrija je v letu 2003 izdelala za okrog 950 milijonov evrov sestavnih delov in komponent. Pri tem je izvozila za okrog 800 milijonov evrov, kar je blizu 7,5 % slovenskega izvoza blaga. V letu 2004 pa so samo člani SAG, ki imajo skupno 16.500 zaposlenih (50 članov grozda), ustvarili prihodke v vrednosti 1,5 milijarde evrov. V povprečju tako izvozijo 80 % svoje proizvodnje. Ustvarjena dodana vrednost na zaposlenega je nad povprečjem predelovalnih dejavnosti in znaša 25.600 evrov [27]. Njihovi kupci so proizvajalci vozil in sistemski dobavitelji v EU (Nemčija 40 %, Francija 21 %, Italija 8 %, Avstrija 6 %, Anglija 6 %, ZDA 4 %, Španija 3 % itn.).

4 REZULTATI IN RAZPRAVA

Raziskava je postregla z zanimivimi rezultati, pri čemer lahko postopek razvoja proizvodnih zmogljivosti opišemo s posameznimi stopnjami.

1. stopnja: zmogljivosti, specifične za podjetja

To stopnjo razvoja zmogljivosti, za katero lahko rečemo, da se ujema s samimi začetki ustanavljanja Slovenskega avtomobilskega grozda, zaznamujejo intenzivno spoznavanje podjetij med seboj, razhajanja v razumevanju postopka grozdenja, pomanjkanje izkušenj pri povezovanju ter naravnanost podjetij v lastne interese. Zastopnik podjetja, vključenega v SAG, pove:

Ko smo se lotili projekta, v bistvu sploh nismo vedeli, v kaj se spuščamo. Na prvih sestankih koordinatorjev smo se spoznavali, opazno je bilo nezaupanje, spraševali smo se, kaj bomo sploh delali, zakaj smo sploh tukaj. Zastavili smo si nekaj začetnih skupnih projektov, poleg skupnega informacijskega sistema še skupne dobaviteljske verige, skupno trženje, skupne razvojno-raziskovalne projekte itn. Srečevali smo se enkrat do dvakrat na mesec. Na začetku je bilo očitno, da je bilo vsako podjetje na svoji strani, bili smo zadržani, saj se v bistvu sploh nismo poznali.

To pojasnilo potrjuje ugotovitev, da prva stopnja v razvoju zmogljivosti pomeni zelo konfliktno izkušnjo na samem začetku ustanavljanja grozda. Na eni strani imamo projekt ustanavljanja pilotskih grozdov,

tions: 2 R&D institutes and 5 faculties. They see the future in the development of key capabilities, in a supportive environment and in the reliable drivers of the cluster development. They can already measure the first success with numbers. In 2003 the Slovenian automotive-supplier industry produced components in a total amount of approximately 950 million euros. Exports accounted for about 800 million euros, which represents almost 7.5% of the total Slovenian exports of goods. In 2004 the members of the ACS, which have 16,500 employees (50 cluster members), generated revenues to the value of 1.5 billion euros. They export, on average, 80% of their production. The added value per employee is higher than the average of the manufacturing branch, and it amounts to 25,600 euros. They sell mostly to producers and system suppliers from the European Union (Germany 40%, France 21%, Italy 8%, Austria 6%, Great Britain 6%, USA 4%, Spain 3%, etc.).

4 RESULTS AND DISCUSSION

This research has produced some very interesting results. The main point is that the process of capability development can be described in several stages.

1st stage: Firm-specific capabilities

This capability-development stage coincides with the beginning of the ACS. The main characteristics of this stage are the first contacts between companies who are getting to know each other, the differences in understanding the clustering process, the lack of experience in establishing linkages, and the focus on the company's own interest. A representative of one of the ACS companies acknowledges:

When we joined the project, we did not know what we were getting into. At the first coordinators' meeting we got to know each other, there was a lot of mistrust, we were wondering what we were doing here. We decided to work on some joint projects – information system, joint supply chain, joint marketing, joint research and development projects, etc. Since then we have met once or twice a month. It was obvious from the beginning that each company looks after itself; we were keeping back because we did not know each other.

This statement points out the first finding, that this capability-development stage represents a very conflicting experience at the beginning of the cluster formation. On the one side we have a cluster-formation pilot project that is a very sensitive process, and on the other ki je zelo občutljiv, po drugi strani pa imamo podjetja, ki s tovrstnim delom v večini primerov nimajo nobenih izkušenj. Rečemo lahko, da je pomanjkanje določenih zmogljivosti zelo otežilo začetno izvajanje zastavljenih projektov, saj so ustvarjalci največ časa porabili za usklajevanje, ne pa za plodno delovanje. Vse dejansko kaže na to, da so bila podjetja na začetku daleč narazen, saj gre za zmogljivosti, s katerimi podjetja vstopajo v grozd ter so specifične za vsako posamezno podjetje. Te zmogljivosti so podjetja razvila kot avtonomne poslovne enote v nekem svojem okolju in niso povezane s postopkom grozdenja. Specifičnost teh zmogljivosti pa se potrjuje na več področjih. Če že pogledamo različnost razvojnih in proizvodnih programov, vidimo, da gre za podjetja z zelo različnim tehnološkim znanjem, različnimi kupci in zato tudi različnimi pričakovanji.

AET Tolmin razvija svečke, Agis Plus sedeže, Cimos je uspešen na področju izdelovanja pedalnih sklopov itn. Skupna jim je le usmerjenost na avtomobilski trg.

Rečemo lahko, da se člani SAG med seboj razlikujejo po tržnih položajih pri kupcih, po obvladovanju določenih proizvodnih programov in tehnologij, po razvojnih zmožnostih in po strategijah. Zelo različna pa je tudi stopnja razvitosti določenih zmogljivosti, ta so rezultat vlog, ki jih imajo podjetja v dobaviteljski verigi. Na primer, nekatera podjetja so že razvojni dobavitelji, druga pa samo dobavljajo različne sestavne dele. Zaradi tega podjetja razvijajo ne samo različne vrste zmogljivosti, ampak je očitna tudi razlika v njihovi stopnji razvitosti. Vso to različnost pa so podjetja v grozdu morala usmeriti v uresničevanje skupnih ciljev, če so želela slediti zastavljenemu videnju, z drugimi besedami, skupni cilji so podjetja začeli siliti v razvoj novih zmogljivosti. Podjetja so spoznala, da jih čaka še veliko dela predvsem na področjih, na katerih imajo iz preteklosti najmanj izkušenj. Podjetja so se morala začeti učiti delati skupaj, za skupne cilje, naučiti so se morala prepoznavati dejanske priložnosti, ki se jim z grozdenjem ponujajo. Z razvojem teh zmogljivosti so podjetja dejansko sprožila postopek, ki pripelje do uresničevanja zastavljene vizije ter do naslednje stopnje razvoja zmogljivosti, ki preide s stopnje zmogljivosti, specifičnih za posamezna podjetja, na stopnjo zmogljivosti izrabe virov.

2. stopnja: zmogljivosti izrabljanja virov grozda

Postopek razvoja zmogljivosti pride do stopnje, ko lahko že prepoznamo zmogljivosti, da

side we have companies that have no experiences with this process. We can assume that the lack of specific capabilities has made the initial implementation of the project extremely hard, since most of the time has to be spent on reconciliation and not for constructive action. It all points to the fact that the companies were far apart at the beginning. The reason is that the capabilities that the companies brought into the cluster are firm-specific. The companies have developed these capabilities as autonomous business entities in their own business environment and they are not in any relation with the clustering process. The specificity of these capabilities is evident in many areas. If we take a look at the differences in the development and production programmes of the companies, we find that these are companies with very different knowledge levels, different buyers and different business expectations.

AET Tolmin produces spark plugs, Agis Plus makes seats, Cimos is successful in the field of pedal systems, etc. Their common point is a focus on the automotive market.

The ACS companies differ in their market positions with buyers, in managing their production programmes and technologies, in development potentials, and in their strategies. But they also differ in their level of specific-capabilities development. This is a result of the different roles that the companies play in the supply chain. Some companies are, for example, system suppliers; others are just delivering different components. This is why the companies develop different types of capabilities and why these are developed on different levels. But all these differences had to be directed towards the implementation of common cluster goals, especially if the companies wanted to follow their cluster vision. To put it in different words: common goals force companies into the development of new capabilities. The companies have realised that there is a lot of work to be done, particularly in the fields where they have very little or no experience at all. The companies had to find a way to work together to achieve common goals. They also have to learn how to recognise opportunities that the clustering process offers to everyone. With the development of these capabilities the companies have launched a process that leads towards the realisation of the cluster vision and to the next stage in capabilities development – the stage of capabilities for using cluster resources.

2nd stage – capabilities for using cluster resources

The capabilities-development process comes to the point where we can observe the capabilities podjetja znajo izrabljati vire, ki jih grozd ponuja. Da so podjetja prešla v to stopnjo, je bil potreben postopek, na katerega ni vplivala toliko strokovnost posameznih podjetij, ampak so podjetja dejansko morala začeti misliti drugače, širše. To je bil odločilen preskok, da so lahko sledili zastavljeni strategiji. Podjetja so naj tej stopnji spoznala, da je za kakršen koli rezultat potrebna dejavnost vseh tistih podjetij, ki v določenih projektih vidijo svoje interese. Na tej stopnji razvoja zmogljivosti pa poleg samega interesa po izrabi virov drugih podjetij, prihaja tudi do vse večjega pomena samih pomanjkljivosti grozdenja in tudi problemov, ki se pojavljajo. Na tej stopnji razvoja grozda se namreč podjetja še zmeraj spoznavajo in iščejo medsebojno dopolnjevanje. Dejansko gre za postopek razvoja zmogljivosti, ki pripelje do tega, da začnejo podjetja prepoznavati nove priložnosti ter premostijo začetne zadržke, ki dejansko izvirajo iz nepoznavanja in neizkušenosti na področju medpodjetniškega povezovanja.

A očitno je podjetjem v triletnem delovanju v grozdu dejansko uspelo preseči začetne ovire ter vzpostaviti določeno enotno raven razumevanja delovanja grozda, saj se v konkretnem delu že kažejo prvi učinki skupnega dela. V prvi številki glasila SAG Novice, lahko na primer naštejemo trinajst skupnih projektov na ravni grozda, ki so bili že izvedeni ali se še izvajajo, šest prepoznanih mogočih projektov in en izveden projekt na področju deficitarnih tehnologij ter še trije mogoči projekti na področju tehnologij. V tej fazi so se torej člani grozda lotili določenih skupnih projektov, od katerih so lahko imeli vsi koristi: projekti vzpostavitve skupnih informacijskih sistemov, projekti vzpostavitve skupne baze podatkov, projekti skupnih tržnih nastopov in promocije, projekti upravljanja dobaviteljskih verig, projekti skupne nabave, projekti popisa in izmenjave kapacitet, projekti izobraževanja in usposabljanja (projektne šole, seminarji) in prvi skupni raziskovalno-razvojni projekti.

Hkrati pa določena podjetja zaradi svoje dejavnosti ter učinkovitega izrabljanja virov in zmogljivosti drugih članic že opažajo dvig inovativnosti v lastnih podjetjih. Zastopnik podjetja, vključenega v SAG, pove:

V našo tehnologijo smo prenesli znanje drugega podjetja in s tem dejansko kupcu ponudili izdelek, ki vsebuje znanje in izkušnje, ki niso bili v celoti razviti v našem podjetju. Osebno menim, da lahko samo v tem projektu pride do štirih ali petih patentov, ki jih še bomo prijavili oziroma so že v fazi prijavljanja. En patent bomo prijavili skupaj z

that enable companies to use cluster resources. In order for companies to achieve this stage a new process took place; this process was not about their expertise knowledge, they had to change their standard way of thinking and start thinking more broadly. This was a decisive turning point in the upcoming common strategies. The companies have realised that to achieve results the active cooperation of all the players that have an interest in specific projects is necessary. At this stage the companies have also become more and more aware of the cluster weaknesses and the problems that might occur. This is still a stage where companies are getting to know each other and where they try to find synergies. A new capabilities-development process is taking place that leads towards a stage where companies start to recognise new opportunities and where they can overcome the initial holding back that originates in ignorance and inexperience in the field of companies cooperation and linkages.

After working together for three years the ACS companies have actually overcome the initial obstacles and have established a specific common level of cluster-activities understanding. The first results can already be recognised. In the first ACS newsletter we can find thirteen common projects on the cluster level that have already been implemented or are being implemented at the moment, as well as six potential projects, one implemented project in the field of deficit technologies and three other potential technology projects. At this stage the cluster members have started to cooperate in many projects that were beneficial for all of them: a joint information system project, a joint database project, joint marketing and cluster promotion projects, supply-chain management projects, joint purchase projects, capacity exchange projects, education and training projects (project schools, seminars) and the first joint research-and-development projects.

At the same time some companies, because of their active role and the effective use of the resources and capabilities of the other cluster members, can observe the growth of innovative activities in their companies. A representative of one ACS company describes a situation in his company:

We have transferred knowledge from another ACS company into our technology, and now we can offer our buyers a new product that includes knowledge and experiences that were not entirely developed within our company. I think that we can come up with four or five patents within this project *našim kupcem, kar pomeni, da je zadeva dobra, resna in pomembna tudi zanj.*

Opisani primer in še mnogo drugih, pridobljenih v raziskavi, potrjujejo dejstvo, da so podjetja, ki so v grozdu dejavna, napredovala v razvoju tistih zmogljivosti, ki bodo podjetjem skupaj omogočile slediti zastavljenim načrtom Slovenskega avtomobilskega grozda. Prišli so do stopnje, pri kateri vzajemno učenje že kaže pozitivne rezultate ter do stopnje, pri kateri so postala podjetja samozavestnejša tako v razmerju do članic grozda kakor tudi v razmerju do svojih kupcev. Vendar pot še zdaleč ni končana. S stopnjo so samo zgradili temelje za razvoj strateške istovetnost grozda.

Po predpostavki dinamika razvoja zmogljivosti pripelje do prepoznavanja zmogljivosti grozda. Njena značilnost je, da ni omejena na eno podjetje. Zmogljivost grozda moramo opazovati s perspektive grozda in pomeni, da podjetja kolektivno izvajajo opravila in ustvarjajo nova znanja, ki jih širijo po celotnem grozdu, tako da imajo skupno korist vsi partnerji v grozdu. Vendar zmogljivosti grozda kot strateške istovetnosti grozda v primeru SAG še ne moremo prepoznati. Vemo, da se zmogljivosti razvijajo v razvojnem postopku [28]. Slovenski avtomobilski grozd pa je še sorazmerno mlad grozd; okolje, v katerem deluje, še ni popolnoma pripravljeno na tovrstno delovanje, podjetja sama so sicer že sposobna kolektivno delovati, vendar se še zmeraj vse pridobljeno znanje ne širi po celotnem grozdu. Še zmeraj je uspeh grozda v veliki meri odvisen od dejavnosti podjetij po eni strani, po drugi strani pa je v grozdu še zmeraj veliko nedejavnih članov. Poleg tega pa še manjkajo izkušnje predvsem pri koordiniranju projektnega dela, saj se podjetja znotraj projektov še zmeraj težko organizirajo. Prav nasprotno pa lahko trdimo za primer AC Styria, kjer pa skozi raziskavo zmogljivost grozda prepoznamo.

5 SKLEPI

Na začetku prispevka smo oblikovali tri predpostavke. Ena izmed njih pravi, da lahko zmogljivosti razvrstimo glede na perspektivo, s katere opazujemo industrijski grozd, in koristi, ki jih imajo vključena podjetja, kar prikazuje slika 1.

Na prvo stopnjo v razvoju zmogljivosti gledamo s čiste perspektive podjetja, saj tovrstne zmogljivosti še nimajo nobene povezave z grozdenjem in so bile razvite za potrebe posameznega podjetja.

that we are going to register. One patent will be registered together with our buyer, and that means that the project is of great importance also for him.

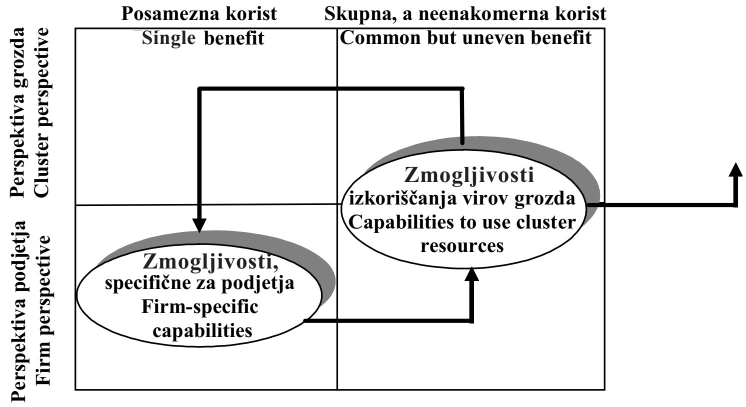
The described example and many others that we came across in our research confirm the fact that the active cluster companies have made progress in the development of those capabilities that will enable companies to follow the ACS vision. They have come to the point where mutual learning gives positive results, and to the point where the companies have become more self-confident in their relationships with other cluster companies and their buyers. But the process is not finished yet. This stage only helps building the foundations for the development of a cluster-strategic identity.

We have assumed that the dynamics of cluster development leads to cluster capability. The main characteristic of cluster capability is that it is not limited to a single company. Cluster capability must be observed from the cluster perspective, where companies collectively perform operations and generate new knowledge that is spreading across the entire cluster in the way that every company gains some benefits. But the cluster capability as a strategic identity of the cluster cannot be recognised in the ACS yet. It is a fact that capabilities are developed in an evolutionary process [28]. The ACS is a young cluster and its environment is not yet fully prepared for all the cluster activities. The companies are capable of performing activities collectively, but generated knowledge is not spread across the cluster. Cluster success depends mainly on the active participation of some companies, since on the other hand there are many inactive cluster companies. There is also a lack of experience in coordinating project work. Companies have difficulties organising common projects. The opposite situation was observed in the AC Styria cluster, where the cluster capability can be identified.

5 CONCLUSIONS

At the beginning of our paper we proposed three assumptions. One of them states that the capabilities can be classified according to the perspective the cluster is viewed from and the benefits that cluster companies can gain (Figure 1).

The first stage corresponds to the company perspective, since these capabilities are not related to the clustering process and they have been developed for the needs of individual companies.



Sl.1. *Postopek razvoja proizvodnih zmogljivosti glede na perspektivo in koristi*
Fig. 1. *Process of manufacturing-capability development regarding perspective and benefit*

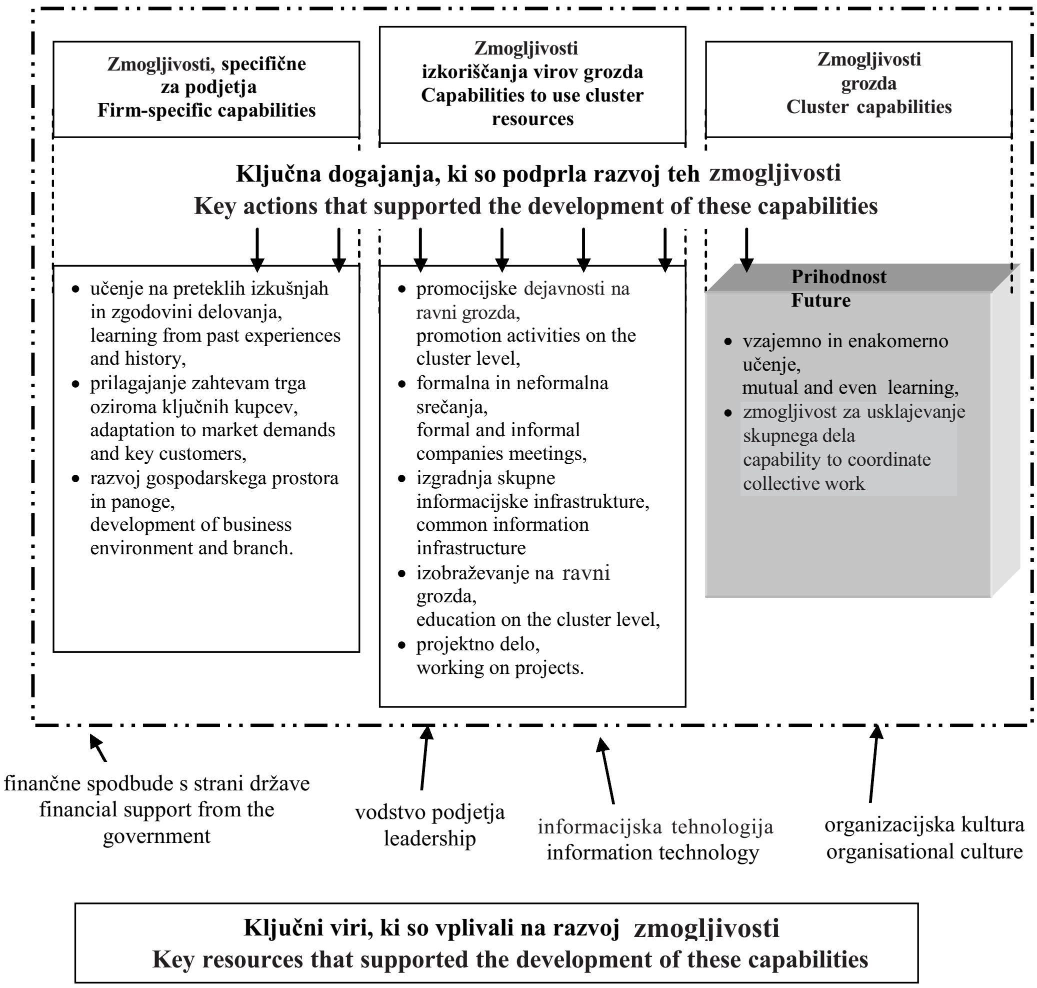
Podobno lahko trdimo tudi glede koristi, saj na tej stopnji opazimo samo posamezne koristi, pri čemer izvirajo samo iz dejavnosti, ki z grozdenjem niso povezane. Ko razpravljamo o zmogljivostih izrabljanja virov grozda, še zmeraj prevladuje perspektiva, ki je sicer osredotočena na individualno podjetje, vendar v določeni meri že gledamo nanje s perspektive grozda, saj prihaja na tej stopnji že do delovanja na ravni grozda. Pri tem lahko govorimo že o nekih skupnih koristih, saj se skozi projekte in skupno delo ustvarja novo znanje, od katerega imajo lahko koristi tudi druga podjetja, ki pa zaradi različne intenzivnosti učenja niso enakomerno razporejene med vse partnerje. Zaradi tega ima podjetje, ki uporablja partnerjeve zmogljivosti in vire, po eni strani lahko več koristi kot partner, ki jih ima, po drugi strani pa zna določeno podjetje zaradi svojih zmogljivosti vire tudi hitreje prepoznati in izkoristiti.

Veliko je dogajanj, ki so na različne načine vplivala na sam razvoj zmogljivosti. Grafično smo predstavili samo tista, ki so se med študijo primerov izkazali kot najočitnejša. Če pogledamo ključna dogajanja za posamezno stopnjo v razvoju zmogljivosti SAG, vidimo, da je prva razvojna stopnja povezana z različnimi dogajanji v podjetjih še pred samim začetkom grozdenja. Omenjena dogajanja posredno ali neposredno ter pomembno ali manj pomembno sooblikujejo strateško istovetnost posameznega podjetja, ki pa za podjetja po vstopu v grozd pomeni pomembno odskočno desko. Povedano drugače, zmogljivosti, razvite na ravni posameznega podjetja še pred vstopom v grozd, pomenijo bistveno izhodišče za nadaljnje uveljavljanje posameznega podjetja v grozdu. Po vstopu podjetij v grozd, v neko novo obliko organizacije in dela, pa podjetja, zavedno ali nezavedno, sprožijo določena dogajanja z željo po hitrejšem

The situation with benefits is very similar. At this stage we can observe specific benefits that arise from activities that are also not related to the cluster. When we deal with the capabilities for using cluster resources, the single-point perspective is still the dominant one, but we are already looking from the cluster perspective, since the companies are already cooperating on the cluster level. We can speak about common benefits, since new knowledge is being generated through joint projects. This knowledge can also be beneficial for other cluster companies, but because of a different learning intensity it is not equally spread among all the partners. This is why a company that uses partners' capabilities and resources gains more benefits than the partner that actually possesses those capabilities and resources. At the same time this company has, because of its capabilities, the ability to recognise and use resources.

Many actions took place in previous years with a different effect on capability development. Figure 2 depicts the most obvious ones. If we take a look at the key actions for each stage in the ACS capability-development process, we can state that the first stage corresponds to actions that took place in companies before the clustering process. These actions directly or indirectly and with more or less impact co-form the strategic identity of a specific company. This strategic identity represents a good basis to join the cluster. The capabilities, developed within the specific company before joining the cluster, represent a fundamental starting point for the future establishment of the company in the cluster. After joining the cluster as a new organisational form, companies intentionally or unintentionally trigger prilagajanju novim razmeram. Tako so dogajanja, kakor so promocijske dejavnosti na ravni grozda, formalna in neformalna srečanja, gradnja skupnega informacijskega sistema, skupno izobraževanje ter konkretno delo na skupnih projektih, dejansko spodbudila postopek nekega skupnega učenja, ki omogoča podjetjem lažje prilagajanje ter s tem vzpostavitev tistih razmer, ki bodo zmanjševale razlike med podjetji, ki so posledica različnih *vstopnih* izkušenj. Povedano drugače, omenjena dogajanja so pomembno vplivala na razvoj zmogljivosti, ki podjetjem omogočijo izrabljati vire grozda. Ker pa v SAG še ne prepoznamo zmogljivosti grozda, lahko na podlagi rezultatov raziskave samo predvidevamo, katera dejanja bodo pomembneje vplivala na razvoj teh zmogljivosti. Skozi raziskavo pa lahko poleg ključnih dejanj, ki so značilna za vsako stopnjo razvoja zmogljivosti posebej,

specific actions to adapt to the new circumstances as soon as possible. Actions, such as the promotional cluster activities, formal and informal meetings, a joint information system, joint education and joint projects have actually stimulated the joint learning process. This learning process allows companies to adapt to the cluster easily and to establish circumstances that reduce the differences between companies that are the result of different *incoming* experiences. These actions have a significant impact on the development of those capabilities that enable the use of resources. Since in the case of the ACS we cannot recognise a cluster capability we can only assume which actions will have an impact on the development of these capabilities. Besides the key actions typical for each capability-development stage, we can also recognise key resources



Sl. 2. *Model razvoja proizvodnih zmogljivosti podprt s ključnimi dejanji in ključnimi viri*
Fig. 2. *Model for manufacturing-capability development supported by key actions and key resources*

prepoznamo tudi ključne vire, ki so pomembno podprli sam postopek razvoja zmogljivosti. Tako naslednja slika prikazuje razvoj proizvodnih zmogljivosti, podprt s ključnimi dogajanji ter ključnimi viri – primer SAG.

Predstavljeni prispevek tako opisuje model razvoja proizvodnih zmogljivosti v industrijskih grozdih, ki je nastal kot rezultat triletne raziskave, izvedene v podjetjih in različnih organizacijah, članov treh industrijskih grozdov. Model ne narekuje obnašanja podjetij, ampak je deskriptiven in opisuje predmet raziskovanja v dejanskem okolju. Opisuje pojav, ki je navzoč tako v podjetju kakor na ravni grozda. Zaradi tega smo želeli z razvitim modelom zagotoviti primerno okolje za nadaljnje opazovanje tega pojava tako menedžerjev kakor raziskovalcev, hkrati pa je model predstavlja tudi ustrezno izhodišče za menedžerje, ki vidijo priložnosti v industrijskih grozdih.

Raziskava je kakovostne narave, zato je razviti model primerno izhodišče za oblikovanje kolikostne metodologije, s katero lahko podjetja ugotovijo stopnjo razvitosti svojih proizvodnih zmogljivosti in s katero lahko učinkoviteje prepoznavajo priložnosti za izrabljanje virov, ki jih ponuja industrijski grozd. Razviti model podjetjem pomaga pri prepoznavi ključnih dejanj in virov, ki neposredno vplivajo na razvoj proizvodnih zmogljivosti, in rabi kot smernica za učinkovito integracijo v industrijski grozd.

that have supported the capability-development process. Figure 2 presents the manufacturing-capabilities development supported by the key actions and the key resources in the ACS.

This paper presents the manufacturing-capability development process in industrial clusters based on three years of research conducted in the companies and other organisations who are members of the industrial clusters. The model does not dictate the companies' behavioural pattern; it is descriptive and it describes the research object in its real environment. The model describes a phenomenon present in companies and in clusters. This is why our primary goal with the developed model was to ensure a suitable environment for further observations of this phenomenon from the managers' and researchers' point of view. At the same time the model represents an appropriate starting point for managers who can see the business opportunities in industrial clusters.

The research is qualitative; this is why the developed model is an appropriate starting point for designing a quantitative methodology that helps companies to identify the manufacturing-capabilities development level and to recognise opportunities for making use of resources, offered by the industrial cluster, more effectively. The developed model helps companies to identify key activities and resources that directly influence the manufacturing-capabilities development and serve as a guide for the effective integration of companies into an industrial cluster.

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6 LITERATURE

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Analiza in določanje lastnosti parametrov nadomestnega sistema vzvojnih nihanj, ki se pojavljajo tudi na dizelskih motorjih za pogon tovornih vozil

Modeling and the Analysis of Parameters in the Torsional-Oscillatory System Equivalent to the Diesel Engines in Heavy-Duty Vehicles

Ivan Filipović - Vlatko Doleček - Dževad Bibić

V prispevku je opisan postopek modeliranja parametrov sistema vzvojnih nihanj na sistemu, ki je podoben dejanskemu sistemu na večvaljnem, vrstnem, vodno hlajenem dizelskem motorju, ki poganja tovorna vozila. Na temelju rezultatov lastnih raziskav in rezultatov drugih avtorjev so predstavljeni modeli in algoritmi za določitev masnih vztrajnostnih momentov nihajočih mas, togosti delov ročične gredi, zunanjega in notranjega dušenja v sistemu vzvojnih nihanj, ki ga povzročajo plinske in vztrajnostne sile. Nekoliko več pozornosti je namenjeno določitvi karakteristik viskoelastičnega jedra ustreznega dušilnika vzvojnih nihanj, ki je pritrjen na ročično gred motorja. Nadomestni sistem in izračun vzvojnih nihanj je modeliran z izvirnim računalniškim programom. Podan je primer izračuna vzvojnih amplitud na posameznih delih motorja s prigrajenim dušilnikom vzvojnih nihanj in brez njega. Računski rezultati so primerjani z rezultati preizkusov na preizkuševališču za motorje. Podobnost rezultatov nas vodi k sklepu, da je predlagani postopek izračuna na nadomestnem modelu vzvojnih nihanj ustrezen za reševanje in analizo dejanskih problemov na tem področju.

(Ključne besede: motorji dizelski, vozila tovorna, nihanja vzvojna, modeli računski)

This paper describes the procedure for modeling and calculating the parameters of the torsional-oscillatory system equivalent to multi-cylinder, in-line, water-cooled diesel engines in heavy-duty vehicles. As a result of a literature search and our own investigation we present models and algorithms for defining the following parameters: the moments of inertia of oscillatory masses, the stiffnesses of engine-crankshaft segments, the external and internal damping in the torsional-oscillatory system, and the excitation of gas and inertia forces. Due to the specific characteristics of the viscoelastic element, somewhat more emphasis is placed on the viscoelastic damper of torsional oscillations in internal combustion engines. For the proposed equivalent torsional-oscillatory system, a suitable model and our own calculation program were developed. The analysis of the amplitude of twisting of individual system components in an actual engine, with and without a torsional-oscillations damper, is given. These results are compared to the experiments conducted on an engine test-bench. The agreement between the analytical and experimental results suggests that the proposed procedure for modeling and computing the parameters of the equivalent torsional-oscillatory systems can be successfully applied in practice.

(Keywords: diesel engine, heavy-duty vehicles, torsional oscillations, mathematical models)

0 INTRODUCTION

The internal combustion (IC) engine is a typical example of the occurrence of varying crankshaft torque during constant rotation speed. Varying crankshaft torque ($\mathcal{M}$) creates torsional oscillations around the state of the constant rotation speed, which in some cases presents the limiting factor in crankshaft modeling.

The IC engine system with crank gears and all other subsystems driven by the crankshaft, including the valve gear of the engine, the fuel-injection system, the oil pump, the alternator, etc., presents a highly complex system. The complexity of the system is manifested in the variable stiffness along the length of the crankshaft, in the need for different joints necessary to drive the subsystems (such as the indented joint, belt joint, hydrodynamic joints, etc.), in the hydrodynamic support of the crankshaft with extremely variable support conditions per single cycle, in the crank-gear variable mass moment of inertia ($\mathcal{J}$) under constant angular velocity (ω), and in the dependence of the lubrication requirements on the engine operation regime. We also need to consider the non-steady operational regimes as well as various applications of the engine, including vehicles, power units, locomotives, ships, etc.

We examine the complexity of the crank gear of an engine containing the crankshaft and all other auxiliary units. Due to its design, the type of connection with the engine housing, and the type of load, the crankshaft is, in addition to torsional oscillations, unquestionably exposed to bending and axial oscillations. Investigations by several authors, as well as practical experiments, demonstrate that the crankshaft bending and axial oscillations do not cause significant fatigue of the crankshaft material, and as such are not separately addressed when testing crankshaft endurance.

Torsional oscillations, whose intensity varies with changing working conditions of the engine, can cause material fatigue and crankshaft breakage. To prevent these oscillations, it is necessary to include all the relevant aspects of potential applications as well as the working conditions of the engine, and then decide whether there is a possibility of significant oscillations under these conditions and constraints, or not. A particular emphasis needs to be placed on the so-called marinized engines, which are in practice obligated for tests of excessive torsional oscillations.

Two approaches are used to understand the impact of torsional oscillations. They are based on:

a) the so-called equivalent systems with disc-shaped concentrated masses ([1] to [4]), or
b) the 3D model of the crankshaft and the application of certain complex numerical methods ([6] and [7]).

In order to effectively apply either of the methods, it is necessary to define the boundary operating values. Especially delicate issues in defining these values in 3D models are the hydrodynamic connections between the crankshaft and its environment, and the transfer of forces and moments under such conditions. For this reason, we chose to study torsional oscillations using the method of the so-called equivalent systems with concentrated masses in the form of discs. This approach to torsional oscillations is not only simpler, but it also leads to the development of the criteria for the risk assessment of torsional oscillations that are nowadays part of engineering practice. This approach to studying torsional oscillations is employed in diagnosing engine parameters [18] and [19], and is normally done by very fast contactless methods for measuring torsional oscillations [8].

In this paper we present an analysis of torsional oscillations using the so-called equivalent system of torsional oscillations. The proposed method includes, first, a definition of all the relevant system parameters for calculating oscillations, and then an experimental validation of the proposed model. In Section 1 we discuss the proposed model of a torsional-oscillatory system, and in Section 2 we describe the relevant parameters of the modeled system. The excitation of the system is presented in Section 3. The analysis is given in Section 4, and the conclusions are summarized in Section 5.

1 MODEL OF A TORSIONAL-OSCILLATORY SYSTEM

Using the model of concentrated masses in the form of discs, two approaches can be used to study the torsional oscillations of an engine crankshaft. They are the equivalent branched system [2], and the in-line equivalent system ([1] to [4]).

For the practical reasons presented in the Introduction, we chose to analyze the torsional oscillations in a so-called in-line equivalent torsional-oscillatory system. A model of a linear system with n degrees of freedom, along with the parameters defining the equivalent torsional-oscillatory system of IC engines, is shown in Figure 1. Since the reduced stiffness of the crankshaft component (c_i) (Figure 1) of the equivalent system must be the same as the stiffness present in the real system, it is calculated by equating the potential energies of real and equivalent systems.

The moments of inertia ($\mathcal{J}_i^*$) of the disc masses of the real and equivalent systems also need to be equal. They are calculated by equating the kinematic energies of the real and equivalent

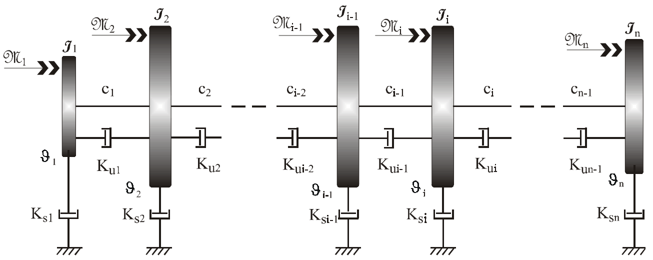

Fig. 1. *General scheme of an in-line equivalent oscillatory system*

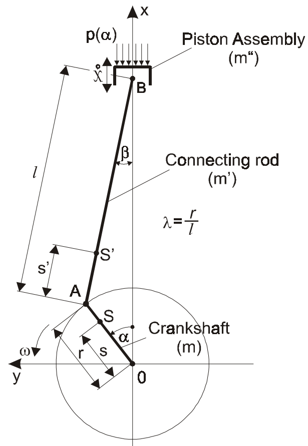

Fig. 2. *Crank gear with torsional-basic parameters*

systems. Other parts of the real system not located on the engine crankshaft axis (valve gear, injection system, water pump, etc.) are replaced with their counterparts on the equivalent system axis, based on equating the kinetic and potential energies of real and equivalent systems. An estimation of the moment of inertia of the crank gear, shown in Figure 2, is the most important aim for further calculation. The parameters of the equivalent torsional-oscillatory system, which include the excitation ($\mathfrak{M}_i$), and internal ($K_{u,i}$) and external ($K_{s,i}$) damping coefficients, are also determined on the basis of the parameters in the real engine.

A system of equations describing the movement of the discs is derived using Lagrange's equations of the second type. For an arbitrary i[th] disc in the system, the equation is:

$$\frac{d}{dt}\left(\frac{\partial E_{ki}}{\partial \overset{\circ}{\alpha}_i}\right)-\frac{\partial E_{ki}}{\partial \alpha_i}+\frac{\partial E_{pi}}{\partial \alpha_i}+\frac{\partial \Phi_i}{\partial \overset{\circ}{\alpha}_i}=\mathfrak{M}_{gi} \qquad (1),$$

where the kinetic energy of the i-th disc is $E_{ki}=1/2\mathcal{J}_i^*(\alpha_i)\dot{\alpha}_i^2$, the potential energy between the *i-1* and the *i*-th crankshaft component is $E_{pi}=1/2\cdot c_{i-1}(\alpha_i-\alpha_{i-1})^2+1/2\cdot c_i(\alpha_i-\alpha_{i+1})^2$, the reduced torsional stiffness per unit length of the crankshaft is c_i, the energy of the internal and external damping of the i^{th} disc is $\Phi_i=1/2\cdot[K_{u,i-1}(\dot{\alpha}_i-\dot{\alpha}_{i-1})^2+K_{u,i}(\dot{\alpha}_i-\dot{\alpha}_{i+1})^2+K_{s,i}\cdot\dot{\alpha}_i^2]$, the moment of the gas forces associated with the equivalent system axis for the i-th disc is $\mathfrak{M}_{gi}$, and the current angle of gyration of the i-th disc is α_i (expressed as $\alpha_i=\omega t+\vartheta_i$ where ωt is the current angle, and ϑ_i is the angle of torsional oscillations around a constant rotation speed).

The set of *n* equations given in (1) describes the movement of *n* discs of the torsional-oscillatory system. Based on these equations we can derive the basic indicators of torsional oscillations, which are the resonant oscillation modes, and the oscillation angles of individual discs (ϑ_i), i.e., amplitudes of disc oscillations (A_i).

The reduced stiffness (c_i) can be regarded as constant when determining the real values of system parameters of the torsional oscillations of the engine, whereas damping can be regarded as being linearly proportional to the relative oscillation velocity. The moments of inertia of the discs masses vary with the crankshaft rotation angle (*ωt)*. Using the above-mentioned assumption, and using the Taylor series expansion around (*ωt),* where we disregard higher terms, Equation (1) can be written as:

$$\mathcal{J}_i^*(\omega t)\cdot\ddot{\vartheta}_i+\omega\frac{d\mathcal{J}_i^*(\omega t)}{d(\omega t)}\cdot\dot{\vartheta}_i+\frac{1}{2}\cdot\omega^2\frac{d^2\mathcal{J}_i^*(\omega t)}{d(\omega t)^2}\vartheta_i+K_{s,i}\cdot\dot{\vartheta}_i+$$
$$+K_{u,i-1}(\dot{\vartheta}_i-\dot{\vartheta}_{i-1})+K_{u,i}(\dot{\vartheta}_i-\dot{\vartheta}_{i+1})+ \qquad (2).$$
$$+c_{i-1}(\vartheta_i-\vartheta_{i-1})+c_i(\vartheta_i-\vartheta_{i+1})=\mathfrak{M}_{g,i}^*(\omega t)-\omega^2\frac{d\mathcal{J}_i^*(\omega t)}{d(\omega t)}$$

Based on the results presented in [9], which demonstrate that the variability of the mass moment of inertia of the crank gears and the angles of oscillation in vehicle diesel engines have relatively small influence, we disregard the second and third terms on the left-hand side of (2), and the actual value of the moment of inertia ($\mathcal{J}_i^*$) we replaced with the mean value of the moment of inertia ($\mathcal{J}_i$). The last term on the right-hand side of (2) is actually the "excitation" of the inertia forces of the oscillating masses of the crankshaft rod.

Under these conditions, the equation has the following form:

$$\mathcal{J}_i \cdot \ddot{\vartheta}_i + K_{s,i} \cdot \dot{\vartheta}_i + K_{u,i-1}(\dot{\vartheta}_i - \dot{\vartheta}_{i-1}) + K_{u,i}(\dot{\vartheta}_i - \dot{\vartheta}_{i+1}) +$$
$$+c_{i-1}(\vartheta_i - \vartheta_{i-1}) + c_i(\vartheta_i - \vartheta_{i+1}) = \mathfrak{M}^*_{g,i}\left(\omega t\right) + \mathfrak{M}^*_{in,i}\left(\omega t\right) \quad (3).$$

Equation (3) presents the usual form of describing the oscillations of the i-th disc. The equation system (3) for *n* discs is a system of linear, non-homogenous differential equations of the second order. These equations are solved either by a numerical method for solving differential equations of the second order (e.g., a central differences method), where the solution is $\vartheta_i = f(\omega t)$, or by dividing the excitation into a group of harmonic functions, and thereby effectively transforming (3) into an ordinary algebraic equation, which defines the resonance modes of the system operations and amplitudes (A_{ij}) of the twisting angles for certain excitation orders (j).

By considering the arrangement of the vectors of the excitation moments for individual excitation orders (j) in multi-cylinder engines, the orders of the resulting moments can be viewed as either main, strong or weak. The "main" excitation orders of a 6-cylinder four-stroke engine are: j = 3; 6; 9; 12 and so on, the "strong" excitation orders are j = 4.5, 7.5, 10.5, and the remaining excitation orders are considered weak. Since engineering practice is concerned only with the main and strong orders, we only consider these when solving differential Equations (3). For example, the "interesting" excitation orders for 6-cylinder engines are only 4.5, 6, 7.5 and 9. Consequently, the number of algebraic equations to be solved is considerably reduced. For the correct analysis of the torsional oscillations, it is very important to define as precisely as possible the parameters of the torsional-oscillatory system, which are the moments of inertia of the discs ($\mathcal{J}_i$), the reduced torsional stiffness (c_i), the internal ($K_{u,i}$) and external ($K_{s,i}$) damping coefficients, as well as the excitation $\mathfrak{M}_i = \mathfrak{M}_{g,i} + \mathfrak{M}_{in,i}$..

We now continue with the discussion of the system parameters.

2 PARAMETERS OF THE TORSIONAL-OSCILLATORY SYSTEM

2.1 Mass Moments of Inertia

The first step in defining mass moments of inertia is the grouping of the individual subsystems and replacing the mass moments of inertia with their counterparts on the axis of rotation of the equivalent system. Certain engine elements have simple forms, thereby making the calculation of their mass moments of inertia easy. The most difficult form for a calculation of the moment of inertia is the crank gear shown in Figure 2, where all the construction characteristics of the mechanism are indicated. Using the principle of substitution of the connecting rod by two real masses (m_A) and (m_B), as a standard approach in engine dynamics, the moment of inertia of the crankshaft rod can be expressed as:

$$\mathcal{J}^*_i\left(\alpha_i\right) = \left[k^2 \cdot m + r^2\left(1 - \frac{s'}{l}\right) \cdot m'\right] + \quad (4).$$
$$+r^2\left(\frac{s'}{l} \cdot m' + m''\right) \cdot \left(\frac{\dot{x}}{r\omega}\right)^2 - \lambda^2\left(\frac{s'}{l - s'}\right) \cdot m' \cdot \left(\frac{\dot{\beta}}{\lambda\omega}\right)^2 r$$

The mean value of the moment of inertia of the crank gear is then computed as:

$$\mathcal{J}_i = k^2 \cdot m + r^2\left[\left(1 - \frac{s'}{2l}\right) \cdot m' + \frac{m''}{2}\right] \quad (5).$$

Expression (5) contains only one parameter, which is the crank-arm radius of inertia (k). This parameter is fairly difficult to determine due to the complex form of the crankshaft. Either experimental or analytical method can be used to determine it. The experimental method is based on the rolling pendulum principle, i.e., the torsional oscillator and "small" oscillations theory. The calculation method is based on a 3D model representing the crankshaft divided into a large number of finite elements, for each of which the expressions of the mass moment of inertia are known.

Both methods are acceptable and provide satisfactory results. Regarding the first method, where errors during measuring "small" oscillations can be accrued, and the fact that one crankshaft has to be destroyed, the second method has an advantage in practice.

2.2 Torsional Stiffness in a Component of the Equivalent System

Since the torsional stiffness (c) of a component of the equivalent torsional-oscillatory system has the most influence on the calculations of torsional oscillations, it is necessary to determine it precisely. An actual part in the torsional-oscillatory system, whether on the crankshaft rotational axis or on another axis, is converted into an equivalent part, based on equating the potential energies of the real and the equivalent part. When determining the stiffness, the cranks are the most sensitive part of the IC engine crankshaft oscillation system, due to their complex construction. The methods used for determining the engine crank stiffness can be either analytical, which range from using classical semi-empirical sources to finite-element methods, or experimental, or a combined analytical-experimental approach. We have used all three methods in our research and we adopt the combined analytical-experimental method as the most efficient one, especially taking into account the very advanced contactless torsional oscillations measurement methods available today [8].

2.3 Damping of Torsional Oscillations in a Crankshaft

The dampings are caused by the relative movement of adjoining elements and the molecules in the material. They can be either external (when caused by surrounding media such as air, oil, water, or an adjoining element), or internal (when caused by the friction between the molecules in the material resulting from the elastic deformations of the material).

The total external and internal dampings in the engine, usually presented under complex working conditions, are very difficult to determine in practice. Available literature on this topic is mostly concerned with addressing the total loss caused by damping, usually by using indirect methods such as the external drive method and the method of disconnecting cylinders of the engine. However, these methods do not address the real dynamic working conditions of the engine, and neither do they specifically address the dampings caused by torsional oscillations. Therefore, the results found in the bibliography need to be treated with caution. Considering the aforementioned, it is obvious that the damping caused by torsional oscillations around the state of constant rotation speed is even more complex. We now present a new way to define the external and internal damping in IC engines, and we compare it to the existing literature.

2.3.1 External Damping as a Result of Torsional Oscillations

The most important locations in which external dampings in the crank gear of an IC engine occur are the piston assembly, the link between the piston and the connecting rod, and the crank pin and crank journal bearings. By considering the working conditions in these locations, including the mechanical and thermal loads, the manner of lubrication and oil quality, the tolerance, and so on, it becomes clear that the external damping caused by torsional oscillations cannot be measured by any direct methods. It is, however, possible to use the so-called indirect experimental-calculation methods. Unfortunately, these are fairly complex, and any error made can result in utterly incorrect values of the external damping coefficients. Most of the bibliographical sources express the external damping coefficient (K_s) through the specific external damping coefficient (μ_s) per piston surface area ($D_k^2 \pi/4$) and per squared crank diameter (r^2).

The coefficient (μ_s) and/or the coefficient (K_s) are given in the bibliographical sources as follows:

- $\mu_s = (4 \text{ to } 5)\ \ 10^4\ Ns/(m^3 rad)$, for larger diesel engines ([3] to [5]),
- $\mu_s = 10^5\ \ Ns/(m^3 rad)$, for diesel engines with dampers of torsional oscillations,
- $\mu_s = 1.5\ \ 10^5\ Ns/(m^3 rad)$, for diesel engines without dampers of torsional oscillations [3],
- $K_s = 0.7 \text{ to } 1.3\ \ Nms/rad$, for mono-cylinder diesel engines [13],
- $K_s = 600\ Nms/rad$, for ship diesel engines, low-speed engines [20], etc.

This data suggests that there is a discordance in the treatment of external damping coefficients in various engines. Some of the mentioned bibliographical sources include the total damping (both external and internal) in the coefficient, and some sources differentiate between engines with and without dampers of torsional oscillations.

By examining our own experimental results for torsional oscillations in 6-cylinder, in-line, water-cooled diesel engines for transport vehicles, with powers between 140 kW and 190 kW, and indirect calculation methods, we estimated the following range for the external damping coefficient for our research: $\mu_s = 1.45 \cdot 10^5 \text{ to } 1.75 \cdot 10^5\ Ns/(m^3 rad)$.

2.3.2 Internal Damping in the Material as a Result of Torsional Oscillations

When analyzing the internal damping in the material caused by elastic deformation due to

torsional oscillations, some researchers disregard this damping because of the small amount of resulting deformation, or compensate its influence by increasing the outer damping values. In such cases researchers only address more prominent damping, such as in oscillation dampers, couplings, propeller shafts, etc. Another approach is to observe the internal damping in all the elements, regardless of its intensity. This principle has been used in this paper as well. When determining internal damping caused by torsional oscillations, two approaches are generally adopted:
- A model with constitutional equations of continuum mechanics, and the knowledge of the physical and chemical characteristics of the materials,
- A practical semi-empirical model, which can be found in the existing literature.

On account of the complicated and costly experiments needed to determine the physical and chemical characteristics of the materials for different temperatures and load conditions, as well as a highly complicated equation system, we adopt the latter method for determining the internal damping (K_u).

One of the most common approaches in defining internal damping is to use the damping ratio (ψ), defined as the ratio of the dissipation energy caused by internal friction per oscillation cycle (W_d) and potential energy (W_p), as $\psi = W_d / W_p$. Under the assumption that the hysteresis loop, which accompanies internal friction, can be approximated by an ellipsoid (which can be accepted as satisfactory if the oscillations in question are harmonic), the internal damping coefficient can be expressed as:

$$K_u = \frac{c \cdot \psi}{2 \cdot \pi \cdot \omega}. \qquad (6).$$

Several authors have dealt with the issue of internal damping in materials in IC engines as a function of its cause. For example, the crankshaft material ([1] and [3]), the viscous damper [3], the viscoelastic damper ([1], [3], [10] and [12]), and the combined viscoelastic-viscous damper [7], are all considered as significant sources of internal damping.

We now focus on defining the internal damping in the crankshaft material and the viscoelastic damping in the torsional oscillation damper (TOD), which is of interest for the vehicle diesel engines analyzed in this paper.

2.3.2.1 Internal Damping in IC Engine Crankshaft Material as a Result of Torsional Oscillations

When determining the coefficient of internal damping in a crankshaft material, the empirical expression $W_d = H\omega^m A$ for dissipation energy per oscillation cycle is frequently used. The recommended values of the constants are $m = 0$ and $n = 3$, and the constant H depends on the type of material [1].

Using expression (6) and the expression for Ψ, as well as the fact that the potential energy per oscillation cycle can be written as $E_p = c\,A^2/2$, where A is the amplitude of oscillation, we express the internal damping coefficient as:

$$K_u = \frac{c}{H_1 \cdot \omega} \cdot \left(\frac{\mathfrak{M}_j^*}{W_0} \right)^{1/2} \qquad (7),$$

where:
- $\mathfrak{M}_j^* = \left[\left(a_j^g\right)^2 + \left(b_j^g + b_j^{in}\right)^2 \right]^{1/2}$ is the amplitude of the excitation moment [Nm] of the j-th order for which the damping is being calculated and whose frequency is ω [rad/s],
- W_0 [m^3] is the polar resistance moment of the section for which the damping is being calculated
- H_1 is a constant (it contains the constant H).

The value of the constant H_1 is given in [1] for the crankshaft materials most frequently used in IC engines.

2.3.2.2 Internal Damping in the Visco Elastic Damper of Torsional Oscillations

Because of its simplicity, cost and efficiency, the viscoelastic torsional oscillations damper (TOD) is used almost exclusively in medium- and high-speed diesel engines. The design of such a TOD is shown in Figure 3.a., and the equivalent scheme of the damper in series with other parts of the torsional-oscillatory mechanism is shown in Figure 3.b. The characteristic parameters of the torsional-oscillatory damper, shown in Figure 3, are the stiffness (c_v) and the internal damping coefficient ($K_{u,v}$). They depend on the material, the dimensions and the working conditions. Since these parameters are defined using measurements during oscillations, they are usually referred to with the prefix “dynamic”. The viscoelastic damper of torsional oscillations has a fairly non-linear value of torsional stiffness, c_v. This stiffness can generally be viewed as a function $c_v = f(t_v, A_{rv}, \omega,$ *type and dimensions of viscoelastic material*) . With our

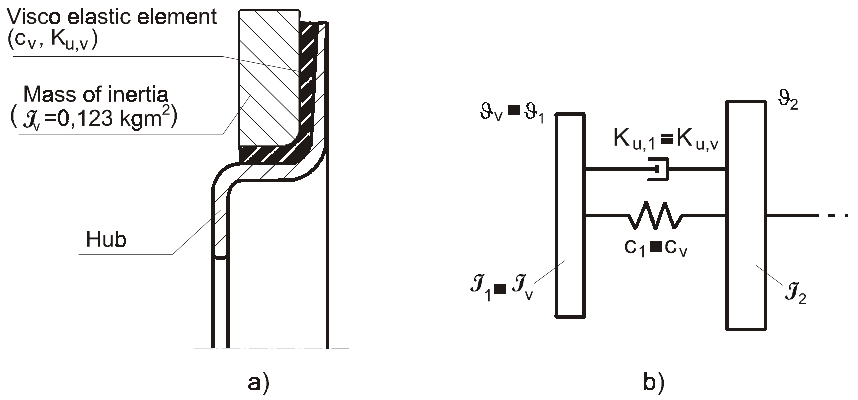

Fig. 3. *Design of viscoelastic damper with equivalent scheme*

experimental measurements, the viscoelastic material surface temperature t_v was in the range $t_v = 60$ to 65 °C, so the average value of the viscoelastic element surface temperature t_v = 62ºC is adopted. Since the focus of our research is only on one damper, the type and dimensions of the material can be excluded as well. Therefore, only the relative amplitude of the oscillation of the viscoelastic element $A_{rv} = A_v - A_2$ and the oscillation frequency are used in the analysis.

As a starting point for defining the dynamic torsional stiffness (c_v) for viscoelastic dampers, the dependence of the natural frequency (f_{vo}) on the relative oscillating amplitude (A_{rv}) is presented. The dependence is based on measurements performed on an assembly specifically made for examining torsional oscillations. The measurements $f_{vo}=f(A_{rv}, t_v)$ are shown in Figure 4.

Based on the results shown in Figure 4, for the temperature t_v = 62 ºC, we express c_v as, $c_v = (2\pi f_{vo})^2 \mathcal{J}_v$. The resulting values of c_v are shown in Figure 5.

To define the internal damping coefficient $K_{u,v}$ we use expression (6), where the potential energy in one cycle is defined as $W_p = \int c_v \cdot \vartheta_{rv} \cdot d\vartheta$. According to [1], for dampers with a viscoelastic element the constants $m = 0$ and $n = 2$ are recommended.

Using the above assumptions, the results shown in Figure 5, as well as the measurements of torsional oscillations in an engine with a torsional oscillations damper, we determine the constants to be $H = 1.6 \cdot 10^4$, $m = 0$, and $n = 1.6$. The coefficient $K_{u,v}$ of the internal damping of the viscoelastic element of the torsional oscillations damper is calculated as:

$$K_{u,v} = \frac{1,6 \cdot 10^4 \cdot A_{r,v}^{1,6} \cdot \left(c_v \cdot \mathcal{J}_v\right)^{1/2}}{2 \cdot \pi \cdot \int_0^{A_{r,v}} c_v \cdot \vartheta_{rv} d\vartheta} \quad (8).$$

The plot of the coefficient of the internal damping of viscoelastic elements based on (8) is shown in Figure 6. The resulting values of c_v and $K_{u,v}$ are used as the input parameters in (3).

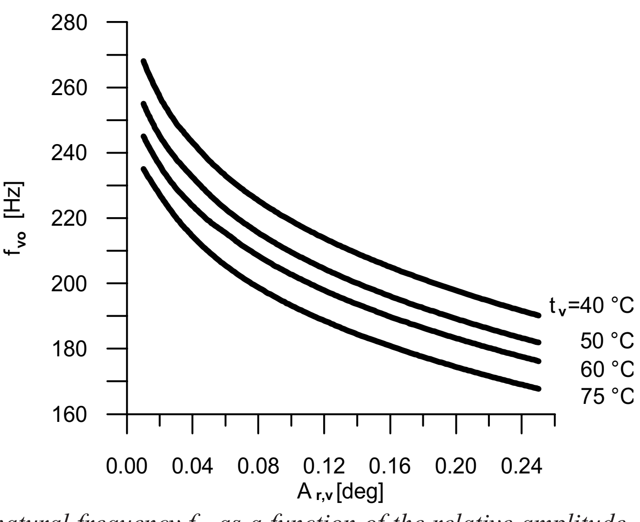

Fig. 4. *Change of natural frequency f_{vo} as a function of the relative amplitude A_{rv} and temperature t_v*

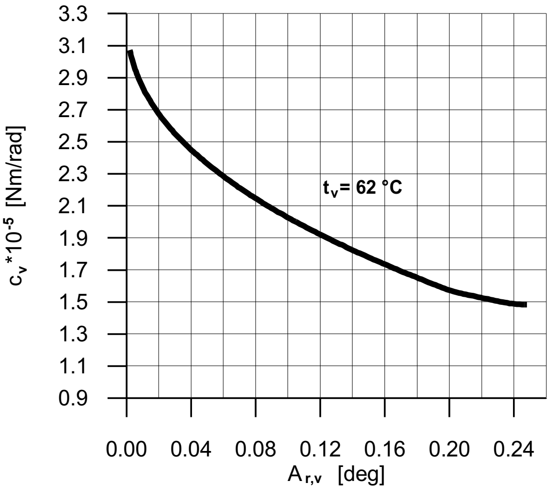

Fig. 5. *Change of torsional stiffness c_v of the viscoelastic element as a function of the relative amplitude $A_{rv.}$*

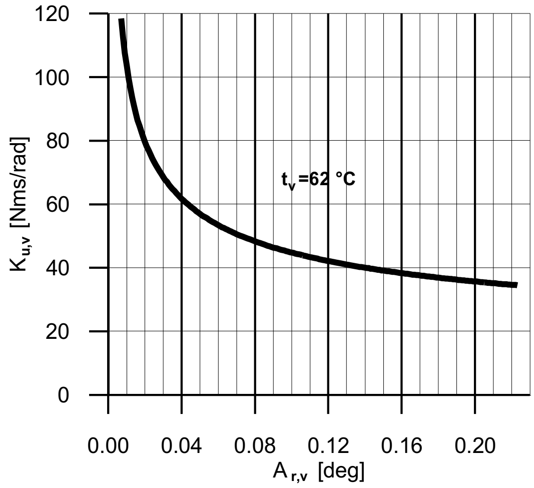

Fig. 6. *Change of the internal damping coefficient $K_{u,v}$ of the viscoelastic element as a function of the relative amplitude $A_{rv.}$*

Other parameters in a torsional oscillations system, such as stiffness and damping of the transmission shaft of the hydraulic test bench, etc., have not been separately addressed here, although they are inevitable in the equivalent system of torsional oscillations when being measured on the engine test bench. The reason for this is the negligible influence of the hydraulic brake on engine oscillations.

3 EXCITATION IN TORSIONAL-OSCILLATORY SYSTEM

According to Equation (3), the excitation in a torsional-oscillatory system consists of the excitation moments of gas forces ($\mathfrak{M}_{gi}$) and the moments-of-inertia forces of the oscillating masses ($\mathfrak{M}_{in}$) of the crank gear. The moment of the gas forces can be expressed as:

$$\mathfrak{M}_g = \left[p(\alpha) - p_0\right]\cdot\frac{D_k^2\cdot\pi}{4}\cdot\left(\cos\alpha - \frac{\lambda\cdot\sin\alpha\cdot\cos\alpha}{\sqrt{1-\lambda^2\cdot\sin^2\alpha}}\right) = $$
$$= \mathfrak{M}_{g0} + \mathfrak{M}_g^*(\alpha) = \mathfrak{M}_{g0} + \sum_{j=0,5}^{\infty}\left[a_j^g\cdot\cos(j\alpha) + b_j^g\cdot\sin(j\alpha)\right] \quad (9),$$

where:
- p_0 is the gas pressure in the crank case,
- $p(\alpha)$ is the gas pressure in the cylinder,
- a_j^g, b_j^g are the coefficients of the Fourier series expansion of the gas-forces excitation.

The excitation moment of the inertial forces of the oscillating masses of the crank gear can be described as:

$$\mathfrak{M}_{in}^*(\alpha) \approx \left(m'' + \frac{s'}{l}\cdot m'\right)\cdot r^2\cdot\omega^2\sum_{j=1}^{6} d_j^{in}\cdot\sin(j\alpha) = \sum_{j=1}^{6} b_j^{in}\cdot\sin(j\alpha) \quad (10),$$

where only the first six excitation terms are of interest, and the remaining terms are disregarded due to their small values. Coefficient d_j is a function of the parameter $\lambda = r/l$ (Figure 2) and can be found in bibliographical sources [3] and [15].

When defining the amplitudes of gas-excitation harmonics (a_j^g, b_j^g) and inertia forces (b_j^{in}), it is important to accurately determine the pressure flow in the engine cylinder $p(\alpha)$. It is possible to simulate one engine cycle using a simplified model (e.g., with a zero-dimensional model in the engine cylinders, and a one-dimensional model in the suction and exhaust part of the engine [17]) and still obtain satisfactory results for the cylinder pressure $p(\alpha)$. The results for $p(\alpha)$ obtained from a simulation are in turn used to determine the coefficients a_j^g, b_j^g using Expression (9). We simulated one cycle on Engine 1 and simultaneously measured the pressure in the cylinder of the engine.

The parameters of Engine 1, on which the simulation was performed, are:
- Suction, six-cylinder, in-line diesel engine with ignition order *1-5-3-6-2-4*,
- Piston diameter/stroke *123 mm/140 mm*, compression ratio $\varepsilon = 16.5$,
- Maximum power/rotation speed *143 kW/ 2200 rpm*;

The amplitudes of the *j*-th order of the excitation moments of the gas forces $R_j^g = [(a_j^g)^2 + (b_j^g)^2]^{1/2}$ are calculated using the instant pressures values

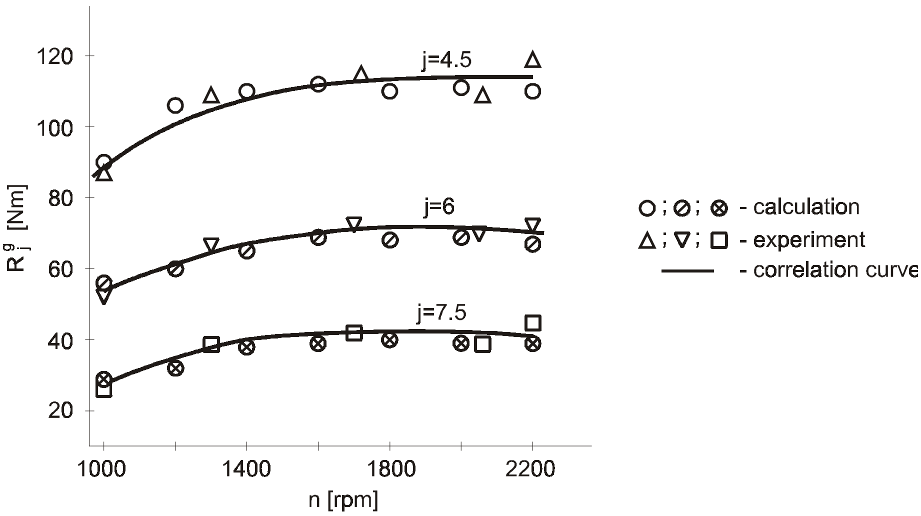

Fig. 7. *Relationship between the excitation amplitude R_j^g and engine revolution n*

measured in the engine cylinder, using piezoelectric sensors, as well as the pressure observed during the simulation of one engine cycle [17], which are shown in Figure 7 for j = 4.5, 6 and 7.5.

Based on the calculation and the experimental results (plotted as points in Figure 7), the resulting correlation curve (continuous line) to be used in the calculations of torsional oscillations is derived.

4 ANALYSIS OF THE CALCULATION RESULTS

The presented analysis includes the calculation and measurements performed on Engine *1*. According to the discussion presented in Section 2, an equivalent torsional-oscillatory engine system with and without a TOD is formed. Typical values of this equivalent torsional-oscillatory system, with and without a torsional oscillations damper, have been calculated based on the discussion in Section 2, and are as follows:

Engine ***1*** without a TOD (Figure 8)

$\mathcal{J}_1=0.03$ kg m^2
$\mathcal{J}_2=\mathcal{J}_4=\mathcal{J}_5=\mathcal{J}_7=0.083$ kg m^2
$\mathcal{J}_3=\mathcal{J}_6=0.062$ kg m^2
$\mathcal{J}_8=1.542$ kg m^2; $\mathcal{J}_9=0.096$ kg m^2
$\mathcal{J}_{10}=0.33$ kg m^2
$K_{s2}=K_{s3}=\ldots=K_{s7}=8.7$ Nms/rad
$c_1=3.074\cdot10^6$ Nm/rad
$c_2=c_3=\ldots=c_6=1.996\cdot10^6$ Nm/rad
$c_7=2.7\cdot10^6$ Nm/rad; $c_8=0.15\cdot10^4$ Nm/rad
$c_9=0.923\cdot10^6$ Nm/rad

Engine ***1*** with a TOD (Figure 9)

$\mathcal{J}_1=0.123$ kg m^2; $\mathcal{J}_2=0.046$ kg m^2
$\mathcal{J}_3=\mathcal{J}_5=\mathcal{J}_6=\mathcal{J}_8=0.083$ kg m^2
$\mathcal{J}_4=\mathcal{J}_7=0.062$ kg m^2
$\mathcal{J}_9=1.542$ kg m^2; $\mathcal{J}_{10}=0.096$ kg m^2
$\mathcal{J}_{11}=0.33$ kg m^2
$K_{s3}=K_{s4}=\ldots=K_{s8}=8.7$ Nms/rad
$c_1\equiv c_v$ (Figure 5); $c_2=3.074\cdot10^6$ Nm/rad
$c_3=c_4=\ldots=c_7=1.996\cdot10^6$ Nm/rad
$c_8=2.7\cdot10^6$ Nm/rad; $c_9=0.15\cdot10^4$ Nm/rad
$c_{10}=0.923\cdot10^6$ Nm/rad

The internal damping in the crankshaft material and the viscoelastic element of the torsional oscillations damper were calculated based on the discussion given in Section 2.3.2.

Natural oscillating frequencies, as well as the relative oscillation amplitudes, are calculated using the approximate Holtzer method for the 1st and 2nd mode of vibrations. The calculation results for Engine *1* without a TOD are shown in Figure 8, and for Engine *1* with a TOD are shown in Figure 9. These results indicate that in both cases, the 1st mode of vibrations has practically no influence on the oscillations of the engine masses, which is a consequence of the low stiffness of the transmission shaft (c_9 = 0.15 10^4 *Nm/rad*) relative to the stiffness of other components. The calculation results for the "interesting" excitation terms, using the approximate values of the natural oscillation frequencies and the developed software for the calculation of amplitudes of disc oscillations, are shown for Engine *1* without

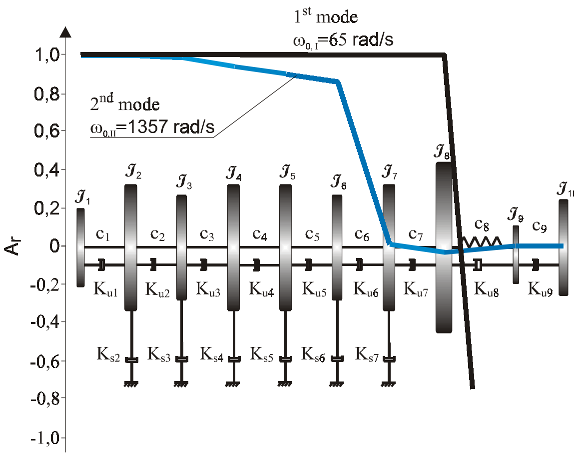

Fig. 8. *Relative oscillation amplitudes of the individual discs for engine 1 without a TOD*

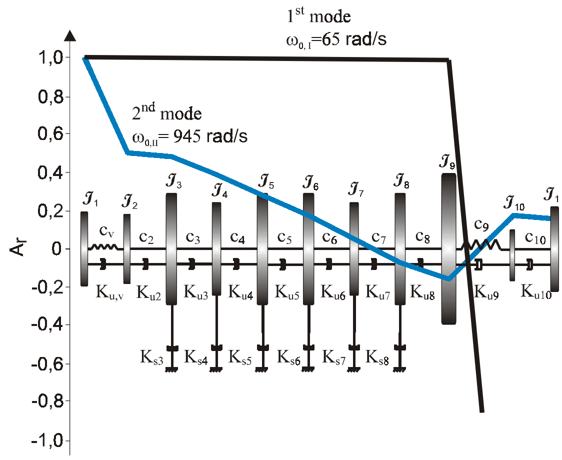

Fig. 9. *Relative oscillation amplitudes of the individual discs for engine 1 with a TOD*

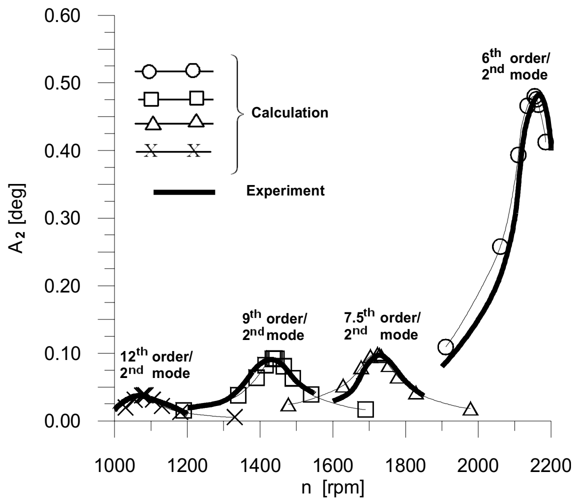

Fig. 10. *Change of twisting amplitude on crankshaft pulley (A_2) in Engine 1 without TOD as a function of engine revolution n, for interesting excitation orders and 2nd mode oscillations*

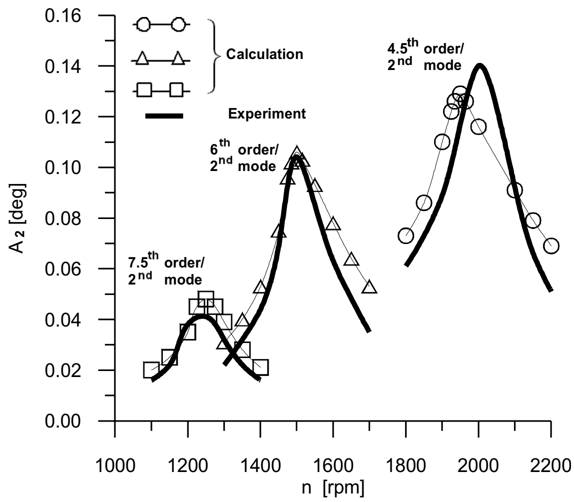

Fig. 11. *Change of twisting amplitude on crankshaft pulley (A_2) in Engine 1 with TOD as a function of engine revolution n, for interesting excitation orders and 2nd mode oscillations*

a TOD, and with a TOD in Figures 10 and 11, respectively. These values are taken in the part of the crankshaft pulley where the twisting angles are the greatest.

Both analytical and experimental results are shown in Figures 10 and 11. The equipment for measuring torsional oscillations with a simultaneous harmonic analyses of the mean orders is described in detail in [3]. It is clear that the predicted and measured values agree well for the engine without a torsional oscillations damper, which in turn validates our choice of parameters for the equivalent torsional-oscillatory system.

There is a certain disagreement between the analytical and experimental results for the engine with a torsional oscillations damper (Figure 11). This is due to the choice of the simplified, proposed model, given by (8), used to determine the internal damping coefficient of the TOD. A detailed study of the data indicates that the largest discrepancy occurs during regimes of faster rotational speeds of the engine, which is mostly influenced by the dynamic value of the internal damping coefficient ($K_{u,v}$). An additional analysis of the parameters that determine the characteristics of the viscoelastic elements of the TOD, namely c_v and $K_{u,v}$, has demonstrated better agreement between the analytical predictions and the experimental results. However, the price paid is a more complicated procedure for determining the coefficient $K_{u,v}$, and therefore it is not presented in this paper.

We consider the proposed approach to be acceptable for engineering practice, where the results can be useful in an assessment of the efficiency of a TOD.

Furthermore, the dynamic endurance of the engine crankshaft can be determined by adopting the proposed methodology in calculating the dynamic amplitudes of torsional stress, and its impact on the twisting of the engine crankshaft segments.

5 CONCLUSION

Based on the results of research of the torsional oscillations in an IC engine presented in this paper, the following conclusions can be drawn. The complicated system of torsional oscillations in the IC engine can be replaced with the so-called in-line equivalent torsional-oscillatory system. Typical values in the equivalent system (moments of inertia, stiffness, and damping) can be calculated using proposed simplified methods, which yield satisfactory results. In particular, the proposed method for calculating the characteristics of the viscoelastic element of a torsional oscillations damper with typical non-linear characteristics is new and can be of practical interest. The easiest method for calculating the external excitation of the torsional oscillations system is to use software for an engine-cycle simulation. We demonstrated the agreement between the results for torsional oscillations obtained using the proposed calculation methods and the realistic measured values. Therefore, the proposed procedure for the analysis of torsional oscillations, which consists of the starting physical model, the methodology for determining the input parameters, the adopted mathematical model, and the numerical solution, is satisfactory from a practical standpoint.

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Numerično modeliranje mešanja v posodi z Rushtonovim mešalom

Numerical Modeling of Mixing in a Vessel with a Rushton Impeller

Matjaž Hriberšek - Matej Zadravec

Prispevek obravnava numerično modeliranje mešanja newtonske tekočine v mešalni posodi, v kateri je nameščeno turbinsko Rushtonovo mešalo. Obravnavan je ustaljeni turbulentni tokovni režim, opisan s časovno povprečenim Navier-Stokesovim sistemom enačb. Numerično reševanje temelji na uporabi dvoenačbnega modela turbulence in metode končnih prostornin. Posebna pozornost je namenjena modeliranju vrtenja mešala ter izračunu mehanske moči za mešanje, kakor tudi nekaterim poenostavitvam, ki omogočajo hitrejši izračun zahtevnih diskretnih modelov.

(Ključne besede: mešala Rushtonova, modeliranje numerično, tok turbulentni, razmere tokovne)

This paper presents numerical modeling of mixing a Newtonian fluid in a stirring vessel with a Rushton impeller. The stationary turbulent flow is governed by the time-averaged Navier-Stokes equations. For the numerical approach, a two-equation turbulence model with the finite-volume method was used. The focus is on impeller rotation, a determination of the stirrer power and a simplification that can lead to faster solving of complicated discreet models.

(Keywords: Rushton impeller, numerical modeling, turbulent flow, flow conditions)

0 UVOD

Mešanje je eden najpogosteje uporabljanih postopkov, lahko poteka samostojno ali kot spremljevalec drugih postopkov. Najpogostejša oblika mešalne naprave v inženirski praksi je mešalna posoda. Poglavitna naloga mešanja je priprava in vzdrževanje čim bolj enakomerne porazdelitve toplote in snovi v napravi, kar omogoča prisilno gibanje tekočine, ki je posledica vnosa mehanske energije prek vrtenja mešala. Pri konstrukciji mešalne posode je najpomembnejši podatek potrebna moč za mešanje, saj je od nje odvisna izbira pogonskega sklopa, medtem ko je za določanje stopnje premešanja in mešalnega časa ter razmer pri prenosu toplote in snovi poglavitno poznavanje tokovnih razmer in mehanizmov mešanja.

Študij mešanja je še do nedavnega temeljil predvsem na znanju in izkušnjah, pridobljenih pri preizkusih na modelnih napravah. Kadar imamo na voljo ustrezno preizkusno opremo, je takšen postopek ustrezen, saj opazujemo dogajanje v dejanskem fizikalnem sistemu. Žal ima modelno preizkušanje pravi pomen tedaj, kadar ima inženir na voljo ustrezne metode merilnega prenosa, ki mu omogočijo prenos spoznanj z modelnega merila na industrijsko merilo. Podobnostna teorija, najpogosteje uporabljan postopek v merilnem prenosu, je ena izmed možnosti, žal pogosto omejena z nasprotujočimi si pravili, kar je izrazito predvsem pri obravnavi lokalnega dogajanja v mešalni posodi ali mešanja večfaznih sistemov. Glavni problem pri merilnem prenosu ni le sprememba izmer, pač pa sprememba tokovnih razmer v mešalni posodi, tako na makro (veliki vrtinci, glavne tokovnice) kakor tudi na mikro ravni, česar podobnostna teorija seveda ne more zajeti.

Turbinsko oziroma Rushtonovo mešalo je dobilo ime po J. H. Rushtonu, ki je prvi preučeval postopek mešanja z uporabo tega mešala. Rushton in drugi ([12] in [13]) je s preizkusom podal krivulje brezrazsežnega Newtonovega števila v odvisnosti od Reynoldsovega števila za različne tipe mešal.

Zaradi velike uporabnosti mešala so bile izvedene številne meritve tokovnega polja v okolici Rushtonovega mešala. Wu in Patterson [10] ter Ranade in Joshi [11] so s pomočjo laserske Dopplerjeve anemometrije (LDA) preučevali tokovne razmere v mešalnih posodah z Rushtonovim mešalom. Wu in Patterson [10] sta se v raziskavi osredotočila na periodično obnašanje toka v okolici mešala zaradi prehoda lopatic mešala glede na preostali del mešalne posode, ter ugotovila, da ima to velik vpliv na turbulentne veličine toka. Rezultati, ki sta jih podala Ranade in Joshi [11], so bili podani s poudarkom na tokovnem polju v okolici mešala, prav tako pa sta rezultate primerjala z že do tedaj opravljenimi preizkusi. Ugotovila sta, da premer mešalne posode nima velikega vpliva na tokovno dogajanje v neposredni okolici mešala.

Raziskave, ki so jih opravili Van't Riet in drugi ([15] in [16]), so pokazale, da za vsako od lopatic Rushtonovega mešala nastaneta dva vrtinca. Prav tako pa je v teh člankih zajeto turbulentno obnašanje toka v okolici mešala.

Na področju inženirskih znanosti je v zadnjem desetletju prišlo do preboja računalniških simulacij z znanstvenega področja na področje inženirstva, kar velja tako za računalniško mehaniko kakor tudi za računalniško dinamiko tekočin (RDT). Vzrok temu je bil hkraten pospešen razvoj matematično-fizikalnih in približnih modelov ter hiter razvoj računalniške hitrosti. Ker je mešanje predvsem problem dinamike tekočin, je z razvojem računalniške dinamike tekočin, ki omogoča natančen vpogled v tokovne razmere v mešalnih posodah, postopkovni inženir tako dobil v roke (sicer zahtevno) orodje, ki v veliki meri nadomešča podobnostno teorijo. To je še posebej pomembno v primeru obravnave tokov v posodah z več mešali, Bašič [2], in pri mešanju nenewtonskih tekočin, Hriberšek [7].

Harvey in Rogers [5] sta s pomočjo Navier-Stokesovih enačb izvedla izračun tokovnega polja v mešalni posodi z Rushtonovim mešalom. Uporabila sta večblokovno računsko mrežo. Primerjala sta dva izračuna, med katerima je bila razlika v modeliranju vrtenja mešala. V prvem primeru sta uporabila model ustaljenega sklopljenega izračuna toka v rotirajočem in mirujočem območju računske mreže (lega rotirajočih delov glede na mirujoče je ves čas enaka), v drugem primeru pa neustaljen sklopljen izračun toka v rotirajočem in mirujočem območju računske mreže (zajet je medsebojni vpliv in časovno spreminjanje toka zaradi spreminjajoče se medsebojne lege mirujočega in rotirajočega območja). Raziskavo vpliva različnih modelov za modeliranje rotirajočega območja na tokovno polje v različnih geometrijskih oblikah mešalnih posod so izvedli tudi Brucato in drugi [3].

Za overitev numeričnih izračunov so potrebni primerni preizkusi. Najugodnejša primerjava numeričnih in preizkusnih rezultatov je v primeru, ko so numerični in preizkusni model ter postopkovni parametri mešalne posode in postopka mešanja enaki. Ranade in Joshi [11] sta primerjala numerične rezultate s preizkusnimi rezultati, dobljenimi z uporabo merilne metode LDA, medtem ko sta primerjavo numeričnih rezultatov z eksperimentalnimi rezultati, dobljenimi z uporabo metode meritev hitrosti s tehniko sledenja osemenjevalnih delcev (PIV), izvedla Lee in Yianneskis [8].

Namen prispevka je podati podroben opis numeričnega modela laboratorijske mešalne posode z Rushtonovim mešalom s poudarkom najpomembnejših matematično-fizikalnih modelov. Poznavanje delovanja takšnih modelov je lahko odločilno za natančnost rezultatov računalniške simulacije, obenem pa inženirju - uporabniku ponujajo tudi boljše razumevanje delovanja standardnih programov (CFX) oziroma uporabniško prirejenih za simulacijo mešanja (CFX-Promixus [4]).

1 ZNAČILNOSTI MEŠANJA V MEŠALNIH POSODAH

Med mehanizme mešanja prištevamo konvekcijo, disperzijo in difuzijo. Konvekcija pomeni gibanje skupka snovi in njegovo raztezanje, disperzija pa razbitje skupka snovi na manjše dele, kar pospeši postopek izenačevanja lastnosti zmesi. Difuzija oziroma mikromešanje pomenita izenačevanje na molekularni ravni, ki je najpočasnejši in v primeru homogenih sistemov tudi zadnji mehanizem mešanja. Z mehanskim mešanjem vplivamo na konvekcijo in disperzijo, medtem ko na difuzijo nimamo vpliva.

Glavni del mešalne posode je mešalo, ki je namenjeno za prenos mehanske energije v kinetično energijo tekočine. Od oblike mešala je odvisno tokovno polje v mešalni posodi. Pri vzdolžnem mešalu je smer črpanja kapljevine na izstopu s področja mešala vzporedna gredi mešala. Pri prečnem mešalu izstopa kapljevina pravokotno glede na gred mešala. Pogosto ima mešalna posoda tik ob steni nameščeno določeno število tokovnih ovir, ki so namenjene za preprečitev gibanja glavnine kapljevine v smeri vrtenja mešala. Eden od znakov takšnega nezaželenega gibanja je sosredno znižanje gladine kapljevine zaradi pojava velikega vrtinca v posodi. Poleg slabšega mešanja lahko v takšnih primerih pride do prodora zraka v kapljevino, kar lahko pomembno vpliva na potek postopka v posodi.

2 RAČUNALNIŠKA DINAMIKA TEKOČIN

Izhodišče računalniškega modeliranja dinamike tekočin je sistem ohranitvenih zakonov mase, gibalne količine, toplote in snovi v diferencialni obliki, ki velja za obravnavo zveznih teles (mehanika kontinuuma). Najbolj vsesplošna oblika ohranitvenih zakonov so enačbe Navier-Stokes, ki jih lahko uporabimo za opis laminarnega in turbulentnega toka, stisljive in nestisljive ter newtonske in nenewtonske tekočine. Omejimo se na mešanje newtonske tekočine, za katero se sistem ohranitvenih zakonov v mirujočem koordinatnem sistemu glasi:

- ohranitev mase:

$$\vec{\nabla} \cdot \vec{v} = 0 \quad (1)$$

- ohranitev gibalne količine:

$$\frac{\partial v_i}{\partial t} + \frac{\partial}{\partial x_j}\left(v_i v_j \right) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \Delta v_i + g_i \quad (2).$$

V primeru mešalne posode oz. naprav z rotirajočimi deli najpogosteje uporabimo kombinacijo zapisa gibanja tekočine glede na mirujoči koordinatni sistem in glede na rotirajoči koordinatni sistem. Rotirajoči koordinatni sistem se vrti s kotno hitrostjo mešala, uporabimo pa ga za opis gibanja tekočine v neposredni okolici mešala. Glede na to, da se koordinatni sistem vrti, lahko rešujemo ohranitvene enačbe za relativno gibanje tekočine glede na gibanje koordinatnega sistema, enačba ohranitve mase je torej sedaj:

$$\vec{\nabla} \cdot \vec{u} = 0 \quad (3),$$

kjer je $\vec{u}$ relativna hitrost delca tekočine.

Tudi enačbo ohranitve gibalne količine zapišemo za relativno gibanje tekočine, vendar pa moramo sile, ki delujejo na delec tekočine zaradi gibajočega koordinatnega sistema, ustrezno modelirati z dodatnimi viri gibalne količine F_i:

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(u_i u_j \right) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \Delta u_i + g_i + F_i \quad (4).$$

Dodatni viri gibalne količine F_i zajemajo Coriolis-ovo (F_{cor}) in centrifugalno (F_{cfg}) silo:

- Coriolis-ova sila:

$$F_{cor} = -2 \cdot \omega \times \vec{u} \quad (5)$$

- centrifugalna sila:

$$F_{cfg} = -\omega \times \left(\omega \times \vec{r} \right) \quad (6).$$

Povezavo vrednosti hitrosti med območjem, opisanim v rotirajočem koordinatnem sistemu, in območjem, opisanim v nepremičnem koordinatnem sistemu, opravimo na meji med obema območjema, pri tem upoštevamo:

$$\vec{u} = \vec{v} - \omega \vec{r} \quad (7),$$

kjer so: $\vec{u}$ hitrost tekočine v rotirajočem se koordinatnem sistemu, $\vec{v}$ hitrost tekočine v mirujočem koordinatnem istemu, ω kotna hitrost vrtenja mešala in $\vec{r}$ položajni vektor.

Preostale spremenljivke, tlak, temperatura in koncentracija ne spremenijo vrednosti na vmesni meji med območjema. Dobljene vodilne enačbe dinamike toka rešimo z uporabo približnih metod [6].

Najbolj razširjena približna metoda v RDT je metoda končnih prostornin. Integracija vodilnih enačb poteka na nivoju končnih prostornin, ki jih definiramo v okolici vsake mrežne točke. Zbir vseh končnih prostornin zavzame celotno prostornino, ki jo definirajo meje računske mreže. Pri izpeljavi diskretnega sistema algebrajskih enačb se upošteva pravilo ohranitve, kar pomeni, da je neto vtok v končno prostornino enak neto iztoku iz končne prostornine, kar zagotavlja tudi globalno ohranitev numerične sheme.

3 MODELIRANJE ROTIRANJA MEŠALA

Uporaba rotirajočega in mirujočega koordinatnega sistema je v RDT znana kot metoda večkratnega koordinatnega sistema (VKS-MFR). Prav z uporabo te metode je mogoče preučevati tokovna dogajanja v mešalnih posodah oziroma v vseh napravah, ki so sestavljene iz rotorja in statorja.

Za povezavo vrednosti hitrosti med rotirajočim in mirujočim delom moramo uporabiti ustrezno interpolacijsko metodo. Ena izmed možnosti je metoda posplošene vmesne površine mreže (PVPM-GGI) [1]. Metoda PVPM poveže mreže različnih območij na njihovih stičnih ploskvah. V splošnem je mogoče z metodo PVPM povezati mreže, pri katerih ni skladnosti vozlišč elementov, tipov elementov, velikosti in oblike stičnih površin, oziroma uporabimo različne modele fizike toka po celotni stični ploskvi.

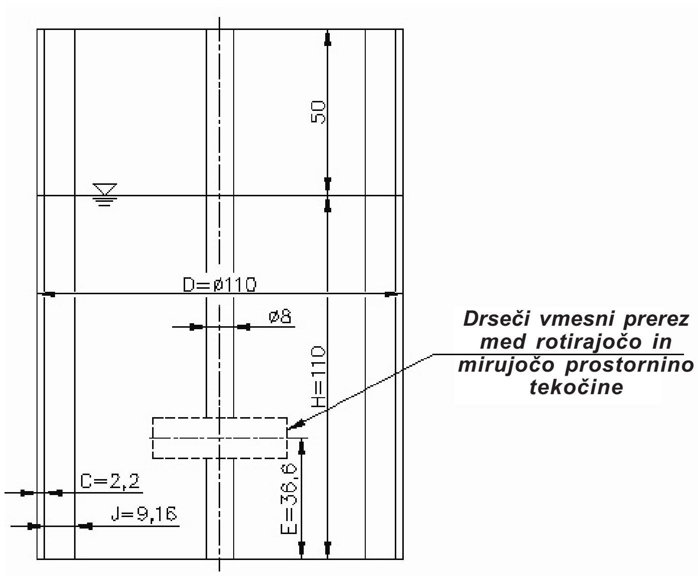
V našem preračunu mešalne posode je bila uporabljena sestavljena mreža s pomočjo tekoče-tekočega drsečega vmesnega prereza. Tak tip drsečega vmesnega prereza se uporablja v modelih, v katerih je opazna sprememba lege enega od območij mreže, ki ju povezuje tak drseči vmesni prerez. V našem preračunu mešalne posode je bil na drsečem vmesnem prerezu uporabljen model zamrznjen rotor [1]. Pri uporabi tega modela se lega enega od območij spreminja, toda relativna usmeritev komponent prek drsečega vmesnega prereza je nespremenljiva. Obe območji mreže sta povezani tako, da ima vsaka določeno relativno lego skozi preračun problema, medsebojni premik pa je določen s spremembo območja po drsečem vmesnem prerezu med mrežama.

Za modeliranje geometrijske oblike modela mešalne posode je bil uporabljen programski paket ANSYS Workbench 8.1, ki združuje orodja za modeliranje in mreženje geometrijske oblike modela. Modeliranje geometrijske oblike mešalne posode se je izvajalo z uporabo mer laboratorijskega modela mešalne posode, izdelanega z namenom eksperimentalne analize tokovnih razmer v mešalni posodi (sl. 1, 2). Naš primer je bil sestavljen iz dveh ločenih geometrijskih oblik, ki sta sestavljali celoto oziroma področje, katerega zapolni tekočina v mešalni posodi (sl. 3).

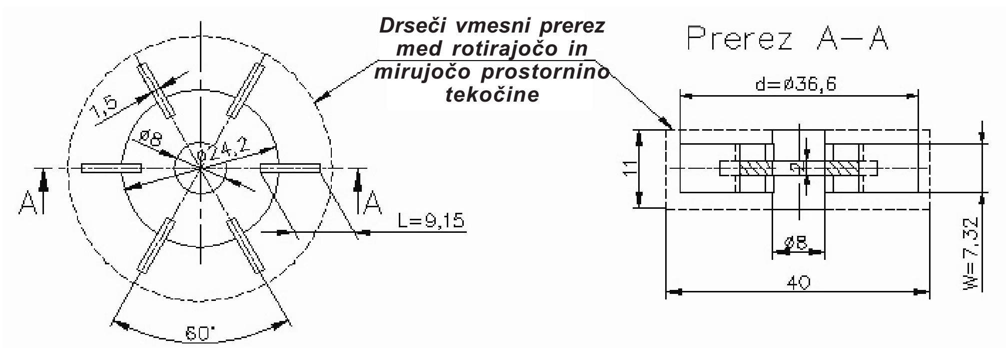
Geometrijsko obliko obeh modelov sestavljajo ploskve, ki morajo dajati zaključeno prostornino. Zaradi osnosimetrične geometrijske oblike mešalne posode je bilo treba modelirati le polovico mešalne posode. Z modeliranjem le polovice mešalne posode se zmanjša število elementov in s tem tudi čas preračuna, medtem ko ostane natančnost preračuna enaka.

Pri modeliranju geometrijske oblike modelov so bile pregrade in lopatice rotorja modelirane s predpisano debelino in ne le kot tanke površine, kar bistveno vpliva na natančnost opisa geometrije fizikalnega problema. Mreži mirujoče in rotirajoče prostornine tekočine sta prikazani na sliki 4. Ko se mreži obeh sestavita, dobimo mrežo, ki ima 757.845 elementov in 157.341 vozlišč, ki so različnih oblik:
- tetraedrov je 701.123,
- prizm je 55.389,
- piramid je 1.333.

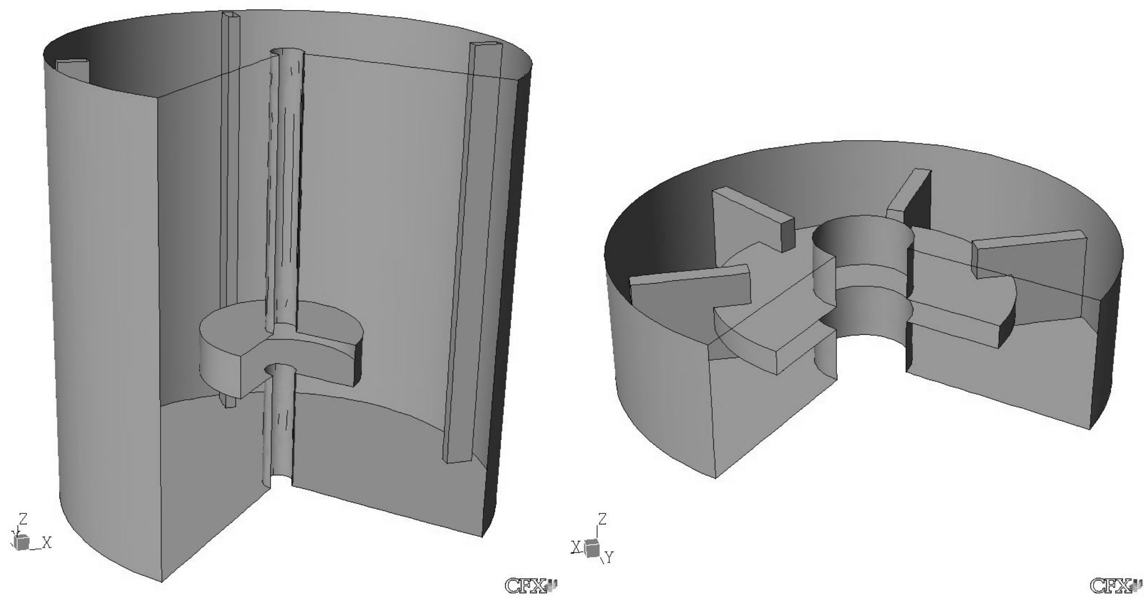
Simulacijo postopka mešanja smo izvedli kot časovno odvisno, celoten čas simulacije pa je znašal 4 sekunde, po preteku katerega so hitrosti in tlaki v tekočini dosegli ustaljene vrednosti. V začetku simulacije se rotirajoče območje vrti s 120 vrt/min, medtem ko v mirujočem delu ni nobenega gibanja tekočine. V naslednjem trenutku se začne gibanje tekočine prenašati iz rotirajočega dela tekočine oziroma vrtečega se rotorja na celotno prostornino tekočine. Preračun ohranitvenih enačb se je izvajal v časovnih korakih 0,01 sekunde, v katerih se pri vrtilni



Sl. 1. *Geometrijska oblika modela mešalne posode z uporabljenimi merami za mirujočo prostornino tekočine (mere v mm)*



Sl. 2. *Geometrijska oblika modela mešalne posode z uporabljenimi merami za rotirajočo prostornino tekočine (mere v mm)*



Sl. 3. *Model mešalne posode mirujoče prostornine tekočine (levo) ter model mešalne posode rotirajoče se prostornine tekočine (desno)*

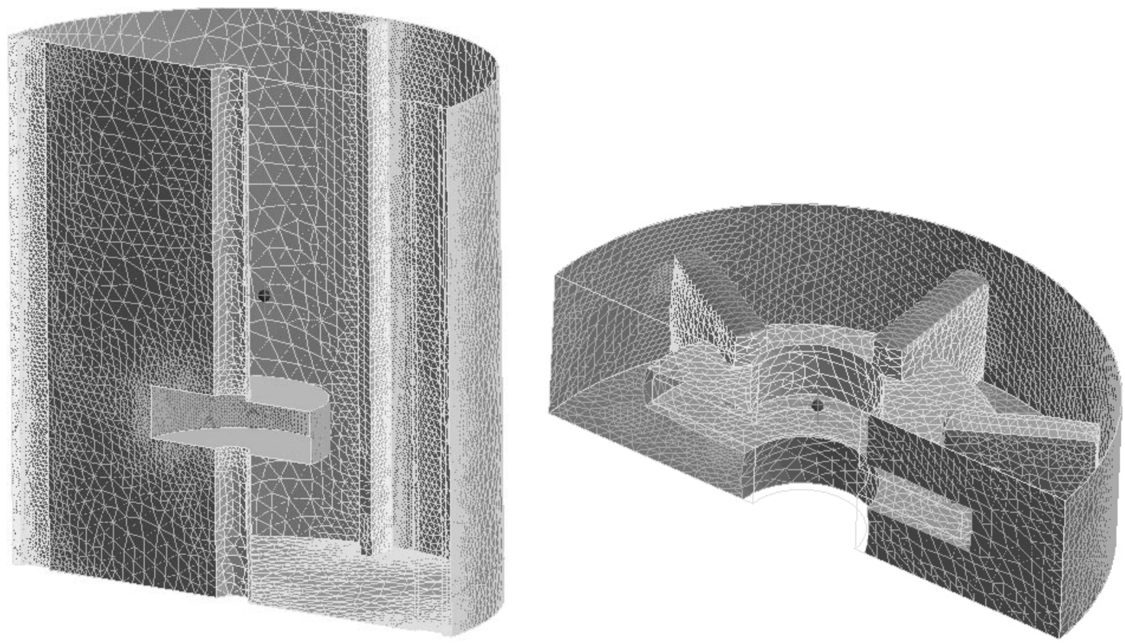
frekvenci rotorja 120 vrt/min ta premakne za 1/50 vrtljaja oziroma 7,2 °C. Izveden je bil še preračun pri vrtilni frekvenci rotorja 1200 vrt/min. Preračun ohranitvenih enačb se je v tem primeru izvajal v časovnih korakih 0,005 sekunde, kjer se pri vrtilni frekvenci rotorja 1200 vrt/min rotor premakne za 1/10 vrtljaja oziroma 36 °C.

Na določenih površinah modela je treba zaradi uporabe simetrije modela mešalne posode predpisati periodične robne pogoje. Model mešalne posode je vključeval tudi preračun proste gladine, kar je zahtevalo podatke začetnih pogojev za prostorninski delež vode, prostorninski delež zraka in tlak glede na višino posode. Podani konvergenčni kriterij je bil za oba primera preračuna 10^{-6}, kar daje zadostno natančnost rezultatov. Medij, ki je bil uporabljen pri postopku mešanja v mešalni posodi, je bila voda. Snovske lastnosti vode so bile vzete pri temperaturi 20 °C (ρ = 998 kg/m^3; ν = 1,01·10^{-6} m^2/s).

4 MODELIRANJE TURBULENTNEGA TOKA V MEŠALNI POSODI

Tokovno polje v napravi je odvisno od več dejavnikov, predvsem od snovskih lastnosti, hitrosti vrtenja mešala oziroma hitrosti toka tekočine ter izmer naprave. Pogosto se dogaja, da je v bližini mešala tok turbulenten, ob stenah mešalne posode laminaren, vmes pa obstaja še območje prehoda med laminarnim in turbulentnim tokom.

Pri mešanju malo viskoznih tekočin poteka mešanje najpogosteje v področju turbulentnega toka.



Sl. 4. *Mreža mirujoče prostornine tekočine (levo) in rotirajoče prostornine tekočine (desno)*

Zanj so značilna prostorska naključna nihanja vrednosti spremenljivk tokovnega polja, torej hitrosti, tlaka, temperature in koncentracije. Značilnost turbulence je tako vedno anizotropnost in nehomogenost. Ker je obravnava turbulence na ravni anizotropnosti in nehomogenosti, mogoča le v obliki neposredne numerične simulacije v okviru računalniške dinamike tekočin ali uporabe natančnih in občutljivih merilnih tehnik, na primer Laser-Dopplerjevih anemometrov, je treba za inženirsko analizo vpeljati določene poenostavitve.

Najpogostejši način obravnave turbulence je vpeljava predpostavke o izotropnosti in homogenosti turbulentnih veličin. V primeru homogenosti turbulence vpeljemo predpostavko, da se v vseh točkah območja pojavljajo enaka časovno povprečena odstopanja oziroma enake lastnosti turbulentnega tokovnega polja. Predpostavka o izotropnosti turbulence v neki točki pomeni enak potek odstopanj v vseh smereh okoli izbrane točke. Najintenzivnejše je turbulentno tokovno polje v neposredni bližini mešala. V tem področju lahko uporabimo predpostavko o homogenosti in izotropnosti turbulentnega polja, torej je uporaba modelov na podlagi turbulentne viskoznosti primerna. Z razdelitvijo spremenljivk toka na časovno povprečne vrednosti in odstopanje od teh vrednosti (oscilirajoči del), lahko enačbo ohranitve gibalne količine zapišemo v obliki, podobni zapisu za laminarni tok, tokrat za časovno povprečne vrednosti $\overline{v}_i$:

$$\frac{\partial \overline{v}_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\overline{v}_i\,\overline{v}_j\right)=-\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i}+\nu\Delta\overline{v}_i+\frac{\partial}{\partial x_j}\left(-\overline{v_i' v_j'}\right)+g_i+F_i \quad (8).$$

Enačba ohranitve gibalne količine turbulentnega toka (8) se razlikuje od enačbe ohranitve gibalne količine laminarnega toka (4) za člen $\rho\overline{v_i' v_j'}$, ki se imenuje člen Reynoldsovih oziroma turbulentnih napetosti in opisuje medsebojni vpliv sprememb hitrosti:

$$\rho\overline{v_i' v_j'}=\frac{2}{3}\rho k\,\delta_{ij}+\left(\rho\nu_T\left[\frac{\partial \overline{v}_i}{\partial x_j}+\frac{\partial \overline{v}_j}{\partial x_i}\right]\right) \quad (9).$$

V zgornji enačbi smo vpeljali turbulentno viskoznost ν_T, ki z viskoznostjo ν pomeni dejansko viskoznost:

$$\nu_{eff}=\nu+\nu_T \quad (10).$$

Vpeljava turbulentne viskoznosti, oz. gradientnega modela opisa Reynoldsovih napetosti, je ugodna z računskega vidika, saj moramo določiti samo vrednost turbulentne viskoznosti, natančnost modela pa je v veliki meri odvisna od načina izračuna turbulentne viskoznosti.

Najpreprostejši diferencialni model na podlagi turbulentne viskoznosti, ki upošteva prenos turbulentnih veličin v toku, je model *k*-ε in njegove izvedenke. Osnova modela *k-e* je izračun dveh karakterističnih veličin turbulentnega polja, turbulentne kinetične energije k in njenega raztrosa ε, ki ju določimo z rešitvijo dveh prenosnih enačb:

$$\frac{\partial k}{\partial t}+\frac{\partial}{\partial x_i}\left(v_i\,k\right)=\frac{\partial}{\partial x_i}\left[\left(\nu+\frac{\nu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+P_k-\varepsilon \quad (11)$$

$$\frac{\partial \varepsilon}{\partial t}+\frac{\partial}{\partial x_i}\left(v_i\,\varepsilon\right)=\frac{\partial}{\partial x_i}\left[\left(\nu+\frac{\nu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}P_k+C_{2\varepsilon}\frac{\varepsilon^2}{k} \quad (12).$$

Števila $C_{1\varepsilon}$= 1,44, $C_{2\varepsilon}$= 1,92, σ_k= 1 in σ_l= 1,3 so empirične stalnice, določene za primer popolnoma razvitega turbulentnega toka, medtem ko je člen P_k nastanek turbulentne kinetične energije. Modeliranje turbulentnega toka ob trdnih stenah je bila izvedena z uporabo zidnih funkcij [1].

Na podlagi izračuna teh veličin izračunamo vrednost turbulentne viskoznosti:

$$\nu_T=C_\mu\frac{k^2}{\varepsilon} \quad (13),$$

kjer je C_μ = 0,09. Iz izraza (13) je razvidno, da predpostavlja model k-ε homogenost, saj uporabimo enak izraz povsod v računskem območju, in izotropnost, saj je turbulentna viskoznost skalar in torej ni odvisna od smeri opazovanja.

5 MOČ ZA MEŠANJE IN PRETOČNO ŠTEVILO

Tokovne razmere v mešalni posodi smo preračunali s programskim paketom CFX 5.7. Uporabljeni so bili štirje vzporedno vezani računalniki Pentium 4 (2,4GHz) z 1GbRam delovnega pomnilnika. Pregled rezultatov je bil izveden s programskim paketom CFX-Post, ki je del programskega paketa CFX 5.7. Simulacija tokovnih razmer v mešalni posodi prvega primera se je odvijala pri vrtilni frekvenci rotorja 120 vrt/min. Reynoldsovo število za ta primer je enako:

$$\mathrm{Re}_{120}=\frac{n_{120}\cdot d^2}{\nu}=2653 \quad (14).$$

V drugem primeru se je rotor vrtel z vrtilno frekvenco 1200 vrt/min. Reynoldsovo število za ta primer pa je:

$$\mathrm{Re}_{1200}=\frac{n_{1200}\cdot d^2}{\nu}=26526 \quad (15).$$

Mešanje v mešalni posodi zahteva najmanjšo moč za pogon mešala P_p. Moč P_p dobimo na temelju seštevka mehanske moči za vrtenje mešala P in moči P_{izg}, potrebne za premagovanje izgub pri prenosu moči med pogonskim strojem in mešalom, kamor prištevamo izgube v ležajih, sklopki in tesnilih:

$$P_p=P+P_{izg} \quad (16).$$

Moč za mešanje je mogoče izračunati z znanim vrtilnim momentom iz enačbe:

$$P=M\cdot\omega=M\cdot 2\pi n \quad (17).$$

Moč za mešanje je zmnožek vrtilnega momenta in vrtilne frekvence. Vrtilni moment na disku z lopaticami je v paketu CFX mogoče prebrati s pomočjo funkcije Calculator [1], ki je vgrajena v programski paket CFX-Post. Prebrana vrednost vrtilnega momenta na disku z lopaticami za prvi in drugi primer preračuna sta:

$$M_{120}=1{,}6779\cdot 10^{-4}\ \mathrm{Nm} \quad (18)$$

in

$$M_{1200}=2{,}6782\cdot 10^{-2}\ \mathrm{Nm} \quad (19).$$

Moči za mešanje, ki sledita iz enačbe (17), sta tako:

$$P_{120}=M_{120}\cdot 2\pi n_{120}=2{,}1085\cdot 10^{-3}\ \mathrm{W} \quad (20)$$

in

$$P_{1200}=M_{1200}\cdot 2\pi n_{1200}=3{,}3656\ \mathrm{W} \quad (21).$$

Z uporabo izračunanih moči za mešanje izračunamo brezrazsežni števili moči oz. Newtonovi števili, ki sta podani z enačbama:

$$Ne_{120}=\frac{P_{120}}{\rho\cdot n_{120}^3\cdot d^5}=4{,}02 \quad (22)$$

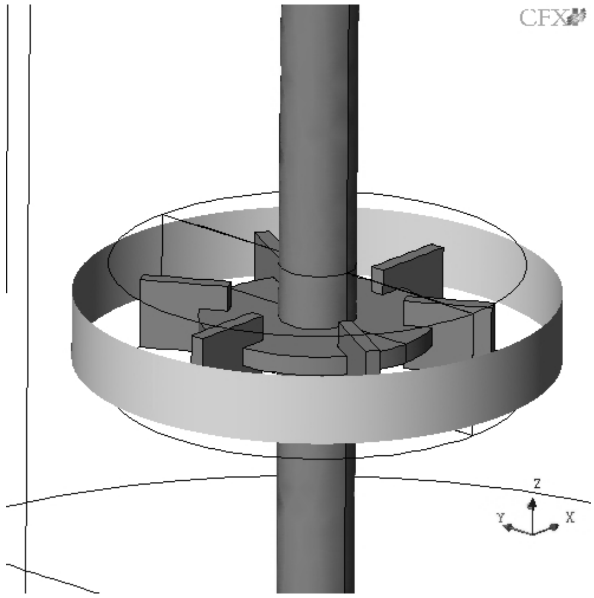
in

$$Ne_{1200}=\frac{P_{1200}}{\rho\cdot n_{1200}^3\cdot d^5}=6{,}4 \quad (23).$$

Izračunani Newtonovi števili primerjamo s preizkusno dobljenimi vrednostmi. Preizkusna vrednost števila moči je za prvi primer $N_{e120,eksp}$ = 4,29 [17] in za drugi primer $N_{e1200,eksp}$ = 6,22 [13]. Tako je odstopanje numerično izračunane vrednosti od preizkusno dobljenih vrednosti brezrazsežnega števila moči v prvem primeru 6% in v drugem primeru 3%.

Poleg števila moči je pomemben podatek tudi pretočno število, ki je podano z enačbo:

$$N_Q=\frac{Q}{n\cdot d^3} \quad (24).$$



Sl. 5. *Površina, na kateri je izračunan povprečni pretok tekočine Q.*

V enačbi za pretočno število se pojavi pretok tekočine Q, ki ga prispeva lopatica rotorja (sl.5). Povprečna masna pretoka tekočine na izstopni površini iz lopatice sta enaka:

$$Q_{120} = 8,634 \cdot 10^{-5}\ \mathrm{m^3/s} \qquad (25)$$

in

$$Q_{1200} = 7,777 \cdot 10^{-4}\ \mathrm{m^3/s} \qquad (26).$$

Iz enačbe (24) se tako preračunata pretočni števili:

$$N_{Q120} = \frac{Q_{120}}{n_{120} \cdot d^3} = 0,881 \qquad (27)$$

in

$$N_{Q1200} = \frac{Q_{1200}}{n_{1200} \cdot d^3} = 0,792 \qquad (28).$$

Izračunani pretočni števili sta primerljivi z preizkusno ugotovljenimi vrednostmi za Rushtonovo mešalo [10]. V osnovi pretočnih števil lahko tudi ocenimo čas premešanja tekočine [9] oz. čas homogenizacije:

$$t_m = \frac{5 \cdot V}{N_Q \cdot n \cdot d^3} \qquad (29).$$

Za prvi primer znaša čas premešanja približno 60 sekund, medtem ko je čas premešanja v drugem primeru nekako 6 sekund. Natančen izračun časa homogeniziranja je mogoč tudi v okviru izračuna RDT, vendar pa je za to potrebno izračunati dodatno prenosno enačbo za neko izbrano sestavino.

6 TOKOVNE RAZMERE

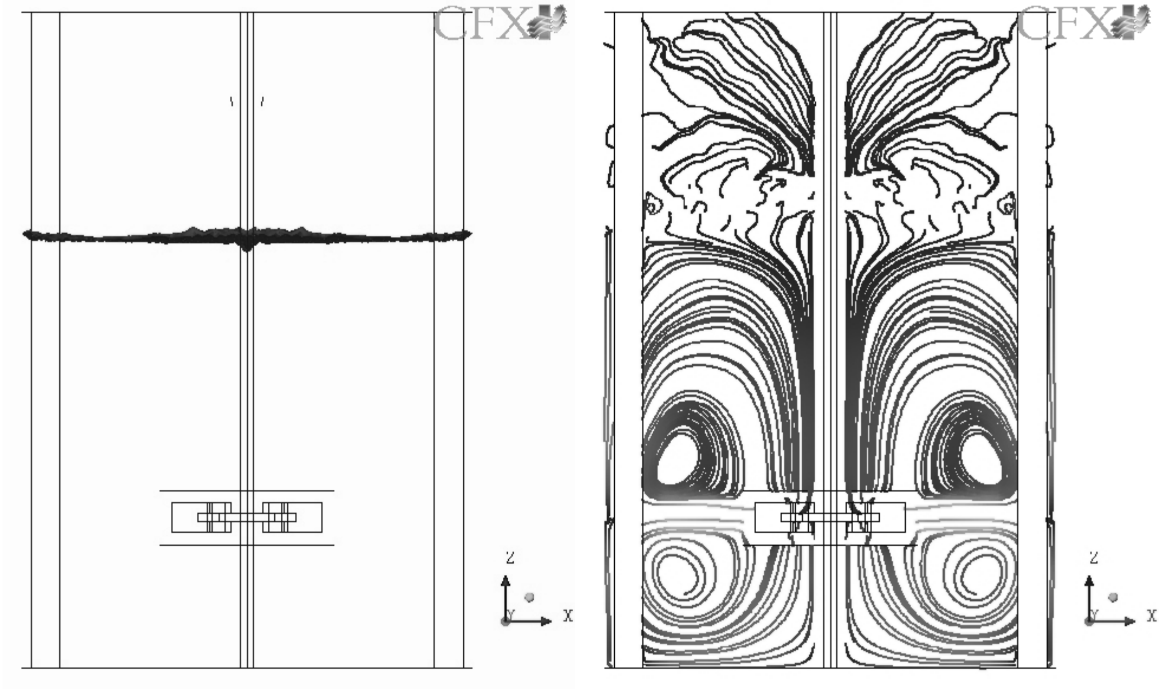
Pri analizi tokovnih razmer v mešalni posodi z Rushtonovim mešalom je znano, da je njegovo tokovno polje prečno. Na sliki 6 so prikazane tirnice delcev v tokovnem polju v mešalni posodi, ki imajo značilno prečni potek. V tokovnem polju je mogoče zaslediti dva globalna vrtinca, enega nad in enega pod ravnino rotorja.

Vektorji tokovnega polja pri različnih vrtilnih frekvencah, iz katerih je razvidna smer gibanja toka tekočine, so prikazani na sliki 7. Vektorji hitrostnega polja so na izstopu iz lopatice usmerjeni navzgor, kar se ujema z eksperimentalno dobljenimi rezultati [8]. Usmerjenost hitrostnih vektorjev navzgor se z oddaljevanjem od roba lopatice zmanjšuje, na določeni oddaljenosti od roba lopatice se vektorji poravnajo v vodoravni smeri oziroma se usmerijo navzdol.

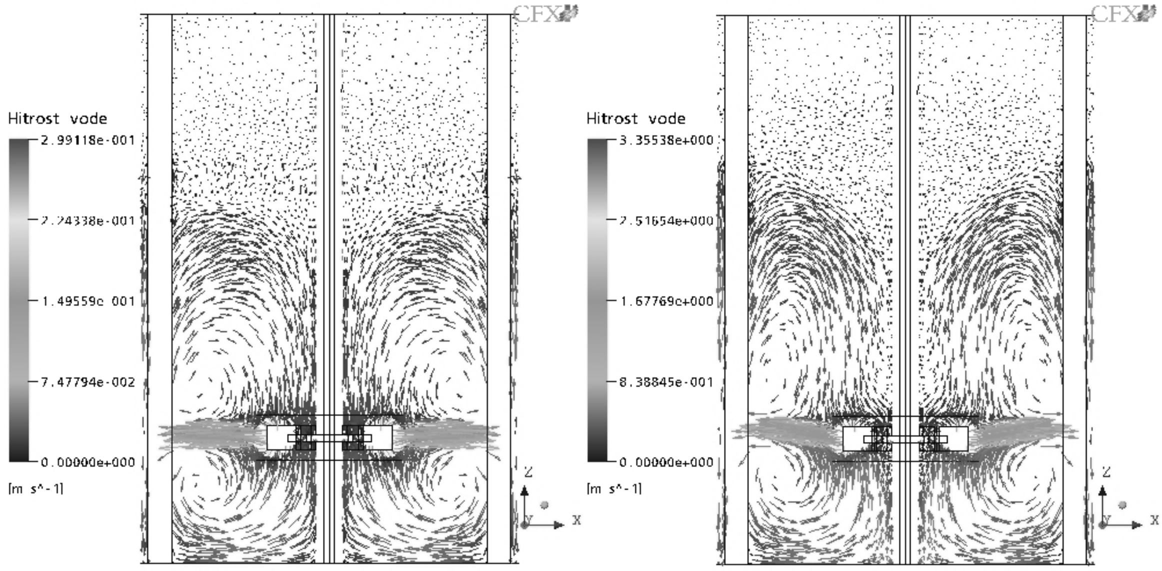
Največje hitrosti tekočine se pojavijo na izstopnem robu lopatice. Hitrostna profila na izstopnem robu lopatice sta prikazana na sliki 8. Hitrostni profil na izstopnem robu lopatice Rushtonovega mešala ima obliko parabole.

S slike 9 je razvidno vrtinčenje toka za pregradami, kar pospeši mešanje toka tekočine in prepreči nezaželeno kroženje toka tekočine po obodu posode, seveda pa poveča potrebno mešalno moč.

Rezultat preračuna RDT je tudi tlačno polje v mešalni posodi. Slika 10 prikazuje tlačno polje v



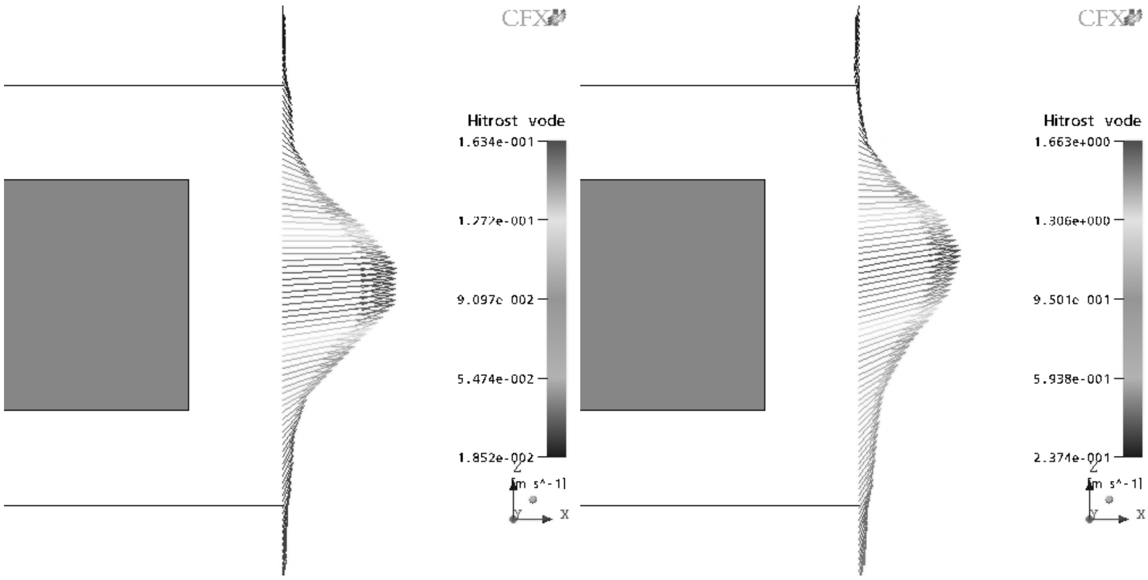
Sl. 6. *Prosta gladina vode v mešalni posodi (levo) in tirnice delcev v radialnem tokovnem polju mešalne posode z Rushtonovim mešalom (desno) pri 120 vrt/min*



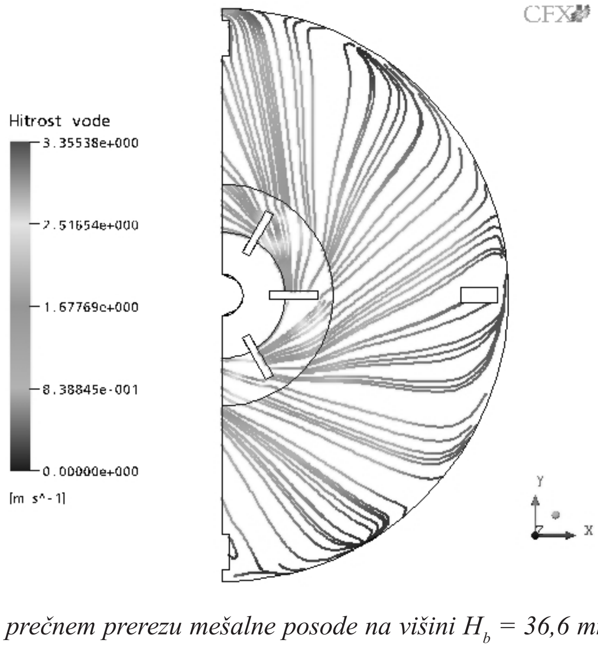
Sl. 7. *Vektorji tokovnega polja v mešalni posodi z Rushtonovim mešalom pri 120 vrt/min (levo) in pri 1200 vrt/min (desno)*

prečnem prerezu mešalne posode na višini 36,6 mm. Največji tlaki se pojavijo v okolici robov lopatice. Pričakovati je bilo, da bodo tlaki v drugem primeru , ko je vrtilna frekvenca dosti večja kakor v prvem primeru, večji. S slik je razvidno, da je porazdelitev tlačnega polja v drugem primeru podobna kakor v prvem primeru, le da so vrednosti tlakov v drugem primeru večje.

Turbulenca je najizrazitejša v okolici lopatic Rushtonovega mešala in se z oddaljevanjem od teh



Sl. 8. *Profil absolutnih hitrosti na izstopnem robu iz lopatice Rushtonovega mešala pri 120 vrt/min (levo) in pri 1200vrt/min (desno)*

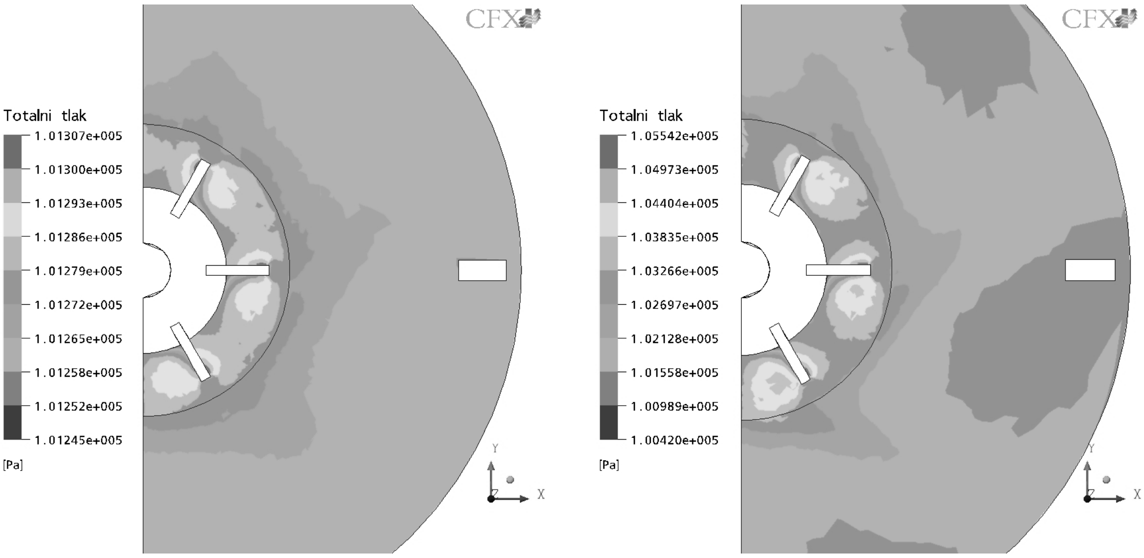


Sl. 9. *Tokovnice v prečnem prerezu mešalne posode na višini H_b = 36,6 mm pri 1200vrt/min*

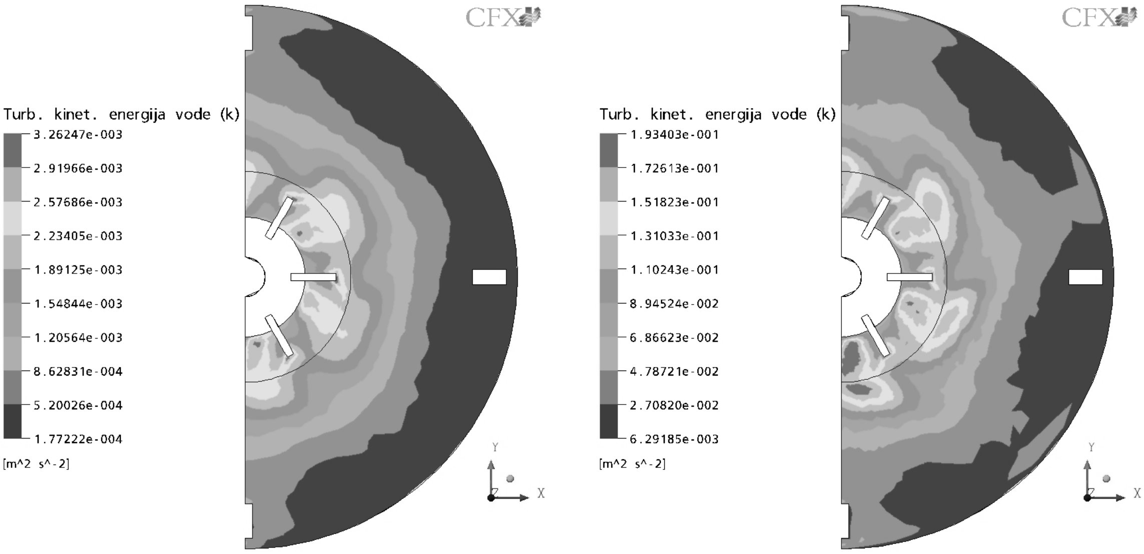
zmanjšuje. S slike 11 so razvidne vrednosti turbulentne kinetične energije na sredini višine lopatice (*z/D* = 0,3). Največje vrednosti turbulentne kinetične energije se pojavijo na vrhu lopatic in za lopaticami, kjer se pojavljajo vrtinci. V prvem primeru, kjer je vrtilna frekvenca rotorja manjša, se pojavijo tudi manjše vrednosti turbulentne kinetične energije kakor v drugem primeru, ko je vrtilna frekvenca večja.

7 SKLEPI

Numerično modeliranje mešanja v mešalni posodi z Rushtonovim mešalom je bilo izvedeno z uporabo metode VKS in dvoenačbnega modela turbulence. Izračunani so bili hitrostni profili na izstopnem robu iz lopatice, značilno tokovno polje mešala, mešalna moč,



Sl. 10. *Tlačno polje v prečnem prerezu mešalne posode na višini H_b = 36,6mm pri 120 vrt/min (levo) in pri 1200 vrt/min (desno)*



Sl. 11. T*urbulentna kinetična energija k v okolici mešala na višini H_b = 36,6 mm pri 120 vrt/min (levo) in pri 1200 vrt/min (desno)*

pretočno število mešala, tlačne razmere v okolici mešala in porazdelitev turbulentne kinetične energije. Rezultati se zelo dobro ujemajo z preizkusnimi izsledki [9], [10], [13] in [14]. Predstavljen približni model je torej moč uporabiti za modeliranje tokovnega polja v mešalni posodi poljubne velikosti, kar je poglavitna prednost uporabe metod RDT.

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Osebne vesti - Personal Events

Prof.dr. Milovan Popovič 1923-2005

Pokojni kolega in prijatelj prof. dr. Milovan Popovič, rojen 21. maja 1923 v Ljubljani nas je tiho zapustil v 82 letu svojega življenja. V pokoju je užival od leta 1993.

Življenjska pot ga je vodila od rojstnega mesta Ljubljane v Mostar in Trebinje, kjer je obiskoval osnovno šolo. Nadaljeval je na nižji gimnaziji, ki jo je obiskoval v Sarajevu, Novi Gradiški in Mariboru. Maturiral je v Beogradu leta 1941. Med okupacijo tedanje Jugoslavije je živel v Zemunu kjer so stanovali njegovi starši in v Zagrebu kjer je bil vpisan na Tehniško fakulteto v akademskih letih 41 do 44. Leta 1944 se je priključil JA v četi za zveze 5-te vojvodinske udarne brigade, 36. jugoslovanske divizije III. armade. Diplomiral je po osvoboditvi v juniju 1947 kot elektrostrojni inženir v Zagrebu.

Služboval je pri podjetju “Elektroistok” oziroma na ministrstvu elektrogospodarstva v Beogradu do leta 1948. V Mariboru je bil zaposlen v Hidromontaži od 1948 do 1955, kot konstrukter hidromehanske opreme in kasneje kot vodja konstrukcijskega oddelka in vodja razvoja hladilne tehnike.

Doktoriral je leta 1979 na strojni fakulteti v Beogradu.

Leta 1963 je bil eden prvih učiteljev tedanje Višje tehniške šole. Leta 1964 je bil prvič izvoljen v naziv višješolski profesor, leta 1970 drugič in zadnjič leta 1975. Leta 1978 je bil prvič izvoljen v naziv izredni profesor in leta 1983 v naziv redni profesor za področje Hidroenergetski sistemi.

Leta 1974 je ustanovil Laboratorij za turbinske stroje, s postavitvijo modela obrnljive turbine, prirejene za obratovanje z zrakom. Laboratorij je bil za tedanje čase izredno dobro opremljen z opremo DISA (danes DANTEC), ki je omogočila prve raziskave toka skozi turbinski stroj, ki so bile vodilna nit raziskovalnih nalog financiranih s strani države.

Objavil je 18 znanstvenih prispevkov na konferencah po celem svetu, en znanstveni povzetek v reviji, izdal več skript in učbenikov s svojega predmetnega področja, preko štirideset končnih poročil o rezultatih raziskav, monografij in drugih zaključenih del in bil mentor mnogim diplomantom takratne Višje tehniške šole, kasnejše Tehniške fakultete in sedanje Fakultete za strojništvo.

Ohranili ga bomo v trajnem spominu kot dobrega sodelavca, enega od ustanoviteljev današnje Fakultete za strojništvo Univerze v Mariboru, kot nesebičnega človeka, ki je znal prisluhniti in pomagati pri reševanju vseh problemov in težav, ki so se porajali v času njegovega dela profesorja, raziskovalca in znanstvenika, kot tudi pri reševanju problemov rasti Višje tehniške šole vse do današnje Fakultete za strojništvo.

prof.dr. Andrej Polajnar

Magisterij in diplome - Master's and Diploma Degrees

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Na Fakulteti za strojništvo Univerze v Mariboru je z uspehom zagovarjal svoje magistrsko delo:

dne 18. novembra 2005: **Bogomir Šetar**, z naslovom: "Določanje kriterijev pasivne varnosti potnikov osebnih vozil z dinamičnimi numeričnimi analizami".

S tem je navedeni kandidat dosegel akademsko stopnjo magistra znanosti.

DIPLOMIRALI SO

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

dne *25. novembra 2005*: Andrej VETRNIK.

Na Fakulteti za strojništvo Univerze v Mariboru sta pridobila naziv univerzitetni diplomirani inženir strojništva:

dne *24. novembra 2005*: Gregor PLEVEL, Mihael ROBEK.

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dne *12. novembra 2005*: Jurij JURMAN, Hinko KLUN, Andrej KOCJANČIČ, Nikolaj SAMSA.

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

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

Papers submitted for publication should comprise:
- Title, Abstract, Main Body of Text and Figure Captions in Slovene and English,
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- 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.

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Članek naj bo napisan v naslednji obliki:
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- 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].

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The paper should be written in the following format:
- A Title, which adequately describes the content of the paper.
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- 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].

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

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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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