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Temperaturne razmere v dotikih z jeklenimi in kompozitnimi zavornimi diski C/C-SiC

Surface Temperatures in the Contacts with Steel and C/C-SiC-Composite Brake Discs

Mihael Kermc - Zmago Stadler - Mitjan Kalin

V običajnih serijskih vozilih so zavorni diski izdelani iz jeklene ali sive litine, zavorne ploščice pa so kompozitne, na podlagi veziv iz organskih smol. Izdelovalci vozil snujejo, predvsem v prestižnem in športnem razredu, vse večja in težja vozila z močnejšimi motorji, ki dosegajo velike hitrosti, zaradi česar potrebujejo taka vozila zavorne sisteme večjih zavornih moči kot jih zagotavljajo običajne zavore. Izboljšanje zmogljivosti zavornega sistema se lahko doseže s povečanjem običajnih sistemov, kar ni najustreznejša rešitev, ali z uporabo novih, boljših materialov za zavorne diske in ploščice. Med obetavne materiale, ki se uporabljajo v te namene, sodijo tudi kompozitni diski C/C-SiC. Kljub majhni obrabi in zmožnosti prenašanja velikih zavornih moči, je njihova uporaba zelo omejena zaradi trenutno neustreznih materialov zavornih ploščic, ki bi se lahko uspešno uporabljali v dvojici s temi diski. Eden izmed glavnih razlogov za to je visoka temperatura, ki nastaja v dotikih z diski C/C-SiC. Zaradi posebnosti materialov in zgodnje faze razvoja takih zavornih sistemov pa ustreznih podatkov v literaturi še ni.

Kot prvi korak pri razvoju ustreznih zavornih ploščic, za že znane zavorne diske lastne proizvodnje iz kompozitov C/C-SiC, smo zato najprej raziskali vrednosti temperatur, ki nastajajo na površinah teh diskov in jih primerjali z običajnimi jeklenimi diski. Spremljali smo tudi potek rasti dotikalnih temperatur na dveh različnih preizkuševališčih, na katerih smo lahko simulirali dinamične pogoje zaviranja in ustaljene pogoje ter razlike med diski C/C-SiC in jeklenimi diski razložili z različnimi toplotnimi lastnostmi raziskovanih materialov. V vseh testih smo za material ploščic uporabili kompozit na podlagi kovinske matrice, prav tako lastne izdelave.

(Ključne besede: diski zavorni, litina jeklena, C/C-SiC kompoziti, razmere temperaturne)

Automotive braking systems normally employ conventional or ventilated brake discs and pads. In these systems the brake discs are made of steel or grey cast iron, which are paired with composite "organic" brake pads. Car manufacturers, however, are designing larger and heavier vehicles, with more powerful engines, which results in higher driving speeds and greater demands being placed on the frictional power of the brake systems. Improving the performance of a braking system requires either a larger conventional brake, which is not the best solution, or the use of new, improved brake-disc and pad materials. One such promising material for brake-disc applications is a C/C-SiC composite. However, despite its low wear rate and high frictional power, its use is still very limited because of the lack of an appropriate pad material that will perform well in combination with these discs under the conditions that are experienced with mass-production vehicles. One of the main reasons for this is the supposed high temperatures generated in these contacts. However, since this research is in its early stages and because of the particular materials and their combinations, relevant data on this topic cannot be obtained from the literature.

Our first step in the development of a pad material for our own design of C/C-SiC composite discs was to determine the contact temperature and make a comparison with conventional steel discs under the same conditions. The evolution of the contact temperature was studied using two different testing machines and methods, where we simulated the dynamic braking conditions that are similar to those observed in real applications and under steady-state conditions. The differences could be explained by the thermal properties of the materials. All the experiments used the same pads, which were made from a metal-matrix composite to our own design.

(Keywords: brake discs, steel, C/C-SiC composite, surface temperatures)

0 UVOD

Zavorni sklopi v vozilnih zavornih sistemih so običajno sestavljeni iz kompaktnega ali zračenega zavornega diska in zavornih ploščic [1]. V običajnih, serijskih vozilih so zavorni diski izdelani iz jeklene ali sive litine, zavorne ploščice pa so kompozitne, na temelju veziv iz organskih smol [2]. Te dvojice materialov so tribološko ustrezne za uporabo v zavornih sistemih zmernih obremenitev, saj jih pri tem odlikuje razmeroma visok in stabilen koeficient trenja, majhna obraba ter običajno tiho delovanje ([3] in [4]). Izdelovalci vozil snujejo predvsem v uglednem in športnem razredu vse večja in težja vozila z močnejšimi motorji, ki dosegajo velike hitrosti, zaradi česar potrebujejo taka vozila zavorne sisteme večjih zavornih moči, kakor jih zagotavljajo običajne zavore. Uporaba le-teh je namreč omejena s dotikalno temperaturo ploščic, ki jo določa piroliza veziva, tj. fenolne smole. Pri temperaturi 240 °C začno zato ti materiali izgubljati svoje, prvotno dobre, lastnosti in postanejo neprimerni za uporabo ([5] in [6]).

Izboljšanje zmogljivosti zavornega sistema se lahko doseže z rekonstrukcijo (povečanjem) običajnih sistemov z dimenzioniranjem za večje obremenitve ali z uporabo novih, boljših materialov za zavorne diske in ploščice. Povečanje sedanjih sistemov ima za posledico tudi povečanje mase sistema, kar ponovno zmanjša zmogljivost vozila in prvotno želen učinek. Zaradi tega je sama rekonstrukcija zavornega sistema mogoča le izjemoma - za manjše povečanje zavornih moči, v nekaterih primerih, npr. v športnih modelih serijskih vozil in še posebej v športno-hitrostnih tekmovalnih vozilih, pa je to neustrezen način rešitve, saj je teža zavornih sistemov eden od ključnih parametrov njihove učinkovitosti ter s tem celotnega vozila. Zaradi tega so že v preteklosti uvajali v najzahtevnejše zavorne sisteme predvsem diske iz novejših in sodobnejših materialov. Npr. v zavornih sistemih v letalstvu in avtomobilskih tekmovalnih razredih se uporabljajo kompoziti na podlagi ogljika (kompoziti C/C) ([7] do [10]), v hitrih vlakih ICE kompoziti s kovinskim vezivom (KKV - kompoziti MMC) [11], za uporabo v širši prevozni tehniki pa so bili razviti kompoziti na podlagi ogljika in keramike (kompoziti C/SiC, C/C-SiC), ([12] in [13]).

Kompoziti C/C-SiC so zanimiv in obetaven material za zavorne diske širokega pasu uporabe. Zaradi majhne gostote so diski iz kompozitov C/C-SiC znatno lažji od navadnih kovinskih in primerljivi z diski iz KKV ter C/C ([7], [12] in [13]). Zaradi dobre korozijske in oksidacijske obstojnosti ter odličnih toplotnih lastnosti lahko obratujejo pri nekaj 100 °C višjih temperaturah kakor navadni kovinski diski ali diski iz KKV [14], kar jim omogoča doseganje izjemnih zavornih moči. V primerjavi z diski na podlagi kompozitov C/C pa imajo znatno manjšo obrabo in s

0 INTRODUCTION

Automotive braking systems normally employ conventional or ventilated brake discs and pads [1]. In these systems the brake discs are made of steel or grey cast iron, which are paired with composite “organic” brake pads [2]. These types of friction materials are suitable for use in braking systems with moderate loads, where they exhibit a relatively high and stable friction coefficient, a low rate of wear and are quiet during operation ([3] and [4]). Car manufacturers’ designs of prestige and sports-class vehicles always tend towards larger and heavier vehicles. These vehicles have powerful engines and reach high driving speeds. Accordingly, they need braking systems that provide more braking power compared to conventional braking systems. The use of conventional braking systems is, however, limited by the contact temperature due to the pyrolisis of the phenolic resin bonding material. Consequently, at 240°C the originally good material properties start to deteriorate and the material becomes useless ([5] and [6]).

Improved braking-system performance can be achieved either by a re-design (i.e., an enlargement) of the conventional brake system, in terms of higher loads, or by the use of new, improved brake-disc and pad materials. A simple re-design of conventional braking systems leads to an increase in the mass of the system, thus reducing the vehicle’s performance characteristics, which means that the beneficial effect of the extra performance is significantly diminished or even negated. A re-design is therefore only applicable for a small increase in the braking power and is not at all suitable for sports vehicles and race-class vehicles, where weight is one of the main performance characteristics of the braking system and of the whole vehicle. Accordingly, new brake-disc materials were introduced for braking systems with higher-performance demands: carbon/carbon composites are used in aviation and racing vehicles ([7] to [10]), fast ICE-class trains use metal matrix composites (MMCs) [11], and for uses in general transportation, a variety of fibre-reinforced ceramic composites (C/SiC, C/C-SiC) were developed ([12] and [13]).

C/C-SiC composites are an interesting and promising material for brake discs with a wide range of applications. The low density of C/C-SiC makes them significantly lighter than classic steel discs and comparable with Al-MMCs and C/C composite brakes ([7], [12] and [13]). Because of their good corrosion and oxidation resistance and their thermal properties, C/C-SiC brake discs can operate at several hundreds of °C higher temperatures than ordinary steel or Al-MMC composite discs [14], which means they can provide much more braking power. When compared to C/C brake discs, the wear of C/C-SiC discs is significantly lower and the lifetimes accordingly tem daljšo dobo trajanja [15]. Zaradi teh prednosti se kompoziti C/C-SiC izkazujejo kot najbolj obetajoč material zavornih diskov za uporabo, poleg športno-hitrostnih vozil, v katera se že redno vgrajujejo, tudi v serijskih vozilih športnega in višjega cenovnega razreda.

Razvoj zavornih sistemov terja poleg ustreznega materiala diskov tudi le-tem tribološko prilagojen material zavornih ploščic, saj mora tak sistem zagotavljati visok in stabilen koeficient trenja v vsem območju delovanja, dobre protiobrabne lastnosti, ustrezne dotikalne razmere, ki ne povzročajo vibracij in hrupa, čim manjšo občutljivost za vlago in vodo idr. Trenutno so v uporabi zavorne ploščice iz treh različnih skupin materialov, in sicer na podlagi materialov z organskimi vezivi, kompozitnih materialov C/C ter KKV. V dosedanjih raziskavah je bilo ugotovljeno ([16] in [17]), da sedanji materiali zavornih ploščic, ki so bili posebej razviti za uporabo v navadnih, KKV ali zavornih sistemih C/C, ne zagotavljajo ustreznih triboloških lastnosti tudi v dotikih z diski iz kompozitov C/C-SiC ter s tem povezanih delovnih lastnosti celotnega zavornega sistema. Zaradi tega so materiali za zavorne ploščice v zavornem sistemu z diski C/C-SiC šibki člen in omejujejo njihovo širšo uporabo ter še posebej uporabo v serijskih vozilih. Med znanimi materiali za zavorne ploščice dosegajo še najboljše rezultate kompoziti na podlagi kovinske matrice in se kljub številnim pomanjkljivostim glede obrabe in hrupa uporabljajo v športnih motociklih [18], zato smo jih izbrali kot temelj za naše raziskave in razvoj.

Dosedanje izkušnje in literatura o triboloških lastnostih v dotikih s kompoziti C/C-SiC, še posebej pri velikih obremenitvah, nakazujejo, da je predvsem precej višja temperatura na dotikalnih površinah pri teh sistemih, v primerjavi z običajnimi kovinskimi diski, razlog za neustrezne lastnosti in uporabo vrste protimaterialov za zavorne ploščice [17]. Podrobnih analiz o višini dotikalnih temperatur in neposredne primerjave z materiali iz običajnih zavornih sistemov pa v literaturi nismo našli. Zaradi potrebe po podrobnejšem poznavanju temperaturnih razmer in njihove morebitne ključne vloge pri razvoju tribološkega sistema med kompoziti C/C-SiC in KKV smo v tem delu raziskali temperaturne razmere v dotikih med kompozitnimi diski C/C-SiC in zavornimi ploščicami na podlagi kompozita s kovinskim vezivom ter jih primerjali z razmerami v dotikih med običajnimi jeklenimi diski in enakimi ploščicami na podlagi kompozita s kovinskim vezivom. Temperaturne razmere smo raziskovali s standardnim preizkusom, s katerim smo skušali simulirati delovanje in razmere pri zaviranju dejanskega zavornega sistema, ter modelnega preizkusa, s katerim smo ugotavljali vpliv toplotnih lastnosti materialov na dotikalno temperaturo obeh sistemov v ustaljenih razmerah.

longer [15]. All of these advantages make C/C-SiC composites the most promising material for the brake discs of racing vehicles, where they are already in use, but also for the serial production of prestige and sports vehicles.

However, the development of an automotive braking system requires a brake-disc material with a tribologically matched brake-pad material. The whole system must provide a high and stable friction coefficient across the whole operating range, as well as good wear resistance, appropriate contact conditions that do not generate noise and vibration, low humidity and water dependence/ sensitivity, etc. Presently, three different types of brake-pad materials are in use: organic, C/C and MMCs. Earlier studies ([16] and [17]) showed that existing brake-pad materials developed for use with ordinary steel, Al-MMCs or C/C composite brake discs do not provide the proper tribological behaviour in the contact with C/C-SiC composite brake discs, and therefore the performance of the brake system is not satisfactory. Accordingly, the brake-pad material represents a weak point in the C/C-SiC brake system and causes major limitations in the use of these systems in serial vehicle production. Among the various brake-pad materials available, metal-matrix composites show the best results and are, despite their deficient wear and noise properties [18], already in use for sports-motorcycle braking systems. Therefore, we decided to use this material as a starting material for our research and development of a new tribological system for brakes.

Early investigations and the literature data about the tribological properties in contacts with C/C-SiC composite brake discs show that, particularly at higher loads, a significantly higher contact temperature compared to conventional steel discs is the main reason for the poor performance and the reduced choice of possible brake-pad materials in contacts with C/C-SiC composite brake discs [17]. We could not find any publications referring to contact temperatures in C/C-SiC brake discs and their comparison with conventional braking systems. However, such data could be very important for the development of a C/C-Si–MMC tribological system. Therefore, in our study, temperatures in the contact of C/C-SiC composite brake discs with MMC brake pads were investigated and compared with the temperatures generated in the contacts of conventional steel brake-disc and the same MMC brake-pad materials. The surface temperatures were studied by using two different experimental devices and procedures: i.e., a standard test, where operation under real braking conditions was simulated; and a model test, where the influence of the thermal properties on the contact temperature under stationary conditions was studied.

1 EKSPERIMENTALNO DELO

1.1 Materiali

V raziskavi smo za vzorce uporabili zavorne diske in zavorne ploščice enakih izmer, kakršne se vgrajujejo v špotno-tekmovalne motocikle. Prvi tip zavornih diskov (MS Production, Bled, Slovenija) je bil izdelan iz kompozita C/C-SiC premera 320 mm in debeline 7 mm. Slika 1 prikazuje prerez diska v bližini površine. Nosilno jedro je izdelano iz 2D kompozita C/C, ki ohranja mehanske lastnosti tudi pri povišanih temperaturah, do 1400 °C. Kompozitno jedro je prekrito s plastjo reakcijsko sintranega SiC [12]. Debelina plasti SiC na dotikalnih površinah znaša 400±20µm. Površinska plast SiC se nadaljuje v mešano plast SiC in C/C ter postopoma preide v čisti kompozit C/C na globini 550±20µm pod površino. Drugi tip diskov, ki smo jih uporabili, so bili običajni jekleni diski (DP320/6, Brembo, Bergamo, Italija) premera 320 mm in debeline 6 mm. Vse preizkuse smo opravili z zavornimi ploščicami izmer 78 x 26 mm, izdelanimi na podlagi kompozita s kovinskim vezivom (tip 4035, MS-Production, Bled, Slovenija).

1.2 Standardni preizkus

V raziskavi smo uporabili dve vrsti preizkusov. Prvi je bil standardni preizkus, s katerim simuliramo delovanje in razmere na zavornih površinah pri zaviranju dejanskega zavornega sistema. Testi so bili opravljeni na

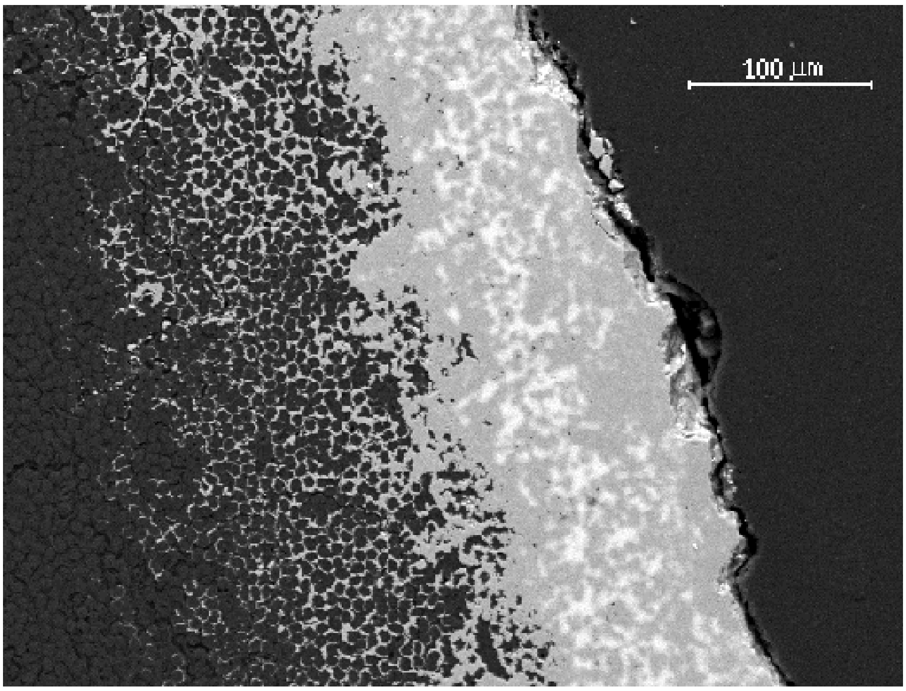
1 EXPERIMENTAL WORK

1.1 Materials

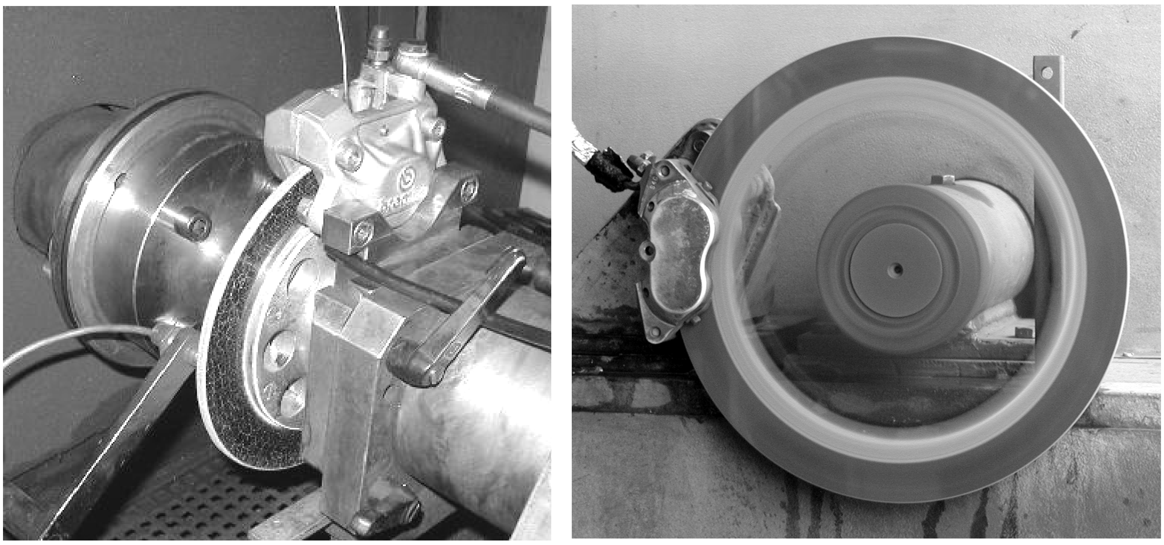
For the research, brake discs and pads with the same dimensions as used in racing motorcycles were used. One type of discs (MS Production, Bled, Slovenia) was made of a C/C-SiC composite material. The diameter of the disc was 320 mm and the thickness was 7 mm. Figure 1 shows a section of the disc near the surface. The supporting core is made of a 2D C/C composite that maintains its mechanical properties even at elevated temperatures, up to 1400°C. The core is covered with a reaction-bonded SiC layer [12]. The layer thickness on the contact surfaces is 400±20µm. The surface's "pure" SiC layer gradually changes with depth from the surface to a mixed layer of C/C and SiC and further on to a pure C/C matrix at 550±20µm below the surface. The second type of brake disc was conventional steel brake discs (DP320/6, Brembo, Bergamo, Italy), with a diameter of 320 mm and a thickness of 6 mm. All the tests were performed by using the same type of MMC brake pads, with dimensions of 78 x 26 mm (MS Production, Bled, Slovenia).

1.2 Standard testing procedure

Two different testing procedures were used. The first was a standard procedure, where the operating and contact conditions of a real braking system were simulated. The tests were performed on a standard KRAUSS RWS75B (Krauss G.m.b.H., Murr, Germany)



Sl. 1. *Mikrostruktura prereza zavornega diska iz C/C-SiC kompozita v bližini površine*
Fig. 1. *Microstructure of C/C-SiC composite brake disc section near surface*



a) b)

Sl. 2. *Shematski prikaz (a) standardnega preskuševališča KRAUSS RWS75B ter (b) modelnega preskuševališča MS-P.*
Fig. 2. *Shematic view of (a)standard testing machine KRAUSS RWS75B and (b)model testing machine MS-P.*

preizkuševališču KRAUSS RWS75B (Krauss G.m.b.H., Murr, Nemčija) v skladu z 8. odstavkom, navodila ECE-R90 Združenih narodov [19], ki predpisuje postopke preskušanja zavornih lastnosti na napravah za preizkušanje. Test je sestavljen iz dveh faz. Prva faza je namenjena zgolj utekanju/prilagajanju dotikalnih površin. Poteka pri hitrosti 5,8m/s ter tlaku 1,16MPa. Sestavljena je iz 30 zaviranj, pri čemer temperatura diska ne sme preseči 250 °C, sicer je potrebno ohlajanje na 50 °C. Sledi druga faza, ki pomeni dejansko preizkušanje za vrednotenje rezultatov. V fazi preizkušanja se izvede šest krat po deset zaviranj, skupaj 60 zaviranj. Posamezen cikel zaviranja je sestavljen iz 5 s zaviranja in 10 s prostega teka pri stalni drsni hitrosti 5,8 m/s ter tlaku 1,16 MPa. Med posameznimi sklopi testa je treba disk ohladiti na 100 °C. Temperature diska se v skladu s postopkom [19] merijo s termoelementom v drsni izvedbi na površini diska ob izstopu iz dotika z zavorno oblogo. Uporabljeno standardno preizkuševališče je shematsko prikazano na sliki 2a.

1.3 Modelni preizkus

Drugi tip preizkusa v tej raziskavi je bil modelni preizkus, s katerim smo želeli ugotoviti končno temperaturo zavornih površin pri ustaljenih pogojih in primerjati vrednosti pri obeh dvojicah materialov ter ugotoviti vpliv toplotnih lastnosti materialov na razvoj temperaturnega stanja. Za dosego tega cilja je bilo treba izbrati novo preizkuševališče, saj predpisana oprema in postopek po [19] ne zagotavljata pogojev za doseganje

testing machine in accordance with Annex 8 of the United Nations ECE-R90 regulation [19], where the determination of friction behaviour by machine testing is regulated. The test consists of two phases. The first phase is the running-in procedure, which is necessary to adapt/ conform the contacting surfaces. The speed in this stage is 5.8 m/s, and the pressure 1.16 MPa. It comprises 30 braking cycles. The complete loading and un-loading of the contact is considered as a braking cycle. If the disc temperature exceeds 250°C during the running-in, cooling of the disc to 50°C is required. The first phase is followed by the second phase, which represents the actual testing for the evaluation of the results. In the second phase, six groups of ten braking cycles, a total of 60 cycles, are performed. Each braking cycle consists of 5 seconds of braking and 10 seconds of free run at a constant sliding speed of 5.8 m/s and a pad pressure of 1.16 MPa. After every 10 cycles a cooling period is required to allow the disc temperature to reach 100°C. In accordance with the procedure in [19], the disc temperature is measured with a thermocouple sliding on the disc surface at the exit from the pad-disc contact. The standard testing machine used for our experiments is shown in Figure 2a.

1.3 Model testing procedure

The second type of testing was a model testing procedure. The purpose of this test was to determine the temperature of the contacting surfaces under stationary sliding conditions, and to compare the values for both disc materials in order to determine the influence of thermal properties on the disc's surface temperatures. To achieve this goal, a different testing procedure had to be chosen, because the standard equipment and procedure according to [19] do not ensure the ustaljene temperaturne ravni. Modelni testi so bili zato izvedeni na lastnem preizkuševališču zavornih sistemov MS-P [20], ki je v zasnovi podobno znanim sorodnim preizkuševališčem [21], in je shematsko prikazano na sliki 2b.

Pred začetkom dejanskega preizkusa smo, podobno kakor pri standardnem testu, opravili fazo utekanja/prilagajanja dotikalnih površin. Pri utekanju smo uporabili enak osnovni cikel zaviranja kakor pri standardnem testu, torej 5 s zaviranja in 10 s prostega teka, v preizkusu pa je bil cikel sestavljen iz 5 s zaviranja in 5 s prostega teka, s čimer smo lahko hitreje povišali dotikalno temperaturo. Utekanje je zajemalo enako kakor v standardnem testu 30 ciklov zaviranj, dejanski preizus pa 20 ciklov zaviranj. Pri tem številu zaviranj smo pri obeh raziskovanih dvojicah materialov dosegli ustaljeno temperaturno stanje. Preizkus je potekal pri stalni drsni hitrosti 26 m/s ter tlaku približno 0,8 MPa.

Za meritev temperature smo uporabili vgradni termoelement, ki smo ga vstavili v mirujočo zavorno ploščico na globini približno 300 μm pod površino. S tem smo se skušali čim bolj približati meritvam »dejanske dotikalne« temperature na zavornih površinah.

conditions for the build-up of stationary temperature conditions. Model tests were therefore performed on a self-built MS-P testing machine [20], which has a similar design to other existing testing machines [21], and is schematically shown in figure 2b.

The testing procedure was, like the standard testing procedure, composed of two phases. At the beginning there was a running-in phase where the contact surfaces were adapted. The running-in phase contained 30 braking cycles of 5 seconds of braking followed by 10 seconds of free run, the same as in the standard test. In the second phase, which was used for the evaluation of the results, the braking cycle was partially modified. The adjusted cycle was composed of 5 seconds of braking and 5 seconds of free run, which allowed us to raise the contact temperature more rapidly and to achieve the stationary conditions faster. Accordingly, only 20 braking cycles were needed to obtain the stationary temperature level. The test was performed at a constant sliding speed of 26 m/s and a pad pressure of 0.8 MPa.

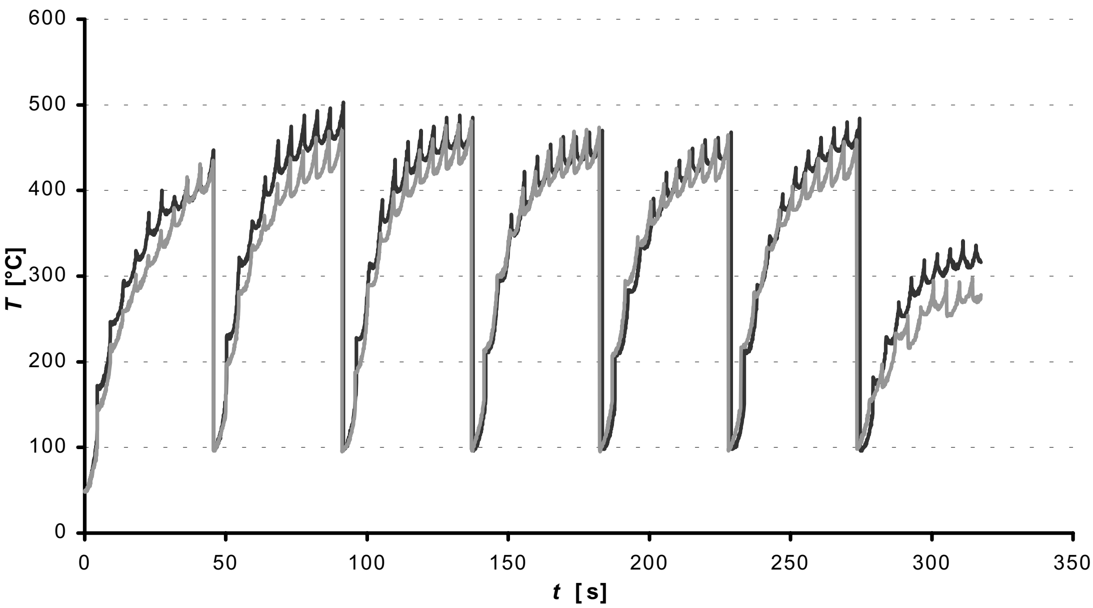
For the temperature measurement a thermocouple built into a stationary brake pad and positioned approximately 300 μm below the contact surface was used. In this way we tried to measure the "real contact" temperature as close as possible to the braking contact surface where the heat is generated.

2 REZULTATI

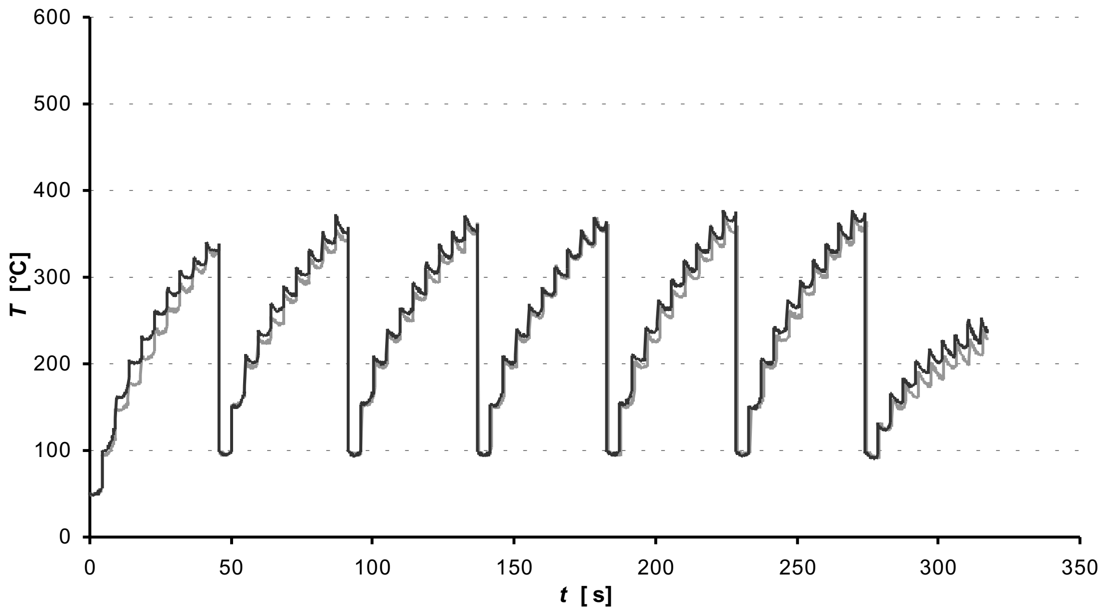
Slika 3 prikazuje rezultate dveh meritev temperature na disku iz kompozita C/C-SiC v dotiku s ploščico iz kompozita MMC, izvedenih na standardnem preizkuševališču. Krivulje poteka

2 RESULTS

Figure 3 shows the results of the two temperature measurements on the C/C-SiC composite brake disc in contact with MMC composite brake pads performed on a standard testing machine. It is clear that in each group of



Sl. 3. *Diagram poteka temperature v odvisnosti od časa preskusa (standardni preskus, disk C/C-SiC, ploščica 4035, v=5,86m/s, p=1,16MPa). Digram prikazuje rezultate dveh preskusov.*
Fig. 3. *Graph of measured temperature over time of measurement (standard test, disc material C/C-SiC, pad 4035, v=5,86m/s, p=1,16MPa). Graph represents results from two measurements.*



Sl. 4. *Diagram poteka temperature v odvisnosti od časa preskusa (standardni preskus, disk jeklo, ploščica 4035, v=5,86m/s, p=1,16MPa). Digram prikazuje rezultate dveh preskusov.*
Fig. 4. *Graph of measured temperature over time of measurement (standard test, disc material steel, pad 4035, v=5,86m/s, p=1,16MPa). Graph represents results from two measurements.*

temperature v vseh spletih zaviranj se dvigujejo dokaj hitro do temperature približno 400 °C, nato pa se krivulje zravnajo, kar nakazuje na približevanje ustaljenim pogojem. Pojav je še posebej izrazit v zadnjih petih sklopih. Kljub temu ustaljeni pogoji v nobenem primeru niso bili doseženi, saj je v skladu z [19] vedno prej sledil vmesni prosti tek z ohlajanjem diska na 100°C. Najvišje dosežene temperature v posameznih sklopih se razlikujejo za 70 °C, vendar pa je bila ponovljivost rezultatov posameznih sklopov zelo dobra, običajno boljša od 10% odstopanj. Najvišja izmerjena temperatura na površini diska je bila 480 °C.

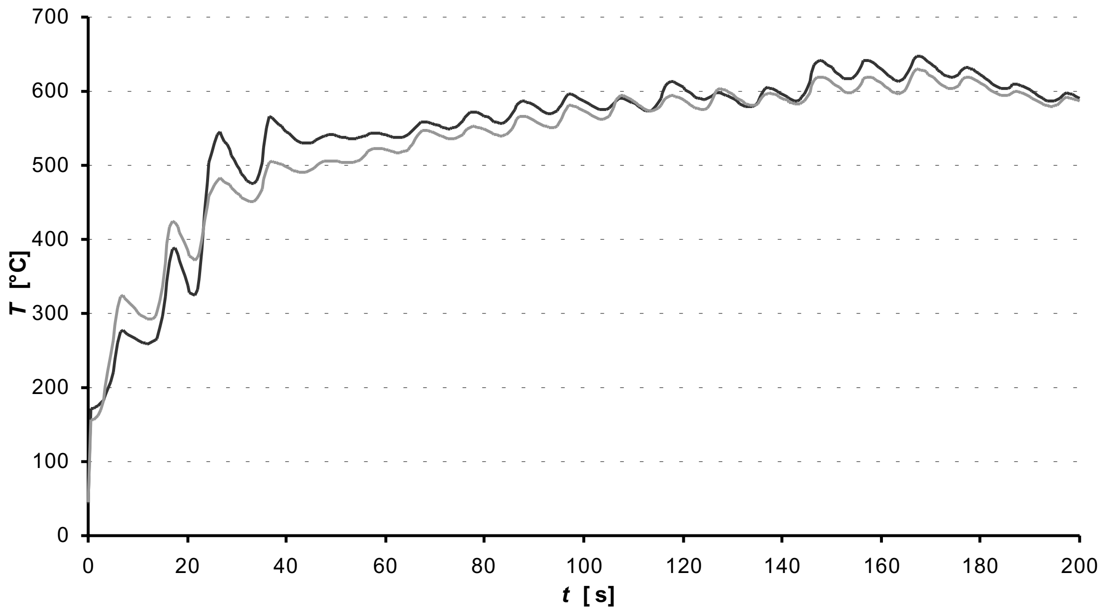
Slika 4 prikazuje rezultate dveh meritev temperature na jeklenem disku v dotiku s ploščico iz kompozita MMC, izvedenih na standardnem preizkuševališču. Krivulje poteka temperature v posameznem sklopu zaviranj so precej različne od krivulj pri disku C/C-SiC. Krivulje so v tem primeru veliko bolj položne in skoraj ravne. Na koncu vsakega sklopa še ni zaznati približevanja ustaljenim pogojem. Najvišja temperatura v posameznem krogu se povečuje in doseže najvišjo temperaturo pri teh pogojih v zadnjem, šestem sklopu, 370 °C. Razlika najvišjih temperatur, doseženih v posameznem sklopu, je za polovico manjša kakor v primeru diskov C/C-SiC (sl. 3), 35 °C. Ponovljivost izmerjenih rezultatov je izjemno dobra, boljša od 5 % odstopanj.

Na sliki 5 vidimo rezultate meritev temperature pod površino ploščice MMC v dotiku z diskom C/C-SiC pri preizkusu na modelnem preizkuševališču. Prikazani so rezultati dveh meritev,

braking cycles the temperature rises relatively quickly until a temperature of approximately 400°C is reached, but then the curves flatten out slightly, which indicates an approach to constant-temperature conditions. This phenomenon is particularly clear in the last five braking-cycle groups. However, the constant-temperature conditions were not observed in any of the braking-cycle groups because, according to the ordinances [19], the free-run cycle with cooling the disc down to 100°C interrupts the frictional heating process. The highest temperatures achieved in these six groups varied by about 70°C, yet the repeatability of the results in separate groups was very good: in general with a deviation of less than 10%. The highest measured temperature was 480°C.

Figure 4 shows the results of two temperature measurements on a steel brake disc in contact with MMC composite brake pads, performed on a standard testing machine. The shape of the temperature curves in each braking-cycle group is different from those obtained with the C/C-SiC brake disc. In this case the curves are not so steep and almost linear. Even at the end of each braking group there are no indications of approaching the constant-temperature level. The highest temperature measured in each group increases in every subsequent group, and is highest in the last (the sixth) group, reaching 370°C. The variation in highest measured temperatures in every braking-cycle group is only half as high as the variation in the C/C-SiC composite brake discs (Figure 3), i.e., 35°C. The repeatability of the measured results is very good, with a deviation of less than 5%.

Figure 5 presents the results from the temperature measurement beneath the contact surface in the MMC brake pad in contact with the C/C-SiC brake disc, performed on a model-testing machine. The results



Sl. 5. *Diagram poteka temperature v odvisnosti od časa preskusa (modelni preskus, disk C/C-SiC, ploščica 4035, v=26,14m/s, p=0,44MPa). Digram prikazuje rezultate dveh preskusov.*
Fig. 5. *Graph of measured temperature over time of measurement (model test, disc material C/C-SiC, pad 4035, v=26,14m/s, p=0,44MPa). Graph represents results from two measurements.*

ki potrjujejo zelo dobro ponovljivost rezultatov preizkusov. Vidimo, da je krivulja zelo strma, kar pomeni zelo hiter dvig dotikalne temperature do približno 550 °C, nato pa veliko počasneješe in umirjeno povečevanje do približno 600 °C, ko je temperatura ostala nespremenljiva. Gradient povečevanja temperature na začetku preizkusa, v prvih štirih ciklih, je znašal približno 30 K/s. Ti rezultati so v tem smislu podobni rezultatom, dobljenim na standardnem preizkuševališču, za katere je bil tudi značilen strm dvig temperature in kasnejše počasno približevanje ustaljenim razmeram.

Potek krivulje temperature v dotikih z jeklenimi diski, merjenimi na modelnem preizkuševališču, prikazuje slika 6. Temperatura je naraščala znatno počasneje kakor v primeru enakih preizkusov z diski C/C-SiC in je v prvih štirih ciklih znašala le 10 K/s. Po približno 10 ciklih je temperatura dosegla najvišjo vrednost, približno 550 °C, nato pa se je začela počasi zniževati, vse do ustaljenih razmer pri približno 420 °C. Čeprav so rezultati meritev temperature v prvem delu testa podobni kakor na standardnem preizkuševališču, tj. razmeroma počasno višanje temperature, pa lahko v tem primeru vidimo, da se pred doseženim ustaljenim stanjem temperatura zniža. Tak potek krivulje dotikalne temperature je povsem različen od poteka pri dotikih z diski C/C-SiC pri enakih razmerah preizkušanja, kar nakazuje na znatne razlike med raziskovanima dvojicama materialov.

3 RAZPRAVA

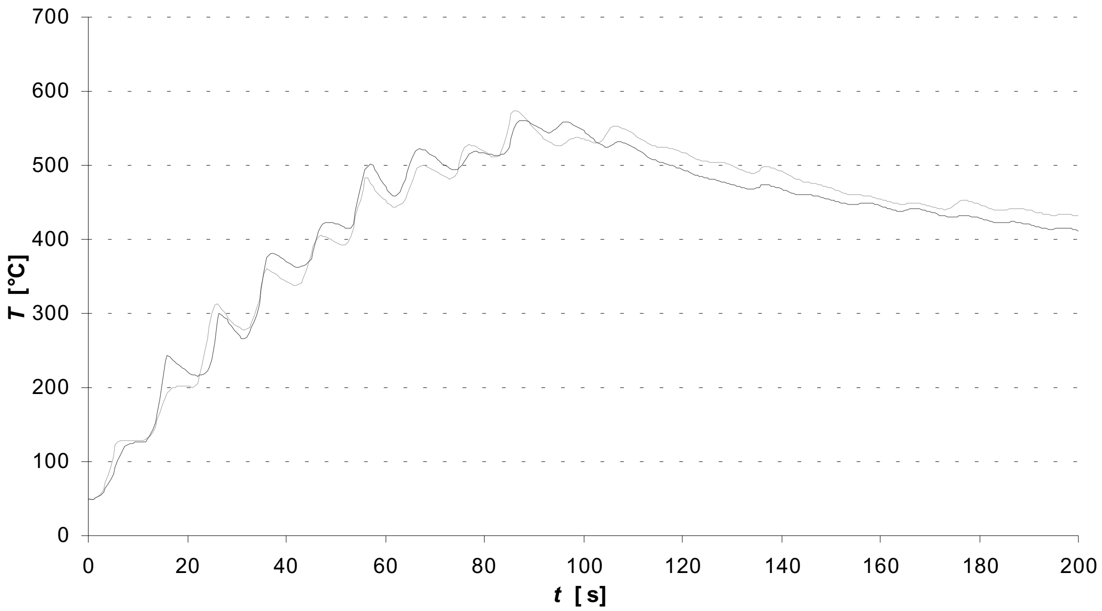
Iz dosedanjih raziskav je bilo ugotovljeno, da ima temperatura na zavornih površinah velik pomen

from two measurements indicate very good repeatability of the results. The curves are very steep, which indicates a rapid increase in the contact temperature up to approximately 550°C. After reaching this level the increase is slower, and the temperature gradually increases to approximately 600°C, where it remains constant. At the beginning of the test (in the first four braking cycles), the gradient of the temperature increase was approximately 30 K/sec. These results are similar to the results obtained from the tests on the standard testing machine, where a steep rise and a subsequent gradual approach to constant-temperature conditions was also measured.

The course of the temperature graphs measured on the steel brake discs using the model-testing machine is shown in Figure 6. The temperature increase was much slower than for the C/C-SiC composite brake discs, and the gradient in the first four cycles was only 10 K/sec. After approximately 10 cycles the temperature reached its highest value, approximately 550°C, and then started to decrease until the constant-temperature level was restored at approximately 420°C. In the first part of the test the results are similar to the results obtained using the standard testing machine, i.e., a moderate temperature increase. However, in the second part of the tests they are different, showing a decrease in the temperature before the constant-temperature level is reached. Such a variation in temperature is also completely different from the one obtained with the C/C-SiC brake discs, which indicates significant, inherent differences between the material couples in this study.

3 DISCUSSION

Earlier studies on different brake materials showed that the surface temperature has a significant



Sl. 6. *Diagram poteka temperature v odvisnosti od časa preskusa (modelni preskus, disk jeklo, ploščica 4035, v=26,14m/s, p=0,44MPa). Digram prikazuje rezultate dveh preskusov.*
Fig. 6. *Graph of measured temperature over time of measurement (model test, disc material steel, pad 4035, v=26,14m/s, p=0,44MPa). Graph represents results from two measurements.*

pri doseganju ustreznih tornih in obrabnih lastnosti za uporabo različnih dvojic materialov v zavornih sistemih ([3], [5] do [9]). Nekateri materiali imajo odlične lastnosti pri zmernih obremenitvah in temperaturah, a so pri povišanih temperaturah povsem neprimerni ([5] in [6]), velja pa tudi nasprotno ([7] do [10]). Zaradi tega je poznavanje temperaturnega stanja in njegova povezava predvsem s toplotnimi lastnostmi materialov izjemno pomembna pri razvoju zavornih sistemov. To še posebej velja za sodobnejše kompozitne materiale na podlagi ogljika in/ali keramike, ki imajo precej različne toplotne in tudi druge lastnosti od običajnih kovinskih materialov. Razvoj zavornih sistemov z uporabo C/C-SiC in podobnih sorodnih materialov je še v začetnem obdobju, tako da dostopnih podatkov o triboloških lastnostih in z njimi povezanih temperaturnih stanj ustreznih dvojic materialov še ni. V tej raziskavi smo zato primerjali temperaturno stanje na zavornih površinah diskov iz kompozita C/C-SiC in običajnih jeklenih diskov v dotikih s ploščicami na podlagi kompozita s kovinsko matrico. Uporabili smo dve vrsti preizkuševališč. S preskusi na standardnem preizkuševališču (KRAUSS RWS75B) smo skušali pridobiti primerljive podatke za standardne pogoje preizkusov, v katerih se simulira dejansko delovanje in razmere zavornih sistemov, na modelnem preizkuševališču MS-P [20] pa smo skušali narediti primerjavo temperature na površinah v ustaljenih razmerah in ugotoviti vpliv toplotnih lastnosti izbranih materialov na razvoj temperaturnega stanja.

Rezultati kažejo precej različno obnašanje in doseganje precej različnih temperaturnih ravni na zavornih površinah. V primeru diskov iz kompozitov

effect on the optimum friction and wear properties of braking systems ([3], [5] to [9]). Some materials exhibit excellent performance under moderate loads and temperatures but are entirely inappropriate at higher temperatures ([5] and [6]), and vice-versa ([7] to [10]). Therefore, knowledge of the surface-temperature conditions and their relation to the thermal properties of the materials is very important for the development of braking systems. This is especially true for modern carbon- and/or ceramic-based composite materials, where the thermal and other properties vary considerably from those of conventional metal materials. The development of braking systems with C/C-SiC and similar composite materials is still in its early stages, and therefore there is no available information on the tribological properties and the related temperature conditions in the contacts with any other materials that are suitable for brake applications. Therefore, in this study the temperature conditions on the surfaces of the C/C-SiC composite and the steel brake discs in contact with MMC-based brake pads were compared. Two types of testing machines were used. By using a standard machine (KRAUSS RWS75B) we tried to acquire comparable data for standard testing conditions, where realistic operating conditions are simulated, whereas by using our own, self-designed model machine MS-P [20] we tried to compare the surface temperatures under stationary conditions and study the effect of the thermal properties on the surface-temperature change of selected materials.

The results show very different behaviour and different temperature levels on the braking surfaces with C/C-SiC composite or steel discs. In

C/C-SiC (sl. 3 in 5) se izmerjene temperature zavornih površin povišujejo precej hitreje kakor v primeru jeklenih diskov (sl. 4 in 6) in tudi dosežejo precej večje vrednosti. Kljub dvema različnima postopkoma testiranja in načinom meritve temperature je bilo to jasno izraženo v vseh preizkusih. Temperaturni gradienti na začetku meritev so bili v primeru diskov iz kompozitov C/C-SiC kar trikrat večji kakor pri jeklenih diskih. Razlog za tako obnašanje gre v veliki meri iskati prav v toplotnih lastnostih obeh materialov, saj je toplotna prevodnost pri jeklenem disku dvakrat večja (14 W/mK) kakor pri površinski plasti SiC v disku C/C-SiC (7 W/mK). Razlike v toplotnih lastnostih pa še veliko bolj poudari jedro C/C kompozitnega diska, ki ima, v odvisnosti od usmerjenosti vlaken, v nekaterih smereh toplotno prevodnost samo 1 W/mK [22]. Zaradi tega se pri diskih C/C-SiC večina nastale torne toplote zadrži na površini, kjer se zaradi tega močno poviša temperatura. Zaradi »toplotno izolativnih« lastnosti se toplota ne prevaja v notranjost diska in zato se temperatura tudi v ustaljenem stanju ne zniža (sl. 5).

V nasprotju s tem pa je dvig temperature pri jeklenih diskih precej počasnejši in doseže nižje vrednosti (sl. 4, 6). Toplotne lastnosti jeklenih diskov omogočajo precejšen prevod nastale torne toplote v notranjost diska. Zato je akumulacija na površini manjša, s tem pa je tudi dotikalna temperatura nižja. V standardnem testu je bila temperatura na površini jeklenega diska kar za 110 °C nižja kakor pri kompozitnem disku C/C-SiC, oziroma približno 25 %, merjeno v °C. Še bolj očitno se je razlika v toplotnih lastnostih obeh dvojic materialov pokazala pri modelnem testu, pri katerem se je temperatura po razmeroma počasnem dvigu, do približno 550 °C, v preostalem delu preizkusa precej znižala: na stalnih 420 °C, kar kaže na zmožnost zelo dobrega prevoda toplote v notranjost diska. V tem primeru je bila temperatura skoraj za 200 °C nižja kakor pri disku C/C-SiC v enakih razmerah testiranja.

Iz tega izhaja, da pri zmernih obremenitvah dosegajo temperature v dejanskih sistemih z jeklenimi diski razmeroma nizke vrednosti, še posebej pri zgolj krajših zavornih ciklih (primerljivih s prvim delom krivulje v vsakem sklopu zaviranj na standardnem preizkuševališču), saj se toplota učinkovito prevaja v notranjost diska. Po naših rezultatih v standardnem testu, ki simulira »preobremenitev«, vendar pri pogojih obratovanja navadnih zavor, so te temperature precej pod 300 °C (sl. 4), kar se dobro ujema tudi z dejanskimi razmerami in omejitvami temperature popuščanja organskega veziva v zavornih ploščicah, tj. približno 240 °C ([5] in [6]). Zaradi teh lastnosti je seveda izbira ustreznih materialov zavornih ploščic za jeklene diske dokaj široka.

V nasprotju z obnašanjem pri jeklenih diskih pa že v kratkih zavornih ciklih pri standardnem testu

the case of C/C-SiC composite brake discs (Figures 3 and 5), the temperatures increase much faster than with steel discs (Figure 4 and 6), and they also reach higher values. This was noticeable in all the tests, despite using two different testing procedures and temperature-measurement methods. The gradient of the temperature increase was three times higher in the contacts with C/C-SiC than with the steel discs. The reason for such behaviour can be explained in terms of the thermal properties of the two materials. The thermal conductivity of the steel is three times lower than that of the SiC surface layer of the C/C-SiC composite. This difference is even more pronounced by the extremely low thermal conductivity of the C/C composite core, which can vary with the fibre orientation, and can have a value only of 1 W/mK in some directions [22]. Therefore, the major part of the generated heat is retained in the surface layer, thus the temperature increase at the surface is very high. Because of the "thermally isolative" properties the heat is poorly conducted into the disc subsurface/bulk and therefore even under stationary conditions the surface temperature remains high, without any decrease being observed (Figure 5).

In contrast, the temperature increase on the steel discs is much slower, and lower values are obtained (Figure 4 and 6). The thermal properties of the steel discs enable considerable conduction of generated heat to the interior of the disc and therefore the accumulation of the heat on the surface is lower and consequently the contact temperature is also lower. Using the standard test the surface temperature on the steel disc was 110°C, or approximately 25% (measured in °C) lower than on the C/C-SiC composite disc. The difference in the thermal properties of both materials was even more obvious from the results obtained using the model tests, where the temperature on the steel disc, after a rather slow increase to 550°C, even decreased and stabilized at 420°C, indicating good conduction to the interior of the disc. In this case the temperature was nearly 200°C lower than on the C/C-SiC disc under the same testing conditions.

Hence it follows that in braking systems with a steel disc under moderate loads the temperatures reach relatively low values, especially during shorter braking cycles (comparable with the first part of the temperature curve in every braking-cycle group on the standard test), because of the effective heat transfer into the disc interior. Based on our results from the standard test, which simulates "overload", but for realistic operating parameters, these temperatures reach values significantly below 300°C (Figure 4). This corresponds well with the actual conditions and limitations of the organic matrix in a conventional brake-pad material, i.e., approximately 240°C ([5] and [6]). Therefore, these properties allow a broad selection of suitable brake-pad materials for conventional braking systems using steel discs.

In contrast to the steel discs, the C/C-SiC discs reach relatively high surface temperatures, over 400°C v dotikih z diski C/C-SiC zaradi akumulacije torne toplote predvsem na površini diskov in zaradi tega velikih gradientov površinske temperature, le-ta doseže vrednosti prek 400 °C (sl. 3). V primeru daljših zavornih ciklov in predvsem večjih obremenitev, za katere naj bi se diski C/C-SiC uporabljali, pa bi temperature dosegle še precej višje vrednosti, kar jasno nakazujejo rezultati z modelnega preizkuševališča (sl. 6), kjer smo se omenjenim pogojem bolj približali. Po 25 sekundah preizkusa v treh zavornih ciklih je namreč temperatura v primeru dotika z diskom C/C-SiC dosegla kar 550 °C (sl. 5). Torej, pri teh, bolj ostrih pogojih lahko ponovno ugotovimo, da je nevarnost pregrevanja v dotikih z diski iz kompozita C/C-SiC bistveno večja kakor pri jeklenih diskih. Kljub doseženim višjim temperaturam, se tudi tu pri jeklenih diskih temperatura dviga umirjeno, precej počasneje kakor lahko pričakujemo v dejanskem zavornem sistemu, in v enakem primerjalnem času, tj. po 25 sekundah preizkusa v treh zavornih ciklih, doseže le 250 °C (sl. 6) - kar 300 °C manj kakor v primeru diska iz kompozita C/C-SiC (sl. 5).

Dodaten pokazatelj pričakovanih zelo visokih temperatur v dotikih z kompoziti C/C-SiC pa je dejstvo, da smo na modelnem preizkuševališču merili temperaturo 300 µm pod zavorno površino, kar je razmeroma blizu vira torne toplote. Znano pa je, da je zaradi nastanka torne toplote na površini zato dvig temperature na površini znatno večji kakor pod površino in se lahko v določenih razmerah temperatura v prvih nekaj 10 do 100 µm zniža kar za več 100 °C ([23] do [25]). Poleg tega meritve »dotikalnih« temperatur pod površino (ali zunaj dotika na površini) zaradi fizikalnih omejitev temperaturnih zaznaval izkazujejo nižje vrednosti od dejanskih ([26] do [30]). Iz tega lahko ugotovimo, da so dejanske razmere na sami površini kompozita C/C-SiC zaradi slabe toplotne prevodnosti še bolj neugodne kakor kažejo izmerjeni rezultati pod površino. To pomeni, da je glede na dobljene rezultate, pri razvoju ploščic za kompozitne diske C/C-SiC treba upoštevati dotikalne temperature precej višje od 550 °C. S tem pa se izbira materialov, ki zmorejo delovati pri tako visokih, četudi samo kratkotrajnih termičnih obremenitvah, bistveno zoži.

Dobljeni rezultati in ugotovitve o temperaturnih stanjih in vplivih toplotnih lastnosti analiziranih dvojic materialov pomenijo prvi korak raziskav pri optimiranju materiala ploščic za diske iz kompozitov C/C-SiC. Ugotovitve so še posebej pomembne, saj nakazujejo na dotikalne temperature precej prek 550 °C, kar bistveno oži izbiro materialov, hkrati pa nas dobro usmerja v iskanje primernih rešitev. Izmerjene vrednosti so zelo pomembne tudi za nadaljnje razumevanje dogajanja na zavornih

(Figure 3), even for short braking cycles during standard tests, which is because of the high frictional heat accumulation in the surface layer and the consequent high surface-temperature gradients. In the case of longer braking cycles and higher loads, for which the C/C-SiC composites are designed, the temperatures would reach even higher values. This can be anticipated from the results of the model tests (Figure 6) – purposely simulated for such conditions. After the first three braking cycles (25 seconds) in the contact with C/C-SiC the temperature already reached 550°C, Figure 5. Therefore, we can conclude that under these severe operating conditions the danger of overheating is substantial for C/C-SiC composite discs, and much higher than for steel discs. Moreover, although higher temperatures were reached in the model tests than in the standard tests, the temperature rise in steel discs was again gradual and much slower than would be anticipated in a realistic braking system. In the same time, i.e., after 3 braking cycles (25 seconds), the temperature reached only 250°C (Figure 6), which is 300°C less than in the case of the C/C-SiC composite brake disc, Figure 5.

An additional indicator of high expected temperatures in the contact with the C/C-SiC composite discs is the fact that on the model testing machine the temperature measurements were taken approximately 300-µm below the contact surface, which is relatively close to the heat source. However, it is known that the temperature rise on the surface is considerably higher than below the surface (due to frictional heat generation on the surface) and that the temperature can decrease by several hundreds of °C over the first 10 to 100 µm ([23] to [25]). Furthermore, due to the physical limitations of the temperature sensors, the "contact" temperature measurement beneath the surface (or outside of the contact on the surface), shows lower values than reality ([26] to [30]). From the above it can be concluded that the actual surface conditions of the C/C-SiC composite are due to low thermal conductivity, and they are even more unfavourable than is suggested by the results from the measurement beneath the surface. This suggests that temperatures well above 550°C should be considered in the development of brake-pad material for use in C/C-SiC composite brake discs. This means that the choice of possible materials that can operate at these temperatures, even for short periods, is very small.

The presented results and findings about the surface-temperature conditions and the influence of the thermal properties of the analysed friction-couple materials represent the first step in the research and development of brake-pad materials for use in combination with C/C-SiC composite brake discs. These findings are of great importance since they indicate that contact temperatures well above 550°C can be expected in such braking systems, which substantially reduces the selection of pad materials; but at the same time directs us quite precisely to possible materials that will provide a solution. The temperatures that were identified in this study are also very important površinah, glede vpliva temperaturnega stanja na nastanek površinskih plasti ter tribokemijskih postopkov ([25], [31] do [35]). Prav ti postopki, s katerimi se bomo ukvarjali v naslednji fazi razvoja zavor na podlagi diskov iz kompozitov C/C-SiC, imajo ključno vlogo pri zagotavljanju ustreznega koeficienta trenja, obrabe ter dinamičnih lastnosti obravnavanega tribološkega sistema ([3], [5] in [6]), s tem učinkovitosti in kakovosti zavor.

4 SKLEPI

1. Rezultati na temelju uporabe dveh različnih preizkuševališč in načinov testiranja ter dveh načinov merjenja temperature kažejo enake sklepe o temperaturnih razmerah na površinah jeklenih in diskov C/C-SiC, in sicer, da so te razmere precej različne.
2. Temperaturni gradienti na zavornih površinah v dotikih s kompoziti C/C-SiC so znatno večji kakor pri jelenih diskih. Predvsem zaradi precej večje toplotne prevodnosti jekla od kompozita C/C-SiC, se ustvarjena torna toplota pri jeklenih diskih prevaja v notranjost v diska, pri diskih C/C-SiC pa se zadrži v precejšnji meri na površini.
3. Posledica takih toplotnih lastnosti so velike razlike v temperaturi na zavornih površinah: po nekaj zavornih ciklih na modelnem preizkuševališču so znašale kar 300 °C, v ustaljenih razmerah pa približno 200 °C.
4. Najvišje izmerjene temperature v dotikih s kompozitnimi diski C/C-SiC so po nekaj kratkotrajnih zavornih ciklih presegle 550 °C. Glede na velike padce temperatur tik pod površino, ocenjujemo, da je dejanska dotikalna temperatura v takih razmerah še za nekaj 100 °C višja.
5. Ugotovljene temperaturne razlike na zavornih površinah potrjujejo potrebo po izbiri drugačnih materialov od uporabljenih v navadnih zavornih sistemih ter na precej ožji izbor ustreznih materialov za zavorne ploščice, ki bodo zmožni delovati pri tako izrednih temperaturah.

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for further understanding the behaviour of contact surfaces in terms of the influence of temperature on the formation of surface layers, various tribo-films and tribochemical processes ([25], [31] to [35]). These processes will be the main subject in our further development of the C/C-SiC composite brake systems, since they have a major influence on the coefficient of friction, the wear and the dynamic characteristics of the discussed tribological system ([3], [5] and [6]), and thus on the efficiency and the quality of the whole braking system.

4 CONCLUSIONS

1. The results from two different testing machines and testing procedures and two different temperature-measurement methods suggest the same conclusions about the temperature on the surface of C/C-SiC composite and steel discs: there are significant differences in the evolution of the contact temperatures and their maximum values.
2. The temperature gradients in the contacts with C/C-SiC composite brake discs are significantly higher than with steel discs. This is mainly because of the much higher thermal conductivity of steel compared to C/C-SiC. Therefore, in contacts with steel discs the frictional heat is conducted into the bulk, whereas with the C/C-SiC discs the heat is to a large accumulated in the SiC surface layer.
3. The consequences of such thermal properties are the big differences in the surface temperatures of the steel and C/C-SiC discs. By using a model testing machine the obtained difference after a few brake cycles was 300°C, and under stationary conditions approximately 200°C.
4. The highest measured temperatures in the contact with C/C-SiC discs exceeded 550°C after a couple of short braking cycles. According to the high-temperature gradient beneath the surface, it is estimated that the actual contact temperature could be even several 100°C higher.
5. The identified temperature differences on the friction surfaces confirm the necessity of choosing different materials for C/C-SiC discs than those used in conventional brake systems. The temperature differences also suggest a much narrower choice of possible materials for brake pads that will be capable of operating under such extreme conditions.

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Inteligentni transportni sistemi pri načrtovanju in usklajevanju gibanja in parkiranja letal na ploščadi letališča

Intelligent Transportation Systems in the Planning and Coordination of Aircraft Traffic at the Airport Apron

Stanislav Pavlin - Slavko Roguljić

Ploščadi letališča so površine za sprejem in odpremo letal, parkiranje in vzdrževanje. Po mednarodnih predpisih mora biti število prostorov na ploščadi najmanj enako številu letal, ki so hkrati na letališču. Na letališču Split je prišlo v polovici 90. let do pomembne rasti prometa letal, ker je letališče postalo logistična baza ZN za Bosno in Hercegovino. Ni bilo sredstev niti prostora za razširitev ploščadi zato so spremenili organizacijo in koordinacijo prometa. Uvedeni so alternativni prostori in omejitve. Razvit je računalniški program za načrtovanje in usklajevanje prometa letal na ploščadi, ki je kasneje dograjen v GIS-u (geografski informacijski sistem) s sistemoma Arc View in Arc View Tracking Analyst.

Glavna funkcija sistema je, da po načrtovanem in dejanskem prometu predlaga optimalno stezo gibanja in prostore za parkiranje letal z upoštevanjem varnostnih razdalj med letali, ki so v gibanju in tistih, ki so parkirani.

(Ključne besede: gibanje letal, parkiranje letal, načrtovanje, koordinacija)

Airport aprons are areas for aircraft handling, parking and maintenance. According to international rules the number of positions at the apron has to be at least equal to the number of aircraft staying at any one time at the airport. The air traffic at Split Airport increased rapidly in the mid-90s when it became the UN logistics base for Bosnia and Herzegovina. There were no means nor free space for further expansion of the apron, so the traffic had to be reorganised and re-coordinated. Alternative positions and restrictions were introduced. A computer program for apron aircraft-traffic planning and coordination was developed, and then later upgraded in GIS (Geographic Information System) by the systems Arc View and Arc View Tracking Analyst.

The basic function of the system is to suggest optimal aircraft movements and parking positions based on the planned and actual traffic, meeting aircraft safety spacing both in movement and in standing positions.

(Keywords: aircraft movement, aircraft parking, planning, coordination)

0 UVOD

Ploščad letališča je namenjena za sprejem in odpremo letal, parkiranje in vzdrževanje. S stezami za vožnjo je povezana z vzletno-pristajalno stezo. Na njej so prostori za parkiranje, vozne steze, po katerih se letala gibljejo pri prihodu na prostor in pri odhodu s prostora, varnostne razdalje (med letali na prostorih, med letali na prostorih in med tistimi, ki se gibljejo), površine za gibanje vozil in opreme za sprejem in odpremo letal ter površine za vozila in opremo.

0 INTRODUCTION

An airport apron is intended for aircraft handling, parking and maintenance. It is connected with the runway by taxiways. It consists of aircraft parking positions, taxiways at the apron for aircraft movement to the parking position arriving to and exiting from it, safety spacing (between aircraft on the positions, and between aircraft on the positions and those in movement), vehicle and aircraft handling equipment movement areas, and areas accommodating vehicles and equipment.

Razdalje med letali v gibanju in na prostorih predpisuje Mednarodna organizacija civilnega letalstva [1] in znašajo od 3m do 7,5m, dnevno in nočno označevanje (vodilne črte na voznih stezah in prostorih, prometnice za vozila in opremo, reflektorje itn.). Ista organizacija predpisuje, da mora zmogljivost ploščadi omogočiti, da morajo imeti vsa letala, ki priletavajo in odletavajo, na letališču svoj prostor. To pomeni, da letalo ne sme čakati na vozni stezi na prosti prostor na ploščadi. Dovoljeni so alternativni prostori na osnovnih prostorih za letala, ki se na primer redko pojavljajo na letališču.

S prostora na vozno stezo se letalo lahko premakne z močjo motorja letala (samomanevrsko) in s potiskanjem, s posebnim vozilom. Samomanevrski prostori zahtevajo večjo površino ploščadi, medtem ko prostori s potiskanjem zahtevajo draga vozila za potiskanje.

The spacings between aircraft in movement and those parked at the position are stipulated by the International Civil Aviation Organization (ICAO) [1] and they range from 3m up to 7.5m, and vary for day and night markings (guiding lines on taxiways and positions, traffic routes for vehicles and equipment, reflectors, etc.). The same organisation stipulates that the apron capacity has to allow all aircraft being handled at the airport have to have their positions, i.c., an aircraft is not allowed to queue on the taxiway waiting for a free position on the apron. Alternative positions are allowed in addition to the basic ones for aircraft, for instance, that appear less frequently at the airport.

Parking positions are divided according to the method of exiting the position into those from which the aircraft exit by the power of their own engines (self-manoeuvring) and those from which the aircraft exits by being pushed by a special vehicle, i.e., equipment. Self-manoeuvring positions require bigger apron areas than the push-back ones, whereas the push-back areas require expensive vehicles, i.e., push devices.

1 LETALIŠČE SPLIT

Letališče Split je odprto za promet od leta 1966. Promet je hitro rastel in je dosegel največje število 1,15 milijonov potnikov in 8 tisoč opravil (pristajanja in vzletanja) v letu 1987. Najpogostejši tip letala je bil DC9 in B727. Površina ploščadi je bila 33 600m^2.

Letališče je zaprla konec leta 1991 Uprava za civilno letalstvo SFRJ. Ponovno ga je odprlo aprila leta 1992 Ministrstvo za promet Republike Hrvaške. ZN so izbrali letališče Split za logistično bazo za Bosno in Hercegovino za humanitarne in vojaške namene. Tipi letal so se spremenili. Prihajajo širokotrupna letala (C5 Galaxy, B747, L1011 itn.) in število operacij v letu 1995 je doseglo skoraj 14 tisoč opravil. Širokotrupna letala so naredila do 3% skupnega prometa.

Povečanje prometa in sprememba tipov letal je pokazala potrebo po:

a) novih prometnih in tehnoloških rešitvah za gibanje in parkiranje letal na ploščadi. Te rešitve določajo alternativne prostore za širokotrupna in tovorna letala,
b) razširitvi ploščadi,
c) načrtovanju vojaškega prometa z ZN,
d) pripravljanju načrta in organizacije prometa kolikor je mogoče učinkovito in prilagodljivo za vsakodnevne potrebe z uvajanjem nove informacijske tehnologije.

Zato je:

a) bila leta 1995 ploščad razširjena na 45.000m^2, tako da je bilo načrtovanih 17 glavnih parkirnih prostorov in 9 alternativnih,
b) bilo novembra leta 1995 prometno načrtovanje na letališču Split dogovorjeno s poveljstvom ZN za

1 AIRPORT SPLIT

Airport Split was opened in 1966. Traffic rapidly grew and reached a maximum of 1.15 million passengers and almost 8 thousand aircraft operations (landings and takeoffs) in 1987. The majority of the aircraft were type DC9 and B727. The apron covered an area of 33,600 m^2.

The Airport was closed at the end of 1991 by the Yugoslav Air Traffic Services and opened in April 1992 by the Croatian Ministry of Transport. The UN chose Airport Split as its logistics base for Bosnia and Herzegovina for humanitarian and military purposes. The aircraft types and mix changed completely. Widebody aircraft started arriving (C5 Galaxy, B747, L-1011, etc.) and the total number of operations in 1995 reached almost 14 thousand. The number of widebody aircraft amounted to 3% of the total traffic.

The traffic growth and the change in aircraft types showed the need for:

a) new traffic and technological design of the aircraft movements and parking on the apron determining alternative positions for widebody and cargo aircraft,
b) extension of the apron,
c) planning of military traffic with the UN,
d) making the planning and organisation of traffic as efficient as possible and adaptable to everyday needs, through the introduction of new information technology.

Therefore:

a) during 1995 the apron area was extended to 45,000 m^2 so that 17 basic parking positions as well as 9 alternative ones were designed,
b) in November 1995 the traffic planning at the Airport Split was agreed upon with those responsible at

obranitev miru v Zagrebu,
c) bil maja leta 1997 prometni in tehnološki projekt ploščadi končan [2],
d) sistem bil dalje razvijan in prva faza je bila končana konec leta 2000.

the UN peace-keeping forces command in Zagreb,
c) in May 1997 the Traffic and Technological Design of the apron was completed [2],
d) the system is being further developed, and the end of the year 2000 saw the completion of the first phase of the project.

2 PROMETNI IN TEHNOLOŠKI PROJEKT GIBANJA IN PARKIRANJA LETAL NA PLOŠČADI

Ploščad letališča Split je povezana z vzletno-pristajalno stezo z dvema voznima stezama: A in B. Širina vozne steze A zadovoljuje vse tipe letal. Vozna steza B ima omejitve za gibanje nekaterih širokotrupnih letal (B747, C5 Galaxy, AN124). Ploščad ima vozno stezo, ki je vozna steza do prostorov in povezuje na ploščadi vozno stezo A in B in omogoča vhod in izhod s prostorov na obe strani vozne steze in vozno stezo za majhna letala (prostori G1, G2 in G3).

Na letališču Split niso imeli vozila za potiskanje letal. Hkrati je bilo veliko število prostorov na eni vozni stezi. To sta bila razloga za izbiro samomanevrskega sistema za parkiranje na ploščadi.

Letala so razdeljeni v 6 skupin, odvisno od izmer. V skupini 1 so majhna letala, v skupini 6 širokotrupno letalo B747 400 in večja letala.

2.1 Glavni prostori

Glavni prostori so označeni z dnevnimi oznakami, neprekinjenimi vodilnimi črtami in prostori za kolesa nosnega podvozja. To so:
1. dva za letala z razponom kril do 34,1m in dolžine do 42m - skupine 3, 2 (prostora 12, 14),
2. osem za letala z razponom kril do 34,1m in dolžine do 37,57m – skupine 3, 2 (prostori 1, 2, 3, 4, 7, 8, 9, 10),
3. tri za letala z razponom kril do 30m in dolžine do 31m – skupina 2 (prostori 5, 6, 11),
4. en za letala z razponom kril do 20m in dolžine do 20m – skupina 1 (prostor 15) in
5. tri za letala z razponom kril do 17m in dolžino do 17m – skupina 1 (prostori G1, G2, G3).

2.2 Alternativni prostori

Alternativni prostori so označeni s prekinjenimi vodilnimi črtami. To so:
1. pet za vojaška tovorna letala C130, razpona kril 34,35m in dolžine 34,35m - skupina 4 (prostori C1, C2, C3, C4, C5),
2. tri za širokotrupna letala z razponom kril 51,66m in dolžino 61,62m - skupina 5 (prostori P1, P2, P3) in
3. en za širokotrupna letala z razponom kril 64,44m in dolžino 70,66m - skupina 5 (prostor P4).

2 TRAFFIC AND TECHNOLOGICAL DESIGN OF AIRCRAFT MOVEMENTS AND PARKING ON THE APRON

The Airport Split apron is connected with the runway by two taxiways: A and B. Taxiway A meets the requirements of all aircraft types. Taxiway B has a restriction for some of the widebody aircraft (B747, C5 Galaxy, AN124). The apron has the apron taxiway, which at the same time is a taxilane connecting taxiways A and B enabling entrance and exit from positions on both sides of the taxilane as well as a taxilane for general aviation aircraft (parking positions G1, G2 and G3).

The large number of positions by one taxilane and no push-back tractors at Airport Split were the reasons for choosing the self-manoeuvring system of parking at the apron.

Aircraft are divided into 6 groups according to their dimensions. Group 1 represents general aviation and group 6 widebody B747 400 and bigger aircraft.

2.1 Basic positions

Basic positions are presented by daily markings, unbraked guiding lines and positions for nose gear. There are:
1. 2 for aircraft wingspans of up to 34.1m and lengths of up to 42m - groups 3, 2 (at positions 12, 14),
2. 8 for aircraft wingspans of up to 34.1m and lengths of up to 37.57m – groups 3, 2 (at positions 1, 2, 3, 4, 7, 8, 9, 10),
3. 3 for aircraft wingspans of up to 30m and lengths of up to 31m – group 2 (at positions 5, 6, 11),
4. 1 for aircraft wingspans of up to 20m and lengths of up to 20m – group 1 (at position 15),
5. 3 for aircraft wingspans of up to 17m and lengths of up to 17m – group 1 (at positions G1, G2, G3).

2.2 Alternative positions

Alternative position are represented by braked guiding lines. There are:
1. 5 for C130 military cargo aircraft, wingspan of 34.35m and length of 34.35 m - group 4 (at positions C1, C2, C3, C4, C5),
2. 3 for widebody aircraft, wingspan of 51.66m and length of 61.62m - group 5 (at positions P1, P2, P3),
3. 1 for widebody aircraft, wingspan of 64.44m and length of 70.66m - group 5 (at position P4).

Z uporabo alternativnih prostorov P1, P2, P3, P4, in C1, C2, C3, C4, C5, je zmogljivost ploščadi zmanjšana, odvisno od števila in prostorov letal, ki so parkirana na alternativnih prostorih.

Za določanje voznih stez in voznih stez na ploščadi je nujno treba upoštevati določene omejitve pri uporabi alternativnih prostorov.

3 RAČUNALNIŠKI PROGRAM ZA ORGANIZACIJO IN KOORDINACIJO GIBANJA IN PARKIRANJA LETALA NA PLOŠČADI

Omejitve, veljavne za vozne steze, in določene prostore za parkiranje so temelj za razvoj pravil za računalniški program, namenjen kot pomoč za organizacijo prometa letal na ploščadi.

V prvi fazi so projekt računalniškega programa razvijali v glavnem v FoxPro 2.6a in delno v C, za operativni sistem Windows 95, 98 in NT kakor tudi za mrežni sistem Novell 4.11 v modularni strukturi.

Z vzpostavljanjem nadzora števila zasedenih letalnih parkirnih prostorov prikazovalnik pokaže število letal na ploščadi v realnem času, preteklosti in sedanjosti in v načrtovanem času za opravila v prihodnosti. Tako lahko prometni koordinator razmeroma hitro ugotovi, ali je napovedano letalo lahko sprejeto v času, ki ga predlaga zračni prevoznik, ali pa mu predlaga najugodnejši čas pristajanja/vzletanja, s tem da se upošteva tip letala, manevrske karakteristike, gostota prometa in zmogljivost ploščadi.

Slika 1 prikazuje prikazovalnik programa parkiranja na ploščadi: številke 1 do 16 označujejo osnovne prostore za parkiranje, P,C in G označujejo alternativne prostore za parkiranje.

By using alternative positions P1, P2, P3, P4, and C1, C2, C3, C4, C5, the apron capacity is reduced depending on the number and positions of aircraft parked at these alternative positions.

While determining both the taxiways and taxilanes and the parking positions, it is necessary to be aware of certain restrictions resulting from the use of alternative positions.

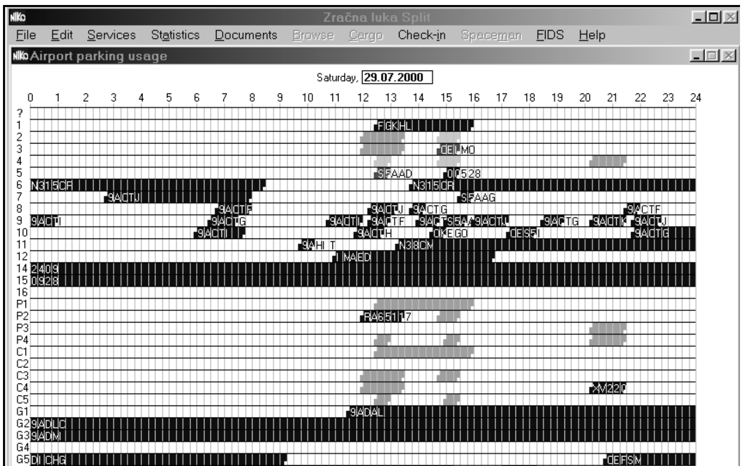
3 COMPUTER PROGRAM FOR THE ORGANISATION AND COORDINATION OF AIRCRAFT MOVEMENTS AND PARKING AT THE APRON

The restrictions valid for taxiways and certain parking positions have served as the basis for developing the rules for the computer program intended to assist aircraft traffic organisation at the apron.

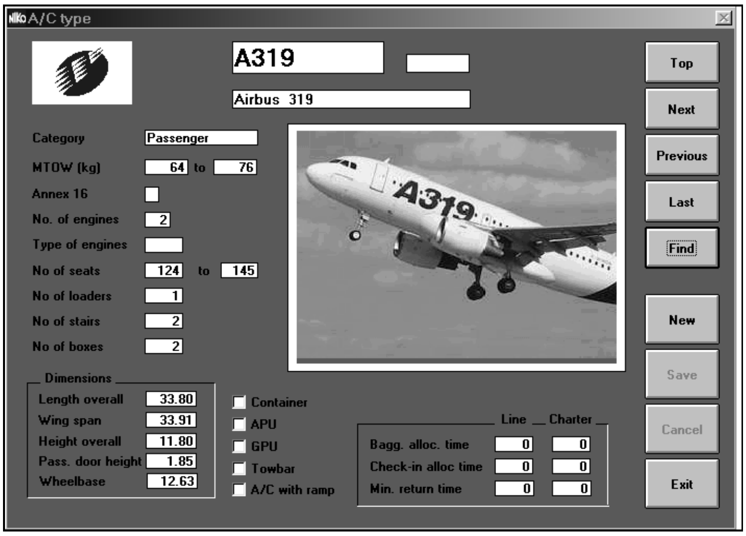
During the first phase of the project a computer program was developed mostly in FoxPro 2.6a and partly in C, for the Windows 95, 98 and NT operating systems, as well as the network system Novell 4.11 in a modular structure.

By switching on the function that controls the number of occupied aircraft parking positions, the display shows the number of aircraft at the apron in real-time, the past and the present, and in planned time for operations in the future. Thus, the traffic coordinator can determine relatively quickly whether an announced incoming aircraft can be accepted within the time suggested by the carrier or the most suitable time of landing/takeoff has to be suggested taking into consideration the aircraft type and manoeuvring characteristics, traffic intensity and apron capacity.

Figure 1 shows the display of the apron parking program: numbers from 1 to 16 mark the basic parking positions and P, C and G mark the alternative parking positions.



Sl. 1. *Uporabniški prikazovalnik programa za koordinacijo gibanja in parkiranja letala*
Fig. 1. *User display of the program for the coordination of aircraft movement and parking*



Sl. 2. *Uporabniški prikazovalnik z osnovno bazo različnih tipov letal*
Fig. 2. *User display with database on various types of aircraft*

Številčna serija od 0 do 24 pomeni ure v enem dnevu. Vsaka celica v časovni seriji pomeni 15 min, tako da eno uro pomenijo štiri celice. Prikazovalnik kaže vsa letala v skladu z registracijo, tipom ali številko leta in ali so bili, so in ali bodo zasedali določen čas tega dne enega od prostorov za parkiranje na letališki ploščadi.

Poudariti bi bilo treba, da računalniški program prikazuje letala natančno na tistih prostorih za parkiranje, ki jih zasedajo. Uporabljajo se barvne oznake:
- prosti prostori (bela),
- prostori, zasedeni z letali enakih ali manjših izmer od tistih za katere so prostori predvideni (temno modro),
- prostori, zasedeni z letali večjih izmer od tistih, za katere so predvideni (temno rjavo),
- sosedni prostori, ki so delno ali popolno blokirani z letalom, večjim od tistega, za katerega je prostor predviden (svetlo rjavo),
- osnovni prostori, ki so popolnoma blokirani z letalom, parkiranim na enem od primernih alternativnih prostorov in nasprotno: alternativni prostori, ki so blokirani z letalom, parkiranim na enem od primernih osnovnih prostorov (svetlo modro).

V časovni seriji celic, označenih z vprašajem, računalniški program prikaže podatke o letalu, za katerega prostor za parkiranje ni določen. Tako prometni koordinator na dolžnosti lahko preveri v katerem koli trenutku število prostih prostorov za parkiranje in lahko odloči o možnostih sprejema novega letala.

3.1 GIS uporabljen za koordinacijo gibanja in parkiranja letala na ploščadi

V sodelovanju z GEOdata iz Splita je model računalnišnega programa na podlagi GIS

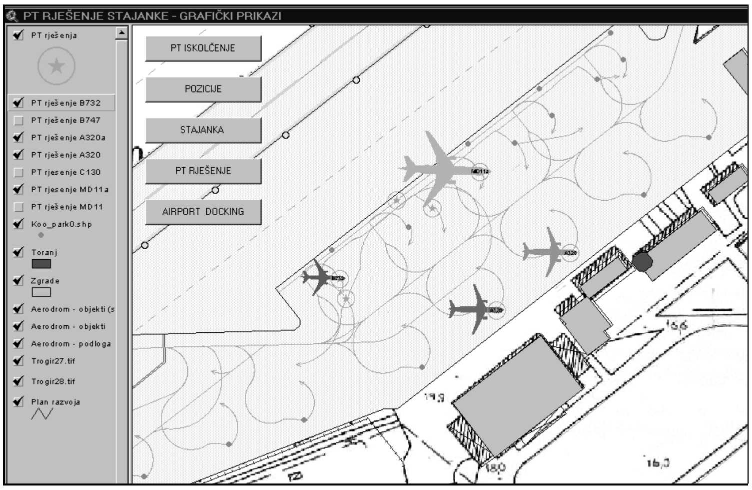
The numerical series from 0 to 24 refers to the hours within one day. Each cell within the time series covers 15 minutes, so that one hour encompasses four cells. The display indicates all aircraft according to registration, type or flight number, and that were, are or are planned to occupy at a certain time of a given day, one of the parking positions on the airport apron.

It should be emphasised that the computer program shows aircraft exactly at those parking positions that they are occupying, using colours to mark the suitable time:
- unoccupied positions (white),
- positions occupied by aircraft of the same or smaller dimensions than those for which they have been designed (dark blue),
- positions occupied by aircraft of dimensions greater than those for which they had been designed (dark brown),
- the adjacent positions that are partly or completely blocked due to aircraft bigger than those for which the position it occupies was designed (light brown),
- basic positions that are completely blocked by aircraft parked at one of the appropriate alternative positions, and vice versa: alternative positions that are blocked by an aircraft parked at one of the appropriate basic positions (light blue).

In the time series of cells marked by a question mark, the computer program displays data on the aircraft for which the parking position has not been determined. Thus, the traffic co-ordinator on-duty can check at any time the number of unoccupied parking positions and decide on the possibilities of accepting a new aircraft.

3.1 GIS applied for the coordination of aircraft movements and parking at the apron

In cooperation with GEOdata from Split, a model of a computer program based on GIS was



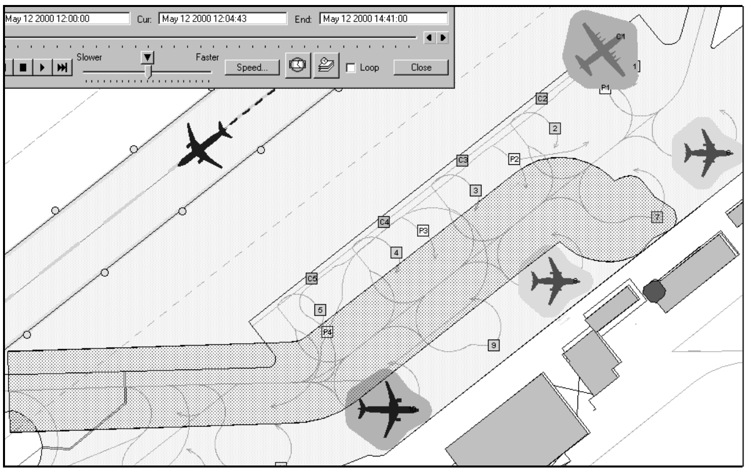
Sl. 3. *Prikazovalnik računalniškega programa za koordinacijo prometa letala v GIS – Arc View*
Fig. 3. *The computer program display for coordination of aircraft traffic developed in GIS - Arc View*

razvit z priključenimi georeferencami in kodiranimi podatki o vseh letaliških objektih, parkirnih prostorih, izmerah in manevrskih karakteristikah različnih tipov letal (sl. 2), varnostnih razmikih med letali itn. (sl. 3). Poglavitna naloga tega programa je, da zagotovi grafično upodobitev gibanja letala po ploščadi v dejanskem času, v preteklosti in prihodnosti, da bi se operater lahko razmeroma hitro odločil glede optimalnega gibanja letala in njegovega parkirnega prostora. Pri tem se morajo upoštevati prostor in izmere že parkiranega letala, izmere in manevrske značilnosti letala, ki parkira, in vozne steze, po kateri letalo prihaja na ploščad.

Uporaba sistema Arc View Tracking Analyst omogoča vidno simulacijo vhoda ali izhoda letala iz danega parkirnega prostora. Preračunan varnostni razmik okoli letala natančno nakaže možne

developed, with installed geo-reference and coded data on all the airport facilities, parking positions, dimensions and manoeuvring characteristics of various types of aircraft (Figure 2), the spacing between two aircraft, etc (Figure 3). The primary aim of this program is to provide graphical visualisation of athe aircraft movements at the apron, both in actual time as well as in the past and future time, for the operator to be able to make, relatively quickly, the correct decision regarding the optimum aircraft movement and its parking position, taking into account the position and dimensions of the already parked aircraft, the dimensions and manoeuvring characteristics of the aircraft that is to be parked, and the taxiway used by the aircraft to enter the apron.

The use of the Arc View Tracking Analyst system enables visual simulation of the aircraft entering or exiting the given parking position. The



Sl. 4. *Računalniški program v GIS – steza gibanja in parkiranja letala A320 z varnostnimi razmiki*
Fig. 4. *Computer program in GIS - path of the A320 aircraft movement and parked aircraft with safety spacing*

točke križanja gibajočega se letala s parkiranimi (sl. 4).

Težave programa, ki je bil razvit v programu FoxPro 2.6a, v prvi projekcijski fazi so bile popravljene z razvojem novega programa, ki ima osnove v programu GIS, ta dovoljuje vsem zaposlenim udeležbo v organizaciji sprejema in odpreme letala, da:

a) lahko preverijo v vsakem času optimalno gibanje in parkirni prostor, ki ga predlaga računalniški program;
b) simulirajo različne verzije gibanja letala po ploščadi, poskušajo dobiti rešitve, ki so različne od predlaganih,
c) oblikujejo varne poti in najboljše parkirne prostore za nove tipe letal na poenostavljen način vhoda primernih tehničnih podatkov.

4 INTEGRACIJA RAČUNALNIŠKEGA SISTEMA

Programi, razviti v FoxPro 2.6a in Arc View Tracking Analyst, so medsebojno združeni tako, da je v vsakem trenutku prostor letala na ploščadi prikazan na prikazovalniku enega programa lahko viden na prikazovalniku drugega programa.

Ti programi so bili nemudoma povezani z računalniškim programom sekundarnega radarja na Kozjaku, da bi lahko natančno določili čas pristajanja. Ti podatki se uporabljajo v sodelovanju s Centrom nadzora zračnega prometa Split, da lahko odločijo, katero vozno stezo bo letalo po pristajanju uporabilo za zapuščanje vzletno-pristajalne steze.

5 SKLEP

Da bi na ploščadi letališča Split lahko obvladali zelo povečani promet, posebej v konicah, v katerih je prevladoval vojaški promet, je bilo potrebno:

- uvesti koordinacijo med ZN in letališčem Split zaradi optimalnega izkoriščanja ploščadi in zmanjšanja zamud,
- uvesti nov sistem parkiranja, ki omogoča na razmeroma majhni površini ploščadi sprejem čim večjega števila letal, od najmanjših do največjih na samomanevrske prostore. Rezultat tega je veliko število alternativnih prostorov in omejitev še posebej pri sprejemu velikih letal,
- uvesti informacijski sistem za načrtovanje, organizacijo in koordinacijo gibanja letal po manevrski površini in na ploščadi, ki bo upošteval vse omejitve in ponudil optimalno uporabo prostorov,
- zaradi preglednosti gibanja letal po ploščadi je sistem dograjen z GIS-om in
- zaradi boljšega ocenjevanja časa pristajanja in gibanja po manevrski površini je sistem povezan z nadzorom zračnega prometa.

calculated safety spacing around the aircraft indicates precisely the possible collision points of the moving aircraft with the parked one (Figure 4).

The drawbacks of the program developed in program FoxPro 2.6a in the first project phase have been corrected by developing a new GIS-based program that allows all the employees participating in the organisation of aircraft handling to:

a) be able to check at any time the optimal movement and parking positions suggested by the computer program,
b) simulate various versions of aircraft movement at the apron, trying to find different solutions from those suggested by the computer program,
c) design safe paths and optimal parking positions for new types of aircraft by means of a simplified input of appropriate technical data.

4 COMPUTER SYSTEM INTEGRATION

Programs developed in FoxPro 2.6a and Arc View Tracking Analyst are mutually integrated in such a way that at any moment the position of an aircraft at an apron presented on the display of one program can be seen on the display of the other program.

These programs are currently being integrated with the computer program of the secondary radar at Kozjak, in order to be able to determine the time of landing of an approaching aircraft with full precision. The data is then used in cooperation with the Air Traffic Control Centre Split to decide which taxiway the aircraft that has landed will use to leave the runway.

5 CONCLUSIONS

In order to be able to accept significantly increased levels of traffic, especially during peak loads with the prevailing military traffic on the Airport Split apron, it was necessary to:

- introduce coordination between the UN and Airport Split for optimum utilisation of the apron and the minimisation of delays,
- introduce a new parking system allowing the handling of the maximum number of aircraft, on a relatively small apron area ranging from the smallest to the biggest on self-manoeuvring positions, which resulted in a solution with a large number of alternative positions and restrictions, especially in the handling of big aircraft,
- introduce an information system for planning, organisation and coordination of aircraft movement across the manoeuvring area and on the apron, which will offer the optimum utilisation of positions taking into consideration all the restrictions,
- upgrade the system with GIS for the sake of the visualisation of aircraft movements,
- connect the system with air-traffic control for improved assessment of the landing time and movement across the manoeuvring area.

Namen razvitih programov je očitno lažje načrtovanje organizacije in usklajevanje gibanja letal na letališču Split. Njihova uporaba je bistveno povečala varnost prometa, vendar opozarja na nujno potrebno gradnjo nove ploščadi.

Programs were developed with the aim of making planning, organisation and coordination of aircraft movements at the Airport Split apron significantly easier. Their application has substantially increased traffic safety, but it has, more than ever, highlighted the urgent need to construct a new apron.

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Računalniški program za uravnoteženje letala

A Computer Program for Aircraft Balancing

Stanislav Pavlin - Slavko Roguljić

Uravnoteženje letala je zelo odgovorno delo za varnost letala v letenju in pristajanju. Navadno se uravnoteženje letala izdeluje na diagramih zračnih prevoznikov, ki niso poenoteni. V načrtovanem času sprejema in odpreme letala zahteva uravnoteženje letala veliko hitrost in natančnost. Program za nadzor sprejema, odpreme in uravnoteženje letala je izdelan na letališču Split, ki je v skladu s standardi Mednarodnega združenja zračnih prevoznikov, definiranih v dokumentu Priročnik za letališki sprejem in odpremo. Program je uspešno uporabljen na letališčih: Split, Dubrovnik, Pulj, Zadar, Osijek in Knock na Irskem za zračne prevoznike in tipe letal, ki pristajajo na teh letališčih in za zračnega prevoznika Air Zimbabwe. Rezultat novega postopka pri računalniškem programm za uravnoteženje letala je univerzalni program, ki ustreza floti katerega koli zračnega prevoznika. Računalniški program so preskusili in odobrili zračni prevozniki: Croatia Airlines, Adria Airways, Austrian Airlines, ČSA, LOT, Malev, Lauda Air, Air Loyd, Fischer Air, Condor in Duo Airways.

(Ključne besede: letala, varnost, uravnoteženje, programi računalniški)

Aircraft balancing is an activity of great responsibility for the safety of aircraft in flying and landing. Usually aircraft balancing is made on air-carrier diagrams that are not unified. Regarding the planned total aircraft handling time, aircraft balancing requires great speed and, at the same time, great accuracy. A program has been developed at Airport Split for ramp handling control and aircraft balancing that fully complies with the standards defined in the International Air Transport Association document Airport Handling Manual. The program has been succesfully implemented at the following airports: Split, Dubrovnik, Pula, Zadar, Osijek and Knock (in Ireland) for air carriers and aircraft fleet landing at those airports, as well as the air carrier Air Zimbabwe. The new approach to the computer program for aircraft balancing resulted in a universal program able to correspond with any air-carrier fleet. This computer program has been tested and approved by the following air carriers: Croatia Airlines, Adria Airways, Austrian Airlines, CSA, LOT, Malev, Lauda Air, Air Loyd, Fischer Air, Condor and Duo Airways.

(Keywords: aircraft, safety, balancing, computer programs)

0 UVOD

Uravnoteženje letala je preračun mase letala in lege težišča letala z optimalno razporejenimi potniki, prtljago in tovorom. Zaposleni na sprejemu in odpremi letala in uravnoteženje morajo poznati standarde, ki jih zahteva zračni prevoznik za določen tip letala, glavne karakteristike letala in omejitve mase letala. To pomeni, da mora nadzornik sprejema in odpreme letala odločiti o razporedu potnikov, prtljage in tovora v letalu o podatkih o številu in masi

0 INTRODUCTION

Aircraft balacing means calculating on aircraft's weight and the position of the aircraft's centre of gravity in order to balance the aircraft by distributing the passengers, baggage and cargo to be carried in the aircraft in the optimum way. The operater working in the aircraft handling control and balancing service has to know the standards required by the air carrier for a certain type of aircraft, the basic characteristics of the aircraft and especially the limiting aircraft weights. This means that based on the data about the number and weight of the potnikov, prostornini in masi prtljage in tovora in trajanju leta [1]. Težišče mora biti znotraj določenih mejnih vrednosti, ki omogočajo letalu varno letenje in pristajanje [2].

passengers, the volume and weight of the baggage and the cargo, and the aircraft flight duration, the aircraft load controller has to make a decision about the arrangement of passengers, baggage and cargo in the aircraft [1]. The center of gravity must be within specified limits which allows aircraft safety in flying and landing [2].

1 MASE LETALA IN PRERAČUN TEŽIŠČA PRAZNEGA IN NATOVORJENEGA LETALA

1 AIRCRAFT WEIGHTS AND CALCULATING THE CENTRE OF GRAVITY OF EMPTY AND LOADED AIRCRAFT

Za vsako letalo obstajajo omejitve mase zaradi aerodinamične stabilnosti in strukturne nosilnosti. Razlikujejo se: največja projektirana masa (na vozni stezi, pri vzletanju, brez goriva, pri pristajanju), največja dovoljena masa (odvisno od fizičnih karakteristik letališča kot so nadmorska višina, nagib vzletno-pristajalne steze in dolžina, ovire,smer in moč vetra, temperatura itn.), operativne mase (prazna po proizvajalcu, osnovna, suha operativna, operativna), in dejanske mase (pri vzletanju, pri pristajanju, brez goriva, na vozni stezi) [3].

Za preračun težišča praznega in natovorjenega letala se uporabljajo naslednje metode:
- analitična,
- grafična in
- indeksna.

There are limits to the weight of every aircraft, both because of aerodynamic stability and because of structural strength. These limits are as follows: Maximum Design Weights (taxi, take off, zero fuel and landing), Maximum Allowed Weights (depends on the physical characteristics of the airport, like altitude, runway gradient and length, obstacles, wind direction and power, temperature; Operating Weights (manufacturer empty, basic, dry operating, operating); and Actual Weights (take off, landing, zero fuel, taxi) [3].

In calculating the centre of gravity of an empty and a loaded aircraft the following methods are used:
- the analytical method,
- the graphical method, and
- the index method.

1.1 Analitična metoda

Za prazno ali naloženo letalo se lahko izračuna lega težišča z uporabo analitične metode. Z drugimi besedami, znotraj določenega koordinatnega sistema se računajo momenti vseh komponent in delijo z maso teh komponent. Ker je moment sile enak sila krat ročica, se lahko tako izračuna ročica, na katerem deluje rezultantna sila [1].

Za prazno letalo se izračuna masa vsakega posameznega dela, vgrajenega v letalo, ali dela, ki je v njem, in natančna lega vsakega dela. Seštevek vseh momentov, deljen s skupno maso, da lego težišča.

Masa vsakega dela letala deluje na ustrezni ročici osi x (npr. Gm na Xm) in iz tega izhaja, da je:

1.1 Analytical method

For an empty or loaded aircraft the point of gravitation force, i.e., the centre of gravity, can be determined by the analytical method. In other words, the moments of all the components are calculated within a certain coordinate system and divided by the weights of these components. Since the moment of force equals force x length, it is in this way that the length is obtained at which the resulting force is acting [1].

Thus, the weight for every single part installed or located in the aircraft needs to be calculated for an empty aircraft, as well as the exact location of every single part. The sum of all the moments divided by the total weight (of all the parts) will yield the position of the centre of gravity.

The weight of every part of the aircraft acts at a certain lenght of the x axis (e.g. Gm at Xm), and therefore:

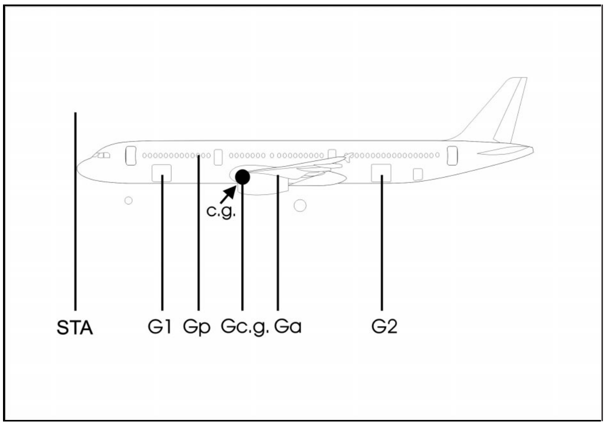
$$X_A = \frac{\sum_{i=1}^{n} G_i X_i}{\sum_{i=1}^{n} G_i} \quad (1).$$

Ker je letalo sestavljeno iz številnih sestavnih delov, analitična metoda uporablja tako imenovani produkcijski prerez namesto osi z, in os letala namesto osi x.

V primeru naloženega letala in znane mase praznega letala in lege težišča praznega letala se uporablja enaka metoda za izračun

Since an aircraft consists of numerous components, the analytical method uses the so-called Manufacturer zero Station instead of the z axis, and the Centre Line instead of the x axis.

In the case of a loaded aircraft, with the known weight of the empty aircraft as well as the position of the centre of gravity of the empty aircraft, the same method is



Sl. 1. *Izračun težišča z analitično metodo*
Fig. 1. *The centre-of-gravity calculation using the analytical method*

težišča za vsakega potnika, blago ali prtljago. Vsak natovorjeni kilogram na določenem mestu v letalu prispeva k premiku težišča.
Sledi:

used to calculate the centre of gravity for every passenger, item of goods or baggage. Thus, every loaded kilogram at a certain position within the aircraft will affect the shift of the final point of gravitation force, i.e., the centre of gravity. It follows that:

$$X_{c.g.} = \frac{G_A X_A + G_1 X_1 + G_2 X_2 + G_p X_p}{G_A + G_1 + G_2 + G_p} \quad (2),$$

G_a= masa praznega letala
G_1= masa tovora
G_p= masa potnikov
G_2= masa tovora

G_a= weight of empty aircraft
G_1= weight of cargo
G_p= weight of passengers
G_2= weight of cargo

1.2 Grafična metoda

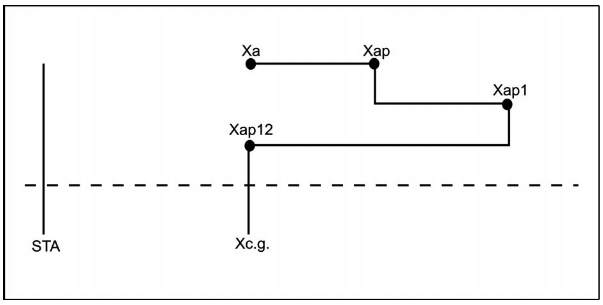
Grafična metoda se razlikuje od analitične tako, da je računanje zamenjano z risanjem. Za vsako komponento se nariše premik težišča letala v smeri nosa ali repa letala v odvisnosti od lege in mase tovora. Primer izračuna težišča letala z analitično metodo bi bil pri grafični metodi videti kakor na sliki 2.

Prazno letalo ima težišče v Xa. Izračuna se masa potnikov in dobi premik težišča v točko Xap, ki ustreza težišču za maso letala + maso potnikov. Nadaljnji premik je odvisen od mase tovora G2 in G1 in težišče se premika v točko Xc.g.,

1.2 Graphical method

The graphical method differs from the analytical method in that it uses drawings instead of calculations. In other words, the shift of the centre of gravity is entered for every component towards the aircraft nose or tail, and depending on the position and weight of the loaded cargo. Thus, as an example of a calculation of the centre of gravity of an aircraft using the analytical method, the application of the graphical method would be as in Figure 2.

The empty aircraft has its centre of gravity at Xa. If the weight of the passengers Gp is calculated, this will yield a shift of the centre of gravity to the point Xap, which corresponds to the point of aircraft weight +



Sl. 2. *Izračun težišča z grafično metodo*
Fig. 2. *Calculation of the centre of gravity by graphical method*

kar ustreza težišču praznega letala, tovora in vkrcanih potnikov. Torej je premik težišča zmeraj odvisen od mase in lege tovora in vkrcanih potnikov [1]. Izračun težišča se z razdelitvijo letala poenostavi na sekcije (npr. potniška kabina – sekcija A, B, C in prtljažni prostori 1 in 2), tovor pa se računa po sekcijah in premika težišče na račun tovora v posamezni sekciji na pripravljeni lestvici (sl. 2).

passengers weight. In the same way a further shift depends on the weight of cargo G_2 and G_1, so that the centre of gravity is further moved to the point Xc.g., which corresponds to the point of force for the empty aircraft plus the value of the loaded cargo and passengers. Thus, the shift of the centre of gravity depends always on the weight and the position of the loaded cargo and passengers [1]. The calculation of the aircraft's centre of gravity using the graphical method is still further simplified by dividing the aircraft into sections (e.g. passenger cabin - sections A, B, C and cargo compartments 1 and 2), so that cargo is calculated per section and the shift of the centre of gravity considering the cargo in a certain section on a prepared scale (Figure 2).

1.3 Indeksna metoda

Ker se pri uravnoteženju letala z analitično metodo uporabljajo decimalna števila in različne merske enote in so mogoče napake pri izračunu, je uveden pojem *indeks* kot spremenjeni moment (številka pomeni moment), ki skupaj z maso letala določi težišče:

Temeljni indeks

1.3 Index method

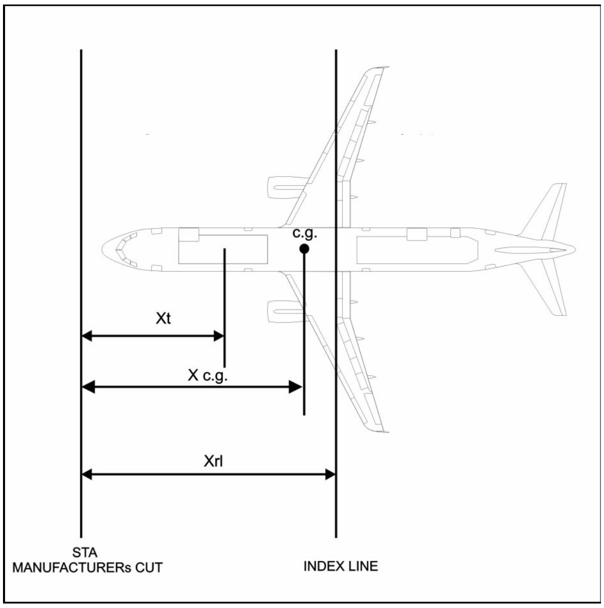
Since decimal numbers and different measuring units are often used when calculating the aircraft balance with the analytical method, resulting in possible errors of calculation, the term *index* has been introduced as the transformed moment (the number which represents moment), which together with the aircraft weight determines the centre of gravity:

Basic Index

$$BI = A - \frac{(X_{RL} - X_{c.g.})G}{B} \quad (3),$$

kjer so:
- A in B – stalnice, ki zavarujejo, da se vrednost indeksa giblje znotraj določenih območij;
- X_{RL} – dolžina od proizvajalčevega prereza (Ø STA) do referenčne črte ali indeksne črte;
- $X_{c.g.}$ – dolžina od proizvajalčevega prereza do težišča praznega letala;
- G – masa praznega letala (basic weight).

where:
- A and B are constants which ensure that the index value remains within certain limits;
- X_{RL} is the length from the manufacturer's cross section (Ø STA) to the reference line or index line;
- $X_{c.g.}$ is the length from the manufacturer's cross section to the centre of gravity of an empty aircraft;
- G is the weight of an empty aircraft (Basic Weight).



Sl. 3. *Uravnoteženje letala z indeksno metodo*
Fig. 3. *Aircraft balance using the index method*

Če se namesto osnovne mase v enačbo, da vrednost suhe operativne mase (SOM - D.O.W.) z ustrezajočo lego težišča letala, tedaj se kot rezultat dobi suhi operativni indeks (SOI - D.O.I.) (sl. 3).

Če se prazno letalo, za katerega je izračunan osnovni ali suhi operativni indeks, želi obremeniti in uravnotežiti, se mora popraviti vrednost indeksa: nov indeks = indeks praznega letala + popravni indeks ali I (natovorjeni 0 D. O. I. + ΔI), in popravni indeks je:

If the Basic Weight in the equation is replaced by the value for Dry Operating Weight (D.O.W.) with the appropriate position of the centre of gravity, then the obtained result is the Dry Operating Index - D.O.I. (Figure 3).

If the empty aircraft with the calculated basic or dry operating index is to be loaded and balanced, the index value has to be recalculated: new index = index of the empty aircraft + corrective index, or I (loaded 0 D. O. I. + ΔI), and the corrective index is:

$$\Delta I = -\frac{(Xrl - Xt)Gt}{B} \quad (4),$$

kjer so:

B – stalnica, enaka kakor za izračun osnovnega indeksa;

Xrl – oddaljenost od proizvajalčevega prereza do indeksne ali referenčne črte;

Xt – oddaljenost težišča tovora (ki je natovorjen v letalo) od proizvajalčevega prereza;

Gt – masa nakladanega tovora.

Rezultati za osnovni indeks (za vsak tip letala posebej) so standardni, vsak zračni prevoznik jih določi zase. Vrednost suhe operativne mase je odvisna od števila in mase članov posadke, mase hrane in pijače za potnike in posadko, mase blaga v brezcarinski prodaji. Vse to je prikazano razpredelnično [1].

Referenčna ali indeksna črta se lahko postavi kjerkoli v letalu (odvisno od tega, za kateri tovor se želi odstraniti velik vpliv rezultirajočega momenta ali indeksa), tako da so za isti tip letala lahko vrednosti indeksa različne.

where:

B is a constant, the same as for the calculation of the basic index;

Xrl is the distance from the manufacturer's cross section to the index or reference line;

Xt is the distance of the centre of gravity of the cargo (loaded in the aircraft) from the manufacturer's cross section;

Gt is the weight of the loaded cargo.

Results for the basic index (for every aircraft type separately) are standard, and every airline determines these individually. The value of the Dry Operating Weight depends on the number and weight of the crew members, the weight of food and beverages for the passengers and crew (catering), the weight of the Duty Free Shop goods, and these are presented in a table [1].

The reference or index line can be set anywhere on the aircraft (depending on for which cargo the large influence of the resulting moment or index needs to be eliminated), so that there may be different index values for the same aircraft type.

2 POMANJKLJIVOSTI SEDANJIH PROGRAMOV ZA URAVNOTEŽENJE LETALA

Zračni prevozniki imajo lastne sisteme za uravnoteženje letala. Podobni programi so bili razviti izključno za velike zračne prevoznike: to so Lufthansa, British Airways, Swisair, Delta za njihove potrebe v skladu z njihovimi kriteriji in standardi. Ti prevozniki so prodajali programe drugim zračnim prevoznikom in jim dali programsko podporo. Pred približno desetimi leti so se prevozniki izogibali uporabi grafične podpore zaradi potrebnega velikega pomnilnika, razmeroma majhne hitrosti in zmogljivosti računalnikov in mreže.

Z dajanjem storitev različnim zračnim prevoznikom prisiljujejo letališko osebje na uporabo različnih računalniških sistemov. To pomeni dnevno uporabo različnih uporabniških vmesnikov kar otežuje delo in zvišuje stroške vadenja.

2 PROBLEMS WITH EXISTING AIRLINE BALANCING PROGRAMS

Airlines normally have their own systems for aircraft balancing. This makes problems for the airport staff in load control, i.e., aircraft balancing. Similar programs have been developed exclusively by big air carriers, e.g., Lufthansa, British Airways, Swissair, Delta, mainly for their own needs and according to their own criteria and standards. These programs are later sold to other air carriers, who are provided with their own program support. Therefore, they avoided using graphical support, both because of the large amount of memory required, and because of the relatively low speed and computer and network capacity, available some ten years ago.

Furthermore the offering of services to different air carriers, forces airport staff to use different computerised systems. That means the daily use of different user interfaces, which makes work significantly more difficult, and increases training costs.

3 RAČUNALNIŠKI PROGRAM ZA URAVNOTEŽENJE LETALA

Računalniški program za uravnoteženje letala, ki so ga razvili na latelišču Split, je tehnološko zamišljen tako, da uporablja isti vmesnik, lahko pa se uporablja za različne zračne prevoznike in popolnoma ohranja njihove posebne standarde.

Glavne značilnosti programa za uravnoteženje letala so:

- program je namenjen za delo na osebnem računalniku v operativnem okolju in grafičnem vmesniku Windows 95, 98, NT, 2000, XP. Osebni računalniki so povezani z Windows 2000 računalniškim omrežjem 4, 11. Slike na zaslonu so izdelane za monitorje z diagonalo 15 palcev, ločljivostjo 800×600 točk in 4 bitne palete barv;
- najpomembnejša značilnost programa je grafični diagram za vsak tip letala, ki omogoča balanserju letala, da vidi v vsakem trenutku, kje je težišče letala;
- program omogoča hkrati delo številnim uporabnikom, ki uravnotežijo različna letala. Vnos podatkov o številu in masi potnikov, prtljage in tovora je avtomatiziran. Prav tako tudi pošiljanje vseh poročil v zvezi z nakladanjem in uravnoteženjem letala;
- glede na to, da so narejeni posebni moduli, baze in grafični diagrami za vsak tip letala za vse zračne prevoznike, je program izdelan tako, da je mogoče dopolnjevanje z novimi tipi letal brez omejitve;
- varnost programa mora biti največja zaradi velikega števila baz, indeksov in podatkov, ki se za vsak let shranjujejo v posebnem delovnem prostoru, direktoriju, na trdem disku;
- program je izdelan v programskem jeziku Fox Pro 2,6a, jeziku, ki je eden od narečij jezika Xbase, namenjen pa je delu z bazami podatkov;
- ker se program za uravnoteženje letala sproži iz glavnega programa za avtomatizacijo dejavnosti sprejema in odpreme letala, potnikov in tovora, je ta način dela programa modularen, kar pomeni, da so v delovnem pomnilniku računalnika hkrati dejavni največ štirje moduli. Delovni pomnilnik (RAM) je najbolj razbremenjen, zato je hitrost programa večja, ostaja pa dovolj prostora za hkratno delo drugih programov;
- da bi lahko program delal usklajeno s postavljenimi zahtevami, obstaja nekoliko preglednic, v katerih so organizirani najpomembnejši podatki o vsaki verziji in tipu letala vsakega zračnega prevoznika.

4 TEHNOLOŠKO DELOVANJE

Računalniški program za uravnoteženje letala ima širok spekter možnosti na različnih

3 COMPUTER PROGRAM FOR AIRCRAFT BALANCING

The computer program for aircraft balancing developed at Airport Split is technologically conceived in a manner that, although using the same users interface, it may be applied to different carriers, entirely respecting their particular standards.

The basic characteristics of the program for aircraft balancing are as follows:

- the program is intended to work on PCs in the operating environment and graphical interface of Windows 95, 98, NT, 2000, XP. The PCs are connected to the Windows 2000 computer network 4, 11. The images on the screen are meant for monitors of diagonal size 15 inches, resolution 800×600 pixels, and a 4-bit colour palette;
- the most important characteristic of the program is the graphical diagram for every single aircraft type, which allows the aircraft load controller to be able to see at any moment where the centre of gravity is;
- the program allows the simultaneous work of a number of users who perform the balancing of different aircraft, and the input of data about the number and weight of the passengers and cargo, as well as loaded goods, and the sending of all messages related to loading and balancing the aircraft is automated;
- since special modules, bases and graphical diagrams are made for every aircraft type, of every single air carrier, the program has been developed in such a way that it can be supplemented by new types of aircraft, free of limitations;
- in order to ensure the maximum safety of program operation, and having in mind the large number of bases, indexes, and the need to keep the data, etc. the data about every flight are stored in a special directory on a hard disc;
- the program has been developed in Fox Pro 2,6a, i.e., a language that represents one of the Xbase dialects, intended for work with databases;
- since the program for aircraft balancing gets activated from the main program for automating aircraft, passengers and cargo handling activities, the program operates in a modular way, which means that a maximum of up to four modules are simultaneously active in the PC RAM. Thus, the operating load on the RAM is minimized, which allows much greater speed of the program, leaving enough room for the simultaneous running of other programs;
- in order to make the program work in compliance with the set requirements, a whole series of tables has been created that provide an organised set of the most important data about single versions and types of aircraft owned by single operators.

4 TECHNOLOGICAL FUNCTIONALITY

The computer program for aircraft balancing has a wide spectrum of possibilities through vari-

zaslonih:
- za izbiro določenega letala,
- prikaz mase,
- osnovni računalniški program,
- z najpomembnejšimi podatki, potrebnimi za uravnoteženje letala,
- za vpis gesla, kadar se spreminjajo vpisani podatki na zaslonu z vsemi najpomembnejšimi podatki,
- prikaz mas z odprtimi polji za vpis potnikov, prtljage, blaga in pošte,
- za vpis stvarne oddane mase in ročne prtljage,
- za vpis skupnega števila potnikov po sekcijah v letalu,
- z grafičnim diagramom uravnoteženja letala,
- možnost računalniškega programa, da svetuje idealno uravnoteženost letala,
- pregled dejanskih in največjih mas,
- pregled podatkov o potnikih,
- pregled podatkov o gorivu,
- vsebina poročila o vkrcanih potnikih in natovorjenem tovoru,
- obrazec za obremenitev in uravnoteženost letala,
- prikaz potniške kabine in zasedenih sedežev,
- prikaz registriranih potnikov in tistih, kimanjkajo,
- prikaz zasedenih sedežev,
- prikaz podatkov o registriranem tovoru za določen let itn.

ous screens:
- for selecting appropriate aircraft,
- displaying weights,
- home screen of the computer programme,
- with the most important data necessary for aircraft balancing,
- requiring password when changing the entered data on the screen displaying all the most important data,
- displaying weights with open boxes for the input of passenger, baggage, cargo and mail,
- for the input of the actual weight of checked and cabin baggage,
- containing the total number of passengers per aircraft section,
- with a graphical diagram showing aircraft balance,
- the possibility of a computer program to suggest the ideal aircraft balance,
- viewing actual and maximum weights,
- viewing data about passengers,
- viewing data about fuel,
- content of the message about the passengers and cargo onboard,
- showing the passenger cabin layout and the occupied seats,
- showing the number of checked passengers and those missing,
- showing the seats occupied by passengers who have boarded the aircraft,
- overview of data regarding cargo checked for a particular flight, etc.

5 SKLEP

Računalniški program je narejen uporabniku kar najbolj prijazno in je prilagojen običajnim metodam dela, ki so bile že prej uporabljene, kar je bistveno skrajšalo vsakodnevno uporabo. Poglavitna razlika tega računalniškega programa za uravnoteženje letala in drugih, podobnih, je:

a. grafični diagram, na katerem je v vsakem trenutku mogoče vidno preveriti lego točke težišča letala v različnih kritičnih trenutkih leta,
b. prilagojenost programa vseh tipov letal vseh zračnih prevoznikov v skladu z njihovimi standardi. Z drugimi besedami uporabnikom tega programa je omogočeno, da za vsakega prevoznika posebej izdelajo bazo podatkov za vsak tip letala v skladu s prevoznikovimi operativnimi masami.

Problem grafičnega prikaza je, da se mora zaradi spremembe operativnih mas zamenjati (to zračni prevozniki občasno delajo), za to pa je pooblaščen samo avtor računalniškega programa. Da bi bili prihodnji uporabniki programa čim bolj samostojni, so razvili dinamični grafični diagram, na katerem so dovoljene meje ustrezajočih največjih mas, ki se zamenjajo avtomatično v skladu s spremembo numeričnih vrednosti. Tak diagram

5 CONCLUSION

The computer program has been made as user-friendly as possible and adapted to the usual methods of work applied previously, which has made the final acceptance and everyday use of this program much easier to implement. The basic difference of the program for aircraft load and trim control developed at Airport Split and other similar programs lies in the following:

a. the existence of a graphical diagram allowing a visual check at any time of the aircraft's centre of gravity in different critical moments of flight,
b. the adaptability of the program to any aircraft type of any air carrier in compliance with its standards. In other words, the users of this program can develop for every air carrier a separate database of every aircraft type in accordance with the carrier's specific operating weights.

The problem with the graphical presentation lies in the fact that when the operating weights are changed, which is done sometimes by air carriers and aircraft owners, also the graphical diagram has to be partly changed, and only the author of the computer program is authorised to do this. Therefore, and with the intention of making the future users as independent as possible when using the program, a dynamic graphical diagram started to be developed, where the allowed limits of the approprije zdaj izdelan za vse tipe letal, ki pristajajo na hrvaških letališčih v Splitu, Dubrovniku, Pulju, Zadru, Osijeku in Knocku na Irskem.

Na koncu je treba poudariti, da je z uporabo računalniškega programa zelo povečana natančnost izračuna, s tem pa stabilnost in varnost letala v času leta. Čas, ki je potreben za izdelavo obrazca za obremenitev in uravnoteženost, je skrajšan od povprečno deset minut, kolikor potrebuje za ročno izdelavo, na samo eno do dve minuti. Tako ostane več časa za popoln in natančen nadzor zaposlenim, ki delajo pri sprejemu in odpremi letala.

Računalniški program za uravnoteženje letal so testirali in odobrili strokovnjaki za uravnoteženje letal naslednjih zračnih prevoznikov: Croatia Airlines, Adria Airways, Austrian Airlines, ČSA, LOT, Malev, Lauda Air, Air Loyd, Fischer Air, Condor in Duo Airways. Air Zimbabwe uporablja ta program za uravnoteženje svojih letal.

ate maximum weights are changed automatically in accordance with the modification of numerical values. Such a diagram has now been developed for all types of aircraft flying to the Croatian airports in Split, Dubrovnik, Pula, Zadar, Osijek and Knock, in Ireland.

Finally, it has to be pointed out that by using this computer program the accuracy of the calculation has been significantly improved, including also better stability and aircraft safety during flight. The duration necessary for completing the Load and Trim Sheet has been shortened from the ten minutes on average required to do this manually, to one to two minutes, thus leaving time for complete and precise control of staff working on unloading / loading of baggage and cargo, and total aircraft handling.

This computer program for aircraft balancing has been tested and approved by the experts on aircraft balancing of the following air carriers: Croatia Airlines, Adria Airways, Austrian Airlines, CSA, LOT, Malev, Lauda Air, Air Lloyd, Fischer Air, Condor and Duo Airways. Air Zimbabwe is also using this balancing program.

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Short scientific paper (1.03)

Ugotavljanje občutljivosti ultrazvočnega toplotnega merilnika s programskim paketom ANSYS

Determining the Sensitivity of an Ultrasonic Heat Meter Using the ANSYS Analysis Tool

Marko Boltežar

V prispevku prikazujemo način in rezultate raziskave merilne občutljivosti ultrazvočnega (UZ) toplotnega merilnika. Namen raziskave je bil ugotoviti, kakšna naj bo oblika pretočne merilne celice, da bo zagotovila ustrezno merilno občutljivost. Pri tem smo uporabili simuliranje s programskim paketom ANSYS, ki temelji na metodi končnih elementov (MKE). Z meritvami smo analize z MKE tudi potrdili. Izkazalo se je, da smo s simulacijami dovolj blizu dejanskim razmeram v pretočnem delu toplotnega merilnika, saj so se rezultati dobro ujemali. Končni rezultat izvedenih meritev in simulacij z MKE je prototip merilne celice, ki zagotavlja ustrezno merilno občutljivost toplotnega merilnika oz. toplotnega merilnika.

(Ključne besede: merilniki ultrazvočni, merilniki toplote, občutljivost, paketi programski, ANSYS)

In this paper an investigation of the sensitivity of an ultrasonic heat meter is presented. The goal of the investigation was to determine the shape of the flow measuring cell that gives the maximum sensitivity. The simulation involved the program package ANSYS, which is based on the finite-element method (FEM). The FEM results were experimentally verified. The simulations turned out to be very close to the actual flow conditions within the flow unit of the heat meter. The experimental results agree well with theory. The final result of the FEM analysis and the experimental measurements is a prototype of the measuring cell that ensures the required sensitivity of the heat meter.

(Keywords: ultrasonic heat meters, sesitivity, software packages, ANSYS)

0 UVOD

Energija postaja dandanes v vseh svojih pojavnih oblikah vedno bolj dragocena. Celoten svetovni razvoj sili k varčevanju energije in k iskanju novih alternativnih virov. Porabnik ima namreč pravico, da plača le tisto energijo, ki jo je dejansko porabil. Vse to terja sistemski postopek tako načrtovanja in izdelave merilnikov porabljene energije kakor tudi krmiljenja in vzdrževanja. Ena od naprav, ki je namenjena merjenju rabe toplotne energije, je toplotni merilnik, ki je namenjen merjenju porabljene toplotne energije v stanovanjih, enodružinskih hišah, stanovanjskih blokih itn.

Toplotni merilniki lahko delujejo po različnih načelih. Prevladujejo še vedno mehanski merilniki, med statične merilnike brez gibajočih se mehanskih delov pa spadajo ultrazvočni in induktivni toplotni merilniki.

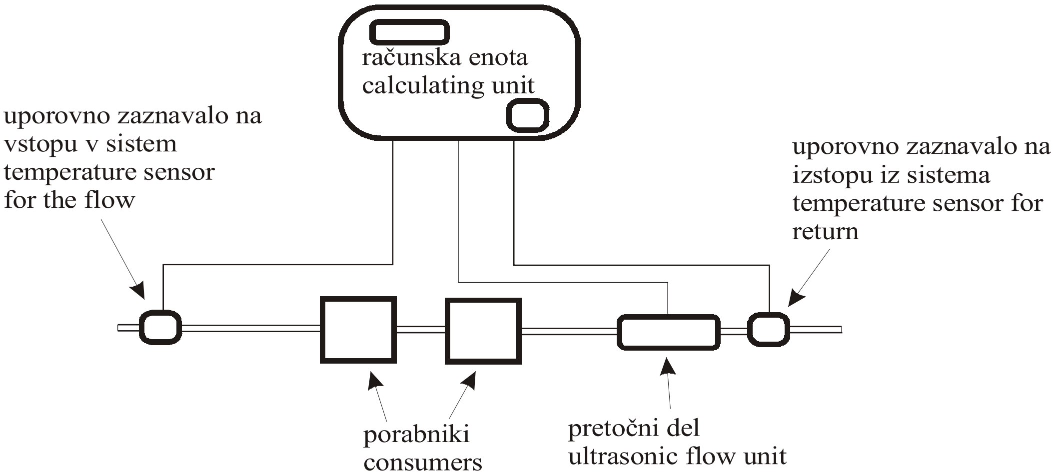
Ultrazvočni toplotni merilnik je sestavljen iz pretočnega dela, dveh uporovnih temperaturnih

0 INTRODUCTION

Energy, in all its forms, is becoming an increasingly valuable commodity. The world is developing in the direction of energy saving and the search for new, alternative sources of energy, regardless of its nature. A consumer has the right to pay only for the amount of energy that he/she has actually consumed. This concept requires a system approach to the design and development of new energy meters. One such device is a heat meter, which serves to measure the consumed heating energy in apartments, family houses and blocks of flats etc.

Heat meters operate on different principles, among which classical mechanical principles still prevail. Modern static heat meters, for example, magnetic inductive or ultrasonic meters have no moving mechanical parts.

An ultrasonic heat meter consists of an ultrasonic flow unit, two temperature sensors for the



Sl. 1. *Vezalna shema toplotnega merilnika*
Fig. 1. *Schematic drawing of a heat meter*

zaznaval in baterijsko napajane računske enote s prikazovalnikom (sl.1)

Pretočni del je sestavljen iz merilne cevi in dveh ultrazvočnih zaznaval. Ta sklop imenujemo tudi pretočna merilna celica.

Kakor bomo videli kasneje, je merilna občutljivost toplotnega merilnika odvisna od dolžine poti med oddajnikom in sprejemnikom in hitrosti vode pri imenskem pretoku. Pri razvoju novega pretočnega dela s krajšimi priključnimi merami ali pretočnega dela, namenjenega drugim pretokom, moramo biti pozorni na ustrezno merilno občutljivost. Pri krajši priključni meri je pot med oddajnikom in sprejemnikom krajša in je zato tudi občutljivost manjša. Tudi hitrosti vode pri imenskem pretoku ne smemo pretirano večati, saj bi s tem presegli dopustni padec tlaka. Občutljivost merilnika, oziroma merilne celice, bomo opazovali s pomočjo povprečne hitrosti vode pri imenskem pretoku v smeri UZ poti ($\bar{v}$) in dolžini UZ poti L. Hkrati lahko opazujemo tudi razliko časov preleta zvočnega signala v in proti smeri toka vode. Pri enem od naših sedanjih merilnikov iz družine UTM-2, s priključno mero 190 mm, ta čas znaša Δt = 240 ns, zmnožek $\bar{v} \cdot L$, pa znaša 0,260 m^2/s. V tem prispevku se ukvarjamo z načrtovanjem toplotnega merilnika s skrajšano priključno mero 110 mm, pri čemer mora biti občutljivost merilne celice enaka ali pa večja od zgoraj omenjene vrednosti.

flow and return and a battery-powered calculating unit with a display (Fig. 1).

The flow unit consists of a special measuring pipe and two ultrasonic transducers. This unit is usually known as the flow measuring cell.

As will be shown later, the sensitivity of the heat meter depends on the length of the sound path between the two transducers and on the fluid velocity at the nominal flow rate. When constructing flow measuring units with either different overall lengths or for different flow rates care must be taken to maintain the meter's sensitivity. With a shorter overall length, the sound path between the transducers is shorter and the sensitivity is therefore lower. As for the fluid velocity at the nominal flow rate, it must be kept within limits so as not to cause an excessive pressure drop. The sensitivity of the heat meter, i.e., of the measuring cell, will be observed on the basis of the mean fluid velocity $\bar{v}$ along the sound path at the nominal flow rate and the length of the sound path L. We can also observe the difference in the transit times for the ultrasonic signals propagating with and against the flow. With one of our existing heat meters from the product family UTM-2 (ultrasonic heat meter) with an overall length of 190 mm the time difference is Δt = 240 ns and the product of $\bar{v} \cdot L$ = 0.260 m^2/s. In this paper the procedure for designing heat meters with a reduced overall length of 110 mm, but where the sensitivity of the measuring cell will be kept at the required value, will be described.

1 TEORIJA

1.1 Prenosni učinek

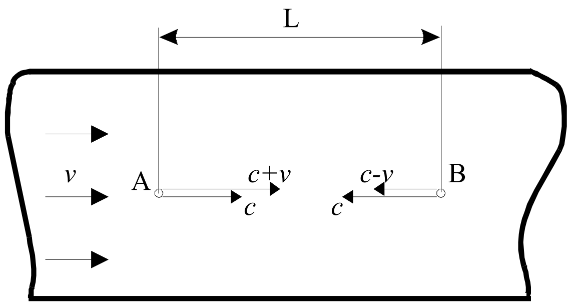
Prenosni učinek [6], po katerem deluje merilnik, sodi med najbolj uporabljene postopke za izvedbo industrijskih merilnikov pretoka. Upošteva spremembo potovalnega časa ultrazvočnega signala v pretočnem sredstvu med točkama A in B, če se ta signal razprostira v smeri ali proti smeri pretoka. Če v pretočno sredstvo

1 THEORY

1.1 Transit time principle

The ultrasonic heat meters of Iskraemeco are based on the well-known transit-time principle [6], which has found broad application in the field of industrial ultrasonic flow meters. The basic idea behind this principle is to take into account the difference in the transit times of an ultrasonic signal odpošljemo ultrazvočni signal iz točke A proti točki B (sl. 2), potem pri mirujočem merjenem sredstvu potuje zvočni signal med točkama z zvočno hitrostjo *c*. Če pa se pretočno sredstvo premika v isti smeri s hitrostjo *v*, dobi zvočni signal rezultirajočo hitrost $(c+v)$, kar pomeni, da bo signal dosegel pri gibajočem se sredstvu točko B v krajšem času t_+, kakor pri mirujočem merilnem sredstvu. Če pa sedaj pošljemo signal od točke B k točki A, torej v smeri nasproti gibanju merjenega sredstva, bo rezultirajoča hitrost $(c - v)$, in signal potrebuje daljši čas t_- da prepotuje enako razdaljo v merjenem sredstvu. Časovna razlika $\Delta t = t_- - t_+$ je merilo hitrosti pretočnega sredstva. Tako lahko določimo hitrost vode in pretok prek razlike časov in konstrukcijskih lastnosti pretočnega dela.

traveling between two points, A and B, when the signal travels alternately with and against the flow of the fluid. With a stationary fluid an ultrasonic signal emitted from point A will propagate towards point B with a sound velocity *c* (Fig. 2). If the fluid is moving in the same direction with a velocity *v*, then the velocity of the ultrasonic signal will be $(c+v)$, thus resulting in a shorter transit time t_+. If, however, the signal is sent in the opposite direction, its velocity will be reduced to $c-v$, leading to a longer transit time t_-. The difference in transit times $\Delta t = t_- - t_+$ is proportional to the flow velocity. We can therefore deduce the flow velocity and the flow rate from the transit-time difference and the constructional properties of the flow unit.



Sl. 2. *Širjenje ultrazvočnega signala med točkama A in B v gibajoči se kapljevini - prenosni učinek*
Fig. 2. *Propagation of an ultrasonic signal between points A and B in a moving fluid - the transit-time principle*

Preprost izračun pokaže, da je časovna razlika Δt enaka:

A simple equation shows that the transit-time difference Δt equals

$$\Delta t = \frac{2vL}{c^2} \quad (1).$$

Pri tem je *L* razdalja med točkama A in B. V splošnem primeru, ko ultrazvočni snop ni preprosto vzporeden s smerjo gibanja kapljevine, in v primeru, ko porazdelitev hitrosti v cevi ni homogena, pa je enačbo (1) treba zapisati v obliki:

where *L* is the distance between the points A and B. In a more general case, when the ultrasonic beam is not in parallel with the direction of the flow and when the velocity distribution within the pipe is not uniform, Equation (1) should be rewritten as

$$\Delta t = \frac{2\bar{v}L}{c^2} \quad (2).$$

Pri tem je $\bar{v}$ povprečna hitrost kapljevine vzdolž zvočne poti med točkama A in B. Časovna razlika Δt je tem večja, čim večji je zmnožek $\bar{v} \cdot L$, to pa pomeni, da je tudi ločljivost toplotnega merilnika, glede na dano rešitev elektronskega vezja, večja. Definirajmo zmnožek $\bar{v} \cdot L$ pri imenskem pretoku, kot mero občutljivosti toplotnega merilnika.

where $\bar{v}$ is the mean fluid velocity along the sound path between the points A and B. The transit-time difference at a given flow rate is proportional to the product $\bar{v} \cdot L$, which also means that the measuring resolution of the heat meter, taking into account the characteristics of the electronic circuitry, increases with increasing $\bar{v} \cdot L$. We therefore define the product $\bar{v} \cdot L$ at the nominal flow rate as a measure of the sensitivity of the heat meter.

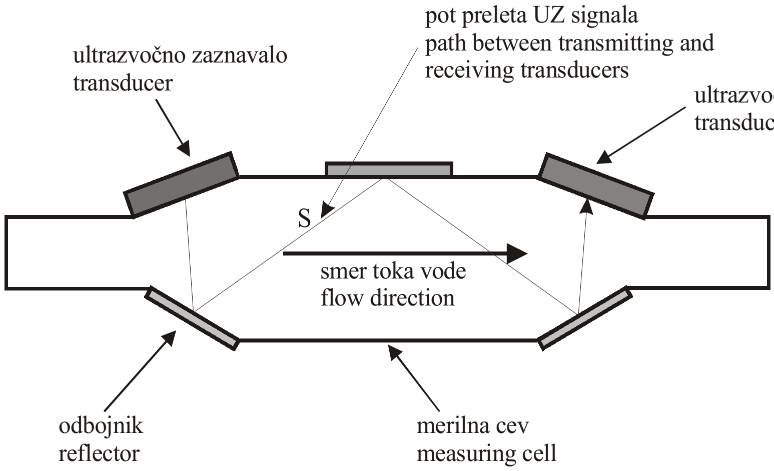
1.2 Prikaz problematike občutljivosti toplotnega merilnika

Občutljivost smo torej definirali kot zmnožek dolžine poti preleta signala *L* in povprečne hitrosti vode v smeri širjenja zvoka ($\bar{v}$) pri

1.2 Flow-unit sensitivity issues

The heat-meter sensitivity has been defined as the product of the flow path *L* between the transmitting and the receiving ultrasonic transducers imenskem pretoku merilnika. Pri tem smo pri širjenju ultrazvoka vzeli kar načela geometrijske optike, saj so vzdolžne in prečne izmere merilne cevi mnogo večje od valovne dolžine valovanja UZ, ki znaša približno pol milimetra. Model merilne celice našega toplotnega merilnika je razviden s slike 3. Vidimo, da se zvok širi skozi merilno celico pod različnimi koti glede na smer toka vode. Poglavitna težava pri določitvi občutljivosti merilnika je torej izračun povprečne hitrosti kapljevine vzdolž širjenja ultrazvoka skozi cev.

and the mean fluid velocity $\bar{v}$ along this path. Here, we have assumed that with ultrasonic propagation in the pipe the principles of geometrical optics apply. This assumption is valid as long as the relevant dimensions of the measuring-pipe section are bigger than the wavelength of the ultrasound, which is in our case approximately 0.5 mm. The model of the measuring cell of our heat meter is shown in Fig. 3. Along the flow path the ultrasonic signal propagates at different angles relative to the flow direction. The main problem in determining the sensitivity of the meter is therefore to calculate the mean fluid velocity along the sound path.



Sl. 3. *Model merilne celice toplotnega merilnika*
Fig. 3. *Measuring-cell model of the heat meter*

Interakcija polja UZ s turbulentnim hitrostnim poljem v merilni cevi je v splošnem zelo zapleten pojav. V modelu, prikazanem na sliki 4, izračunamo preletna časa t_+ in t_- z enačbama:

The interaction of the ultrasonic field within the pipe with the turbulent velocity field is generally a very complicated phenomenon. In the simplified model shown in Fig. 4, the transit times t_+ and t_- can be calculated with equations:

$$t_+ = \int_0^s \frac{ds}{c+v(s)} \quad (3)$$

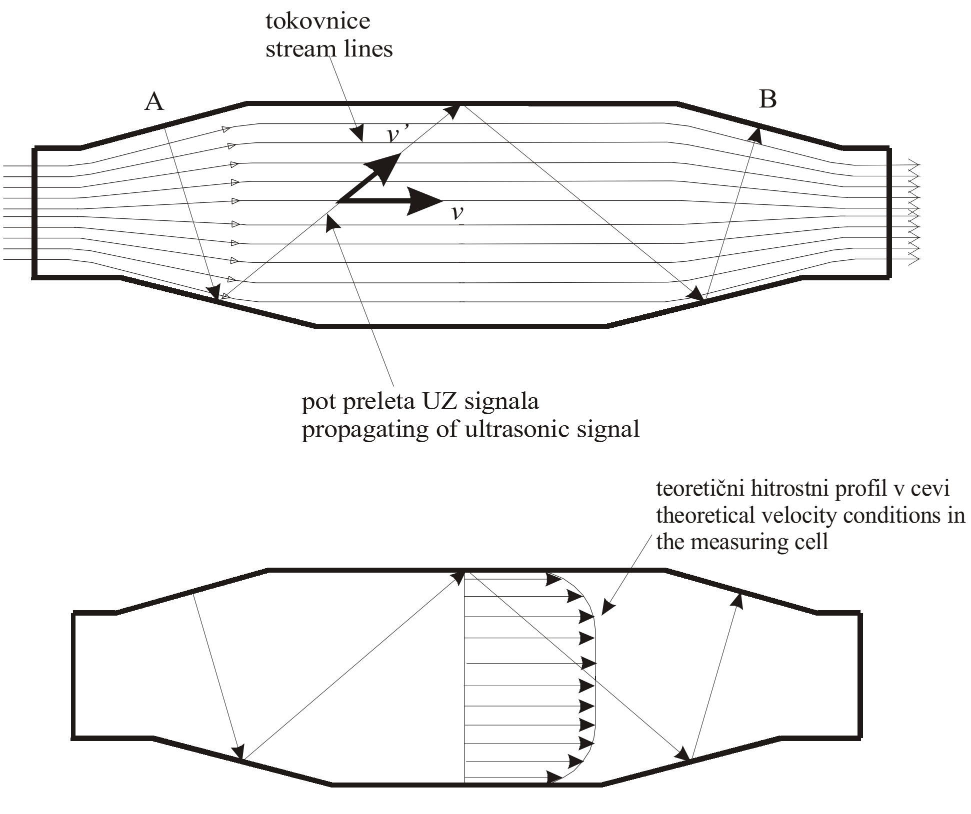
$$t_- = \int_0^s \frac{ds}{c-v(s)} \quad (4).$$

Pri tem je treba poznati porazdelitev hitrosti vzdolž poti *v(s)*. Model je dvorazsežen v prvem približku, saj trirazsežna analiza, ob poprej omenjeni poenostavitvi širjenja zvočnega curka, ne bi bila primerna.

Iz povedanega izhaja, da je izračun dejanske porazdelitve hitrosti dokaj zapleten problem in ga analitično ni mogoče rešiti. Zato smo se tega problema lotili s programskim paketom ANSYS, ki problem reši z uporabo metode končnih elementov.

where the integration is taken along the sound path *s*. This model is a two-dimensional one and requires a knowledge of the fluid velocity distribution *v(s)* along the path *s*. In this first approximation a 3D analysis was not taken into consideration in view of the previous simplifications related to the ultrasonic propagation within the pipe.

The calculation of the exact velocity distribution within the pipe is a complex problem that cannot be dealt with analytically. We have therefore solved the problem with the use of the finite-element method and the program package ANSYS.



Sl. 4. *Hitrostne razmere v merilni celici*
Fig. 4. *Velocity conditions within the measuring cell*

2 IZDELAVA MODELA IN IZRAČUN POVPREČNE HITROSTI

Programski paket ANSYS ([1] do [3]) je eno od orodij za simuliranje in analizo različnih fizikalnih pojavov in tehničnih sistemov. Reševanje teh poteka preko uporabe metode končnih elementov. V splošnem se delo s tem programom deli v tri dele, in sicer :
- priprava
- rešitev
- obravnava.

V prvem delu pripravimo model. V drugem koraku sledi definiranje robnih pogojev in izračun, v tretjem delu pa lahko na različne načine opazujemo in analiziramo dobljene rezultate.

V prvem koraku je treba definirati obliko modela merilne celice in ga omrežiti z dvorazsežnimi elementi s prostostnimi stopnjami hitrosti, tlaka in temperature.

Naslednji korak je določitev robnih pogojev. Ti so prikazani na sliki 5. Vsi izračuni se nanašajo na imenski pretok. Za to smo na vstopu v merilno celico definirali vstopno hitrost pri imenskem pretoku v smeri X (ν_{xo}), medtem ko je hitrost v smeri Y (ν_{yo}) na vstopu enaka nič. Ob stenah celice je hitrost v obeh smereh (ν_x, ν_y) enaka nič. Na izstopu pa smo definirali tlak p = 0 bar.

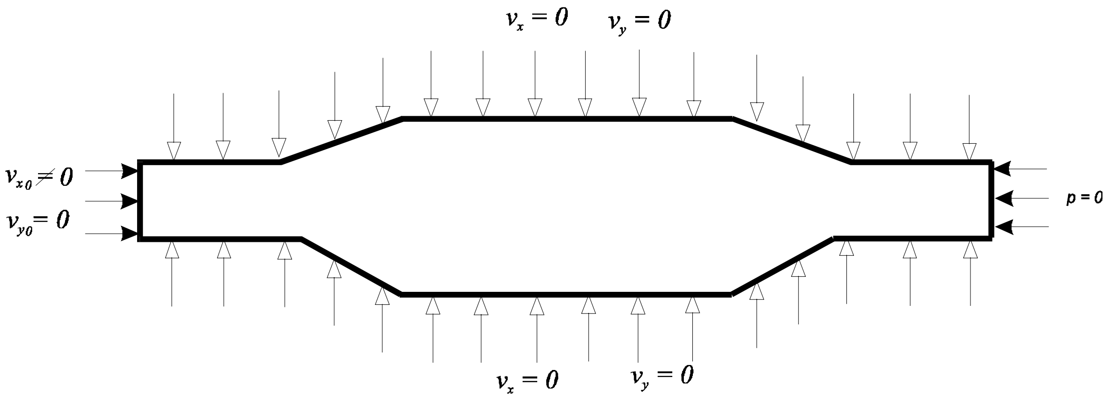
2 BUILDING THE FEM MODEL AND THE DETERMINATION OF THE MEAN FLUID VELOCITY

The program package ANSYS ([1] to [3]) is a tool for the analysis and simulation of different physical phenomena and technical systems. The problem solving is carried out with the help of the finite-element method. Generally, a typical procedure can be divided into three steps:
– preprocessing,
– solution,
– postprocessing.

In the first step a problem model is prepared. In the second step, boundary conditions are applied and the numerical solution is carried out. In the third step, the obtained results can be observed in many different ways and further analyzed.

In the first step we defined a model of the measuring cell with a mesh of 2D finite elements with velocity, pressure and temperature degrees of freedom.

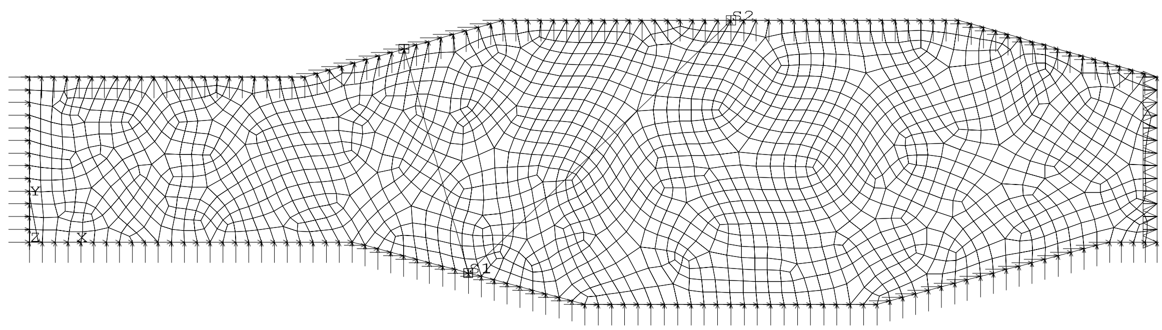
In the second step we applied the appropriate boundary conditions, as shown in Fig. 5. All the calculations were performed at the nominal flow rate. We therefore specified, at the measuring-cell inlet, the corresponding fluid velocity in the X direction (ν_{xo}), whereas the velocity component in the Y direction (ν_{yo}) at the inlet was set to zero. The velocity components ν_x and ν_y on the walls of the cell were set to zero. At the outlet the pressure was set to a value of p = 0 bar.



Sl. 5. *Definirani robni pogoji*
Fig. 5. *The applied boundary conditions*

Na sliki 6 je prikazan končni model MKE. Vstopni del celice smo podaljšali, da bi s tem zagotovili veljavnost robnih pogojev ($\nu_{xo} \neq 0$ in $\nu_{yo} = 0$).

In Fig. 6. the complete FE model can be seen. The inlet section of the cell was extended in order to ensure the validity of the boundary conditions ($\nu_{xo} \neq 0$ and $\nu_{yo} = 0$).



Sl. 6. *Omre□eni model v ANSYS-u*
Fig. 6. *The meshed model in ANSYS*

Ko imamo izračunano hitrostno polje v merilni celici, je treba iz dobljenih rezultatov izračunati povprečno hitrost v smeri poti UZ. Najprej je treba določiti povprečno hitrost v smeri *x* in *y,* vzdolž poti UZ. Skupno povprečno hitrost potem lahko določimo prek geometrijske oblike celice. Oblikovali smo dve poti (S_1 in S_2), ki sta označeni na sliki 7. Na teh poteh smo z enim od orodij v ANSYS-u po enačbah od (5) do (8), izračunali povprečne hitrosti:

After the fluid velocity field has been calculated we have to determine the mean fluid velocity along the path of the ultrasonic signal. To do so, we first determine the mean velocity components in the X and Y directions along the path. The mean fluid velocity can then be obtained using the geometrical properties of the measuring cell. We created the two paths, S_1 and S_2, given in Fig. 7. Along these two paths we then calculated, with one of the ANSYS tools, according to Equations (5) to (8) the corresponding mean velocities:

$$v_{x1} = \left[\int v_{XS1} dS_1 \right] / l_1 \qquad (5),$$

$$v_{y1} = \left[\int v_{YS1} dS_1 \right] / l_1 \qquad (6),$$

$$v_{x2} = \left[\int v_{XS2} dS_2 \right] / l_2 \qquad (7),$$

$$v_{y2} = \left[\int v_{YS2} dS_2 \right] / l_2 \qquad (8),$$

v_{x1}... povprečna hitrost v smeri *x* na poti S_1
v_{y1}... povprečna hitrost v smeri *y* na poti S_1
v_{x2}... povprečna hitrost v smeri *x* na poti S_2

v_{x1}.... mean fluid velocity component *X* along the path S_1
v_{y1}... mean fluid velocity component *Y* along the path S_1
v_{x2}.... mean fluid velocity component *X* along the path S_2

v_{y2}.... povprečna hitrost v smeri y na poti S_2
v_{XS1}....hitrosti v smeri x na poti S_1
v_{YS1}...hitrosti v smeri y na poti S_1
v_{XS2}...hitrosti v smeri x na poti S_2
v_{YS2}...hitrosti v smeri y na poti S_2
l_1... dolžina poti S_1
l_2... dolžina poti S_2.

Nadalje lahko izračunamo povprečno hitrost na poti UZ. Iz geometrijske oblike merilne celice (sl.7) dobimo enačbi:

v_{y2}... mean fluid velocity component Y along the path S_2
v_{XS1}...velocity component X along S_1
v_{YS1}... velocity component Y along S_1
v_{XS2}... velocity component X along S_2
v_{YS2}... velocity component Y along S_2
l_1... path S_1 length
l_2... path S_2 length

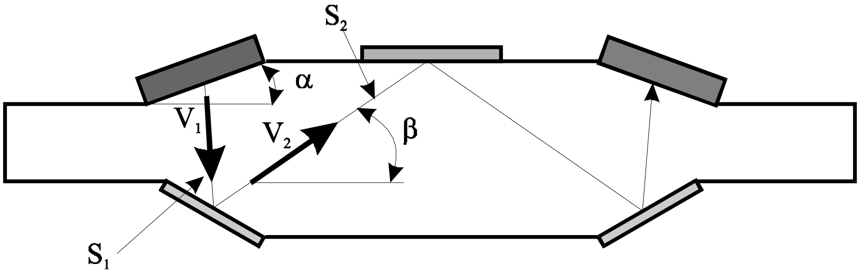
The final mean fluid velocity along the sound path can then be determined. With the use of the geometrical properties of the measuring cell (Fig. 7) we obtain equations:

$$v_1 = v_{x1} \cdot \cos(90-\alpha) + v_{y1} \cdot \cos\alpha \quad (9),$$

$$v_2 = v_{x2} \cdot \cos(90-\beta) + v_{y2} \cdot \cos\beta \quad (10),$$

v_1... povprečna hitrost vode na poti S_1
v_2... povprečna hitrost vode na poti S_2

v_1... mean fluid velocities along S_1
v_2... mean fluid velocities along S_2.



Sl. 7. *Geometrijska oblika merilne celice in prikaz poti S_1 in S_2*
Fig. 7. *Measuring-cell geometry and the paths S_1 and S_2*

Po enačbi (11), izračunamo povprečno hitrost vode ($\bar{v}$) na celotni ultrazvočni poti:

With Equation (11) we calculate the mean fluid velocity along the whole sound path:

$$\bar{v} = (l_1 \cdot v_1 + l_2 \cdot v_2)/(l_1 + l_2) \quad (11).$$

Razlika časov Δt se izračuna po enačbi (2), kjer je L celotna dolžina zvočne poti, c pa hitrost zvoka v vodi (c = 1485 m/s pri 20 °C [5]). Dolžino celotne poti izračunamo po enačbi:

The difference Δt in the transit times for the signal propagating in the downward and upward directions can be calculated with Equation (2), where L is the overall sound-path length and c the sound velocity in water (c=1485 m/s, temperature 20°C [5]). The total path length can be determined with equation:

$$L = 2 \cdot (l_1 + l_2) \quad (12).$$

3 TEORETIČNO UGOTAVLJANJE OBČUTLJIVOSTI IN POTRDITEV S PREIZKUSI PRI RAZLIČNIH IZVEDBAH MERILNIH CELIC

Za dano izvedbo elektronskega vezja toplotnega merilnika je zadovoljiva razlika časov Δt = 240 ns. Ta čas zagotovi ustrezno občutljivost merilnika. Pri razvoju merilnika s krajšimi priključnimi merami moramo torej zagotoviti vsaj to razliko v časih preleta, lahko pa tudi večjo.

3 THEORETICAL PREDICTION AND EXPERIMENTAL VERIFICATION OF THE PERFORMANCE OF SEVERAL MEASURING-CELL DESIGNS

Given the characteristics of the electronic circuit of the heat meter, a sufficient difference in the transit times to achieve the required resolution of the meter is approximately Δt = 240 ns. Therefore, when constructing an ultrasonic flow unit with shorter overall dimensions, care must be taken to achieve at least an equal or possibly a longer time difference.

Z osnovnim pretočnim delom, ki je v bistvu samo manjša različica že razvitega pretočnega dela, smo desegli Δt = 227 ns. Kasnejša analiza z metodo končnih elementov, pa je dala čas Δt = 222 ns, kar se dobro ujema s preizkusom. Ti rezultati nas pripeljejo do tega, da je treba narediti več simulacij in se ob ustreznih rezultatih odločiti za takšno merilno celico, ki bo zagotavljala ustrezno merilno občutljivost toplotnega merilnika.

Kakor že vemo, je občutljivost merilnika odvisna samo od povprečne hitrosti kapljevine v smeri poti UZ in od dolžine poti UZ. Vendar smo tako pri dolžini poti kakor tudi pri večanju hitrosti omejeni. Pri daljšanju poti smo omejeni s priključnimi merami pretočnega dela. Za povečanje hitrosti moramo zmanjšati pretočni prerez. Tu pa imamo zahteve za padec tlaka. Ta je namreč omejen, poleg tega pa ne smemo prekinjati pot signalu UZ, saj bi ga s tem oslabili.

Narediti je bilo torej treba več modelov merilne celice, ki so predstavljeni na slikah od 8 do 12. Najprej je bilo treba narediti analizo z MKE, potem pa rezultat preveriti na pretočni merilni progi pri imenskem pretoku. Te rezultate smo potem primerjali z osnovnim pretočnim delom s priključno mero 110 mm. Naredili smo naslednje primere:

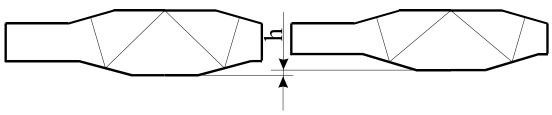
1. Zvišali dno celice, s čimer smo povečali hitrost kapljevine, a obenem tudi nekoliko skrajšali pot zvoka (sl.8).
2. Podaljšali celice do največje mogoče dolžine, pri čemer smo podaljšali tudi pot zvoka (sl 9).
3. Kombinirali 1. in 2. različico (sl.10).
4. Zvišali celice z oviro, kar povzroči povečanje hitrosti kapljevine, ne vpliva pa na dolžino poti zvoka (sl.11)
5. Kombinirali 2. in 4. različico (sl.12).

With the basic flow-unit model, which was a simple miniaturization of one of our previously designed flow units, the achieved transit time difference was Δt = 227 ns. A later finite-element analysis gave a value of Δt = 222 ns, which agreed well with the experiment. We therefore decided to make several additional FE calculations and choose from them the design with the required sensitivity.

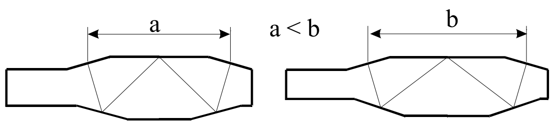
As explained, the sensitivity of the heat meter depends on the mean fluid velocity along the ultrasonic path and on the length of the path. However, with both parameters certain limitations exist. The path length is limited by the overall dimensions of the flow unit. The fluid velocity, on the other hand, can be increased by diminishing the inner cross-section; however, this may lead to an increase in the pressure drop or an obstruction of the propagated ultrasonic waves.

Several variations of the basic measuring cell, presented in Figs. 8 to 12 have been considered. The expected transit-time difference was first predicted with the FE method and then determined experimentally on a test flow rig at the nominal flow rate. These results were then compared to the basic version of the flow unit with the overall dimensions of 110 mm. The following models were made:

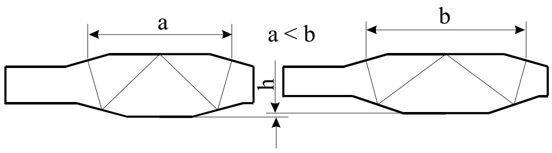
1. Cell with a raised bottom relative to the basic model - larger fluid speed but shorter sound-path length (Fig. 8)
2. Cell with a maximum overall length - maximum achievable sound-path length (Fig. 9)
3. Combination of 1. and 2. (Fig. 10)
4. Cell with a raised bottom with a protuberance - larger fluid speed but unaffected sound-path length (Fig.11)
5. Combination of the 2. and 4. point (Fig.12).



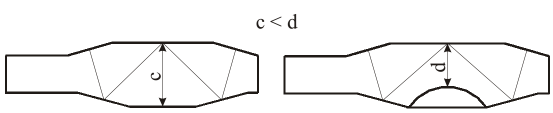
Sl. 8. *Zvišanje dna celice za povečanje hitrosti vode*
Fig. 8. *Cell with a raised bottom to increase the fluid speed*



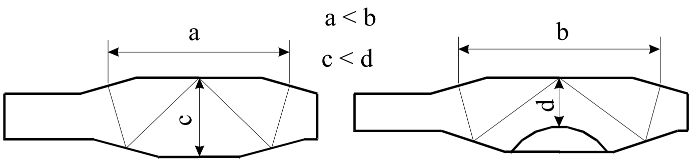
Sl. 9. *Podaljšanje celice za podaljšanje zvoka poti*
Fig. 9. *Cell and its sound path lengthened*



Sl. 10. *Zvišanje in hkrati podaljšanje celice*
Fig. 10. *Cell with a raised bottom and increased length*



Sl. 11. *Zvišanje celice z oviro, ki ne skrajša poti zvoka*
Fig. 11. *Cell with a part of the bottom raised with a protuberance leaving the sound path length unaffected*



Sl. 12. *Zvišanje celice z oviro, ki ne skrajša poti zvoka, in podaljšanje celice*
Fig. 12. *Cell lengthened and with a protuberance which doesn't shorten the sound path*

Rezultati, ki smo jih dobili z MKE in nekatere potem tudi s preizkusi potrdili, so prikazani v preglednici 1. Kakor lahko vidimo, se ne razlikujejo za več ko nekaj odstotkov. Opazimo tudi, da merilna celica z največjo merilno občutljivostjo (primer 5: $\overline{v} \cdot L = 0{,}291$) zagotavlja tudi največji Δt, kar potrjuje tudi teorija v poglavju 2.

The results obtained with the FE model and those obtained experimentally are shown in Table 1. As seen from the results the theoretically predicted time difference agrees, to within a few percent, with the experimentally obtained values. It can be seen that the measuring-cell design with the maximum sensitivity (case 5, $\overline{v} \cdot L$=0.267 m^2/s) also exhibits the maximum transit-time difference Δt, which confirms the theory of Section 2.

Preglednica 1. *Rezultati simulacij in izvedenih meritev*
Table 1. *Simulated and measured results*

Primer **Case**	$\overline{v} \cdot L$ m^2/s MKE / FEM	Δt ns MKE / FEM	Δt ns meritev measured	Δt % napaka error
Osnovna kratka celica Basic measuring cell	0,245	222	227	2,2
Primer 1 - zvišanje dna celice Case 1- raised bottom	0,239	217	/	/
Primer 2 - podaljšanje celice Case 2 - lengthening	0,249	226	220	2,7
Primer 3 - podaljšanje in zvišanje celice Case 3 - raised bottom and lengthening	0,259	235	/	/
Primer 4 - zvišanje celice z oviro Case 4 - protuberance	0,262	238	259	8,1
Primer 5 - podaljšanje in zvišanje celice z oviro Case 5 - protuberance and lengthening	0,267	242	264	8,3

4 SKLEP

Z uporabo programskega paketa ANSYS smo analizirali različne modele ultrazvočnih merilnih celic. Tako smo s teoretičnih predvidevanj določili model, ki glede občutljivosti najbolj ustreza. Iz preglednice 1 lahko vidimo, da je razlika med rezultati, pridobljenimi s simulacijami, in rezultati, pridobljenimi z meritvami, dokaj majhna. Se pa poveča v primerih, ko imamo v celici vgrajeno oviro, za povečanje pretoka. Ta ovira očitno zelo spremeni razmere v merilni celici. Določena odstopanja pa so tudi posledica dvorazsežne analize in poenostavljenega modela širjenja valov ultrazvoka.

Izbrano merilno celico bo treba preveriti še s hidrodinamičnega vidika. Lahko se namreč tlak v celici preveč zniža, ta pa je s standardom omejen in ga

4 CONCLUSION

With the help of the ANSYS analysis package we analyzed several design models of an ultrasonic measuring cell. From the theoretical predictions we managed to select the design that yields the required cell sensitivity. The experimentally obtained values of the transit-time difference agree, to within a few percent, with the theoretically predicted values. The discrepancies become larger in cases where a protuberance to increase the fluid velocity is mounted in the measuring cell. This protuberance obviously changes the conditions within the cell considerably. Some discrepancies can also be attributed to the 2D fluid-velocity solution as well as to the simplified model of the propagation of the ultrasonic waves.

The selected measuring cell will have to be further verified with respect to its hydrodynamic properties. At the nominal flow rate an excessive ne smemo preseči. Poleg tega je pomembna tudi možnost izdelave izbrane oblike merilne celice.

Vidimo, da kljub različnim računalniškim orodjem, praktično ne moremo nekega izdelka razviti brez prototipa. Lahko le bistveno hitreje določimo prototip, potem pa ga je kljub vsemu treba izdelati in preveriti njegovo delovanje v dejanskih razmerah.

pressure drop in the cell can result; however, this drop is limited by standards and must not be exceeded. Also, manufacturing issues have to be considered.

In spite of advanced computer-design tools a product cannot be developed without a prototype. However, with the help of these tools, a prototype can be designed in a much shorter time and then be verified experimentally.

5 LITERATURA
5 REFERENCES

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Strokovna literatura

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Nove knjige

Janko Hodolič - Miroslav Badida - Milan Majernik - Dušan Šebo:
Mašinstvo u inženjerstvu zaštite životne sredine
Zal.: FTN Izdavaštvo, Novi Sad, 2003
Format 13,7 × 23,5 cm, 273 strani, 112 slik, 22 preglednic.
Cena je 4 €.

Normalno naravno ravnovesje je v zadnjih nekaj desetletjih postalo močno moteno zaradi različnih dejavnosti človeka in njegovega vpliva na okolje. V nasprotju od živali in rastlin človek iz okolja ne črpa samo toliko, kolikor je potrebno za njegov obstoj, temveč pred sebe postavlja visoke zahteve, ki jih imenuje življenjski standard. Pri tem imamo v mislih vse tehnične dosežke (avtomobili, računalniki, elektronika ipd), kakor tudi različne storitve, ki povečujejo udobje njegovega bivanja (stanovanja, pohištvo, bela tehnika, avdiovizualne naprave, ipd). Kljub temu, da je regenerativna zmožnost narave edinstvena in neponovljiva, ni prilagojena tako hitrim spremembam in številnim škodljivim vplivom.

Na podlagi izkušenj desetletnega dela na področju ravnanja z okoljem avtorji izhajajo iz teze, da se človeštvo pri svojem izjemno hitrem tehničnem napredku razvija tudi intelektualno in je doseglo točko zavedanja pomena varovanja okolja za nadaljnji obstoj civilizacije. Pookoljenje v strojništvu prinaša s seboj delovanje na treh osnovnih področjih:

- na področju strojniških izdelkov v inženirstvu ravnanja z okoljem,
- na področju proizvodnih sistemov v strojništvu, v inženirstvu ravnanja z okoljem,
- pri načrtovanju in izdelavi strojev in naprav za zmanjševanje vpliva industrijske proizvodnje, gospodarskih dejavnosti in naselij na okolje (ekotehnika).

Da bi bralci laže sledili postavljeni tezi ter omenjenim nalogam, so avtorji vsebino knjige razdelili na osem poglavij:

1. Sistemski spopad med okoljem in potrebami človeške civilizacije.
2. Kritična področja industrijske proizvodnje z vidika ravnanja z okoljem.
3. Strojništvo in vpliv na okolje.
4. Metoda analize vpliva dejavnosti na okolje.
5. Metodika ekološkega vrednotenja in označevanja izdelka.
6. Sistemi upravljanja pri varovanju okolja (ekomenedžment).
7. Večkriterijska ocena obremenitve okolja.
8. Metoda ocenjevanja dobe trajanja (LCA) tehničnega sistema.

Težišče knjige je na tretjem poglavju, kar je logično, saj je knjiga namenjena študentom strojništva v Novem Sadu ter Tehniške univerze v Košicah na Slovaškem. V ta namen je knjiga izdana tudi v slovaškem jeziku.

Vsebina knjige je napisana pregledno, v razumljivem strokovnem jeziku, z izvirnimi in zanimivimi slikami, strokovno in didaktično korektno, zato jo priporočamo tudi našim študentom strojništva, prav tako strokovnjakom na področju inženirstva ravnanja z okoljem kakor tudi načrtovalcem sistemov ravnanja z okoljem. Kot primerno gradivo lahko rabi tudi načrtovalcem različnih programov izobraževanja in usposabljanja kadrov na področju upravljanja z okoljem.

M. Sokovič

Navodila avtorjem

Instructions for Authors

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

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

Vsebina članka

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

Oblika članka

Besedilo naj bo pisano na listih formata A4, z dvojnim presledkom med vrstami in s 3 cm širokim robom, da je dovolj prostora za popravke lektorjev. Najbolje je, da pripravite besedilo v urejevalnilku Microsoft Word. Hkrati dostavite odtis članka na papirju, vključno z vsemi slikami in preglednicami ter identično kopijo v elektronski obliki.

Prosimo, da ne uporabljate urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata. V urejevalniku LaTeX oblikujte grafe, preglednice in enačbe in jih stiskajte na kakovostnem laserskem tiskalniku, da jih bomo lahko presneli.

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

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).

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

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

The format of the paper

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

The layout of the text

Texts should be written in A4 format, with double spacing and margins of 3 cm to provide editors with space to write in their corrections. Microsoft Word for Windows is the preferred format for submission. One hard copy, including all figures, tables and illustrations and an identical electronic version of the manuscript must be submitted simultaneously.

Please do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering. Graphs, tables and equations in LaTeX may be supplied in good quality hard-copy format, so that they can be copied for inclusion in the Journal.

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.

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).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Za pripravo diagramov in risb priporočamo CDR format (CorelDraw), saj so slike v njem vektorske in jih lahko pri končni obdelavi preprosto povečujemo ali pomanjšujemo.

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.

Za vse slike po fotografskih posnetkih je treba priložiti izvirne fotografije ali kakovostno narejen posnetek. V izjemnih primerih so lahko slike tudi barvne.

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 controler 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, številke telefona in faksa ter naslove elektronske pošte.

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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.

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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. Figures may be saved in any common format, e.g. BMP, GIF, JPG. However, the use of CDR format (CorelDraw) is recommended for graphs and line drawings, since vector images can be easily reduced or enlarged during final processing of the paper.

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.

Good quality black-and-white photographs or scanned images should be supplied for illustrations. In certain circumstances, colour figures may be considered.

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 controler 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 following information about the authors should be enclosed with the paper: names, complete postal addresses, telephone and fax numbers and E-mail addresses.

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