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Vsebina
Contents

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Eksperimentalno ovrednotenje analitičnega preračuna deformacije krogle zaradi tipalne sile pri kalibraciji

The Experimental Validation of an Analytical Calculation of Sphere's Deformation that Results from Probing Force During Calibration

Bojan Ačko

Kalibracija premera majhnih kroglic je z vidika merilne negotovosti zelo problematična, kar dokazujejo rezultati številnih mednarodnih laboratorijskih primerjav. Posebni problem pomeni določitev deformacije zaradi merilne sile. Vzrok je predvsem v netočnem poznavanju mehanskih lastnosti materialov tipal merilne naprave in kroglice, ki jo kalibriramo. V prispevku je predstavljen postopek za eksperimentalno določitev deformacije krogle med kalibracijo in rezultati analize na primeru tipalne kroglice iz rubina. Prikazana je tudi primerjava z rezultati analitičnega preračuna, v katerem smo uporabili vrednosti mehanskih lastnosti materialov, ki smo jih dobili od različnih proizvajalcev merilne opreme.

(Ključne besede: sile merilne, deformacije, kalibriranje premerov, negotovosti merilne)

The calibration of a sphere of a small diameter is very problematic in terms of the uncertainty of the measurement. This fact has often been demonstrated during numerous international interlaboratory comparisons. A particular problem occurs when calculating the deformation is caused by the measurement force. The reason for this is that we do not know enough about the mechanical properties of the probes of the measurement device or the sphere that is being calibrated. This paper introduces a procedure for the experimental determination of a sphere's deformation during a calibration and an analysis of the results of an example of a ruby probe sphere. A comparison of these results with analytical calculation results is also presented. The analytical calculations were based on the material's mechanical properties which were provided by different measurement-equipment manufacturers.

(Keywords: measurement force, deformations, diameter calibrations, uncertainty of measurements)

0 UVOD

Kalibracija premera krogle je pomembna predvsem z vidika točne določitve dimenzij kroglic merilnih tipal, ki jih uporabljamo za točne meritve v dimenzionalni merilni tehniki. Posebni merilni problemi terjajo določitev premera tipalne kroglice z negotovostmi pod 0,5 μm. Če hočemo doseči takšno točnost merjenja premera kroglice, moramo določiti deformacijo zaradi merilne sile z negotovostjo, manjšo od 0,2 μm. Ta naloga ni lahka, ker se pri kalibraciji majhnih premerov na standardnih merilnih napravah pojavljajo zelo velike deformacije (pri kalibraciji rubinaste kroglice premera 0,3 mm s silo 1,5 N je deformacija 1 μm).

Z uporabo analitičnih obrazcev ali z metodo končnih elementov lahko sicer točno izračunamo deformacijo, vendar moramo zelo dobro poznati module elastičnosti in Poissonove količnike

0 INTRODUCTION

Sphere's diameter calibration is important because we need to determine that exact dimensions of the probe spheres used for precise measurements in dimensional measurement techniques. Special measurement problems require very exact diameter determination with uncertainties under 0,5 μm. If such diameter measurement accuracy is demanded, the deformation caused by the probing force needs to be determined with an accuracy of better than 0,2 μm. This task is not easy, because big deformations occur during the calibration of small diameters on conventional measurement machines (e.g. 1 μm when calibrating a ruby sphere with a diameter 0,3 mm using a measurement force of 1,5 N).

It is possible to calculate the deformation precisely using analytical formulae or the finite-element method, but only if the elasticity moduli and Poisson's ratia of the sphere and probe materials are materialov tipal merilne naprave in kroglice, ki ju kalibriramo. To pa je v praksi velik problem, ker tudi proizvajalci merilne opreme v mnogih primerih ne navajajo točnih vrednosti. Da bi lahko ovrednotili negotovost analitičnega izračuna, smo se odločili za izvedbo eksperimentalne meritve kroglic različnih premerov s stopnjevanjem merilne sile.

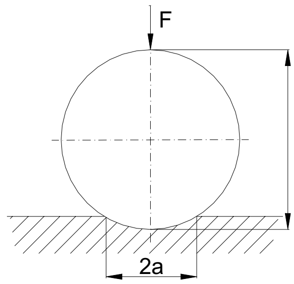
known exactly. This can, however, be a great problem because measurement-equipment producers do not usually give the exact values. In order to be able to evaluate the uncertainty of the analytical calculation, we decided to perform an experiment with spheres of different diameters, which were measured with different measurement forces.

1 ANALITIČNI IZRAČUN DEFORMACIJE

Zaradi merilne sile F, ki deluje na kroglico, se pojavi deformacija, ki je enaka vsoti sploščitve kroglice in vgrezu kroglice v merilno površino tipala ([1] in [4]). Na sliki 1 je predstavljen primer deformacije pri tipanju z eno merilno površino (enotočkovno tipanje). Razdalja med točko, v kateri deluje merilna sila, in merilno površino ni enaka premeru kroglice, ampak je zmanjšana za vrednost x, ki pomeni deformacijo. V primeru dvotočkovnega tipanja je ta deformacija dvakrat večja.

1 ANALYTICAL DEFORMATION CALCULATION

The measurement force F on the sphere causes a deformation, which is the sum of the sphere's deformation and the indentation into the probe surface ([1] and [4]). Figure 1 shows an example of probing with one measuring surface (one-point probing). The distance between the probing surface and the point where measurement force is acting is not equal to the sphere's diameter. It is reduced by an amount x, which represents the deformation. In the case of two-point probing this deformation is twice as big.



Sl. 1. *Deformacija krogle in merilne površine tipala zaradi merilne sile*
Fig. 1. *Deformations of a sphere and a probe surface, caused by a measurement force*

Deformacijo x za enotočkovno tipanje [1] izračunamo po enačbi:

The deformation x for one-point probing [1] is calculated using equation:

$$x = 1,04\sqrt[3]{\frac{F^2 C_E^{\,2}}{d}} \quad (1).$$

Količnik C_E v enačbi (1) opisuje mehanske lastnosti materialov:

The factor C_E in equation (1) describes the mechanical properties of the materials:

$$C_E = \frac{1-\nu_1^{\,2}}{E_1} + \frac{1-\nu_2^{\,2}}{E_2} \quad (2).$$

V preglednici 1 je predstavljenih nekaj rezultatov izračunov za primer, ko je merjena kroglica iz rubina, tipali merilne naprave pa iz karbidne trdine. Iz preglednice je lepo razvidno, da so deformacije kritične pri merjenju majhnih premerov.

Table 1 presents some calculation results for the case where a ruby sphere is measured using hard metal probes. These results demonstrate clearly that deformations are critical for small sphere's diameters.

1.1 Negotovost izračuna deformacije

Izračunane vrednosti deformacije v preglednici 1 so točne ob predpostavki, da so točni podatki za modula elastičnosti E_1 in E_2 in Poissonova količnika ν_1 in ν_2 v enačbi (2) in uporabljeno silo F (en. 1). V praksi moramo predpostaviti, da teh podatkov ne poznamo absolutno točno. Še najbolj zanesljivo lahko

1.1 Uncertainty of the deformation calculation

The calculated values in Table 1 are only exact if the data for the elasticity moduli (E_1 and E_2), and Poisson's ratia (ν_1 and ν_2 in equation 2) and the force (F in Equation 1) are known with absolute accuracy. In reality this is never the case and we shall assume that these data are not known exactly. The most accurate

Preglednica 1. *Deformacije pri merjenju kroglice iz rubina s tipali iz karbidne trdine za različne premere merjene kroglice in različne tipalne sile*

Table 1. *Deformations during ruby sphere measurement by using hard metal probes for different ball diameters and different measurement forces*

x - µm										
d mm	*F* - N									
	0,1	0,2	0,5	0,7	0,8	1	1,5	2	5	10
0,1	0,2372	0,3766	0,6937	0,8681	0,9490	1,1012	1,4429	1,7480	3,2198	5,1112
0,2	0,1883	0,2989	0,5506	0,6890	0,7532	0,8740	1,1453	1,3874	2,5556	4,0567
0,3	0,1645	0,2611	0,4810	0,6019	0,6580	0,7635	1,0005	1,2120	2,2325	3,5439
0,4	0,1495	0,2372	0,4370	0,5469	0,5978	0,6937	0,9090	1,1012	2,0284	3,2198
0,5	0,1387	0,2202	0,4057	0,5077	0,5550	0,6440	0,8438	1,0222	1,8830	2,9890
0,7	0,1240	0,1969	0,3626	0,4538	0,4961	0,5756	0,7543	0,9138	1,6832	2,6719
1	0,1101	0,1748	0,3220	0,4030	0,4405	0,5111	0,6698	0,8113	1,4945	2,3724
1,5	0,0962	0,1527	0,2813	0,3520	0,3848	0,4465	0,5851	0,7088	1,3056	2,0725
2	0,0874	0,1387	0,2556	0,3198	0,3496	0,4057	0,5316	0,6440	1,1862	1,8830
5	0,0644	0,1022	0,1883	0,2356	0,2576	0,2989	0,3917	0,4745	0,8740	1,3874

določimo merilno silo, ki jo v večini primerov ustvarimo z utežjo. To utež lahko zelo točno izmerimo, preostane le določena sila trenja vrvice, prek katere je utež vezana na tipalo.

Če predpostavimo, da lahko silo določimo z relativnim pogreškom 5%, module elastičnosti in Poissonove količnike pa z relativnim pogreškom 10%, se pri izračunu deformacije za silo 1,5 N in premer kroglice 0,3 mm pojavi razpon rezultatov 0,18 µm. Ker ne poznamo statistične porazdelitve rezultatov, predpostavimo po celotnem intervalu enako verjetnost, kar pomeni, da je porazdelitev pravokotna. Standardno negotovost ([2], [3] in [5]) izračunamo po enačbi:

data is the measurement force, which is usually established with an appropriate weight. This weight can be measured very precisely, the only problem is the friction of the rope that binds the weight to the probe.

If it is assumed that the force can be determined with a relative error of 5% and the material properties (elasticity moduli and Poisson's ratia) with a relative error of 10%, the result span of the deformation calculation for a probing force of 1,5 N and a sphere's diameter of 0,3 mm would be 0,18 µm. Since the statistical distribution is not known, an equal probability is assumed for the whole interval (rectangular distribution). The standard uncertainty ([2], [3] and [5]) is calculated using equation:

$$u = 0{,}09\ \mu m / \sqrt{3} = 0{,}05\ \mu m \qquad (3).$$

Ker so vrednosti relativnih pogreškov zgolj predpostavke, sta izračunana srednja vrednost deformacije in standardna negotovost vprašljivi. Zato smo skušali s preskusom dokazati pravilnost omenjenih izračunov.

Since the values of the relative errors are only assumptions, the validity of the calculated deformation and the standard uncertainty are doubtful. Therefore, an experiment was performed in order to prove the correctness of the above calculations.

2 PRESKUSNA DOLOČITEV DEFORMACIJE

2 EXPERIMENTAL DETERMINATION OF DEFORMATION

2.1 Opis preskusa

Preskus smo izvedli na univerzalni dolžinski merilni napravi Carl Zeiss ULM 01-600C. Uporabili smo 2 ravni tipali iz karbidne trdine (eno tipalo je pomično oz. merilno, drugo pa fiksno in rabi kot naslon), za dolžinski merilni sistem smo uporabili laserski interferometer HP 5528 A [5] . Za vzpostavitev osnovne merilne sile smo uporabili originalno utež merilne naprave z maso 150 g, ta ustvari merilno silo prek vrvice, ki je pritrjena na merilno tipalo. Merilno silo smo stopnjevali tako, da smo osnovni uteži

2.1 Description of the experiment

The experiment was performed on a Carl Zeiss ULM 01-600C universal measurement device. Two hard metal probes (one moving res. measuring probe and one fixed probe) were used with a linear measurement system that was based on a HP 5528 A laser interferometer [5]. The basic measurement force came from a weight of 150 g that was bound to the measuring probe with a rope. The force was then increased by adding 10 g weights, which were made especially for this experiment, to the 150 g weight.

dodajali uteži z maso 10 g, ki smo jih izdelali posebej za ta namen. Takšnih uteži je bilo 10, pred uporabo pa smo jih stehtali s standardno negotovostjo 10 mg. Merili smo tipalne kroglice iz rubina premerov 0,8 mm, 1 mm, 1,35 mm, 2 mm in 5 mm. Premere posameznih kroglic, ki smo jih izmerili z različnimi merilnimi silami, smo med seboj primerjali in na podlagi te primerjave izračunali deformacije. Te deformacije smo primerjali z deformacijami, ki smo jih izračunali po analitičnih obrazcih [1].

2.2 Izvedba preskusa

Vsako kroglico smo najprej izmerili z osnovno merilno silo 1,5 N, potem pa smo silo stopnjevali v desetih stopnjah po 0,1 N (dodajali smo uteži mase 10 g na osnovno utež). Meritev smo pri vsaki merilni sili ponovili 5-krat, celotno serijo meritev smo potem še enkrat ponovili, tako da smo za vsak premer in vsako merilno silo dobili 10 merilnih vrednosti. Po izvedbi ene serije meritev smo meritev vedno ponovili pri osnovni sili, da smo ocenili vpliv naključnih pogreškov na rezultate. Uporabili smo le tiste vrednosti, pri katerih sprememba med prvo in zadnjo meritvijo ni bila večja od 0,1 µm.

Skupna standardna negotovost meritve dolžine z laserskim interferometrom [5] v nadzorovanih razmerah, ki smo jo točno ovrednotili že v mnogih akreditiranih kalibracijskih postopkih, je znašala: $u = 0{,}01$ µm in je bila pri vrednotenju deformacij praktično zanemarljiva.

Primer beleženja rezultatov meritev za kroglico premera 1 mm je prikazan v preglednici 2.

There were ten such 10-g weights, each with a standard uncertainty of 10 mg. Ruby probe spheres with diameters of 0,8 mm, 1 mm, 1,35 mm, 2 mm, and 5 mm were measured. Each individual diameter was measured using different probing forces, the results were compared, and the deformations were calculated. These deformations were compared with the deformations that were calculated using analytical formulae [1].

2.2 Performance of the experiment

Each sphere was first measured with the initial force of 1,5 N. Subsequently, the force was increased in ten steps of 0,1 N (weights of 10 g were put on the 150-g weight). The measurement was repeated five times for each measurement force. After this the whole procedure was repeated once again, so that ten measurement values were obtained for each measurement force. After a single series of measurements was finished, the measurement was repeated with the 150-g weight in order to evaluate the influence of random deviations on the result. Only the values where the difference between the first and the last measurement did not exceed 0.1 µm were taken into account.

The combined standard uncertainty of the length measurement using the laser interferometer under the controlled environmental conditions [5], which was already precisely evaluated in many accredited calibration procedures, was: $u = 0{,}01$ µm and was practically negligible for the deformation evaluation.

An example of the measurement result record for the 1-mm sphere's diameter is shown in Table 2.

Preglednica 2. *Rezultati ene serije meritev za kroglico premera 1 mm*
Table 2. *Results of one series of measurements for a sphere's diameter of 1 mm*

Utež št.	Masa	**Razbirek/Indication - µm**				
Weight No.	Mass	M1	M2	M3	M4	M5
1	150 g	-0,06	-0,05	-0,05	-0,06	-0,03
2	160 g	-0,08	-0,08	-0,09	-0,09	-0,08
3	170 g	-0,1	-0,11	-0,14	-0,14	-0,1
4	180 g	-0,14	-0,14	-0,17	-0,16	-0,11
5	190 g	-0,18	-0,17	-0,21	-0,17	-0,15
6	200 g	-0,22	-0,19	-0,25	-0,2	-0,16
7	210 g	-0,25	-0,23	-0,3	-0,26	-0,18
8	220 g	-0,26	-0,27	-0,32	-0,32	-0,2
9	230 g	-0,28	-0,33	-0,36	-0,36	-0,22
10	240 g	-0,33	-0,36	-0,42	-0,38	-0,24
11	250 g	-0,36	-0,42	-0,45	-0,39	-0,26
0	150 g	-0,07	-0,14	-0,14	-0,09	0,06
Razlika/Difference 11-0		-0,29	-0,28	-0,31	-0,3	-0,32

2.3 Rezultati meritev

Pri preračunu deformacij smo predpostavili, da je premer kroglice enak imenskemu premeru, kar v praksi seveda ne drži. Zato je izračunana deformacija pri sili 1,5 N netočna in rabi le kot izhodišče za preračun relativnih deformacij pri večjih obremenitvah. Izračunane srednje deformacije iz dveh serij po 5 meritev so prikazane v preglednici 3.

2.3 Measurement results

The sphere‘s diameter that was used in the deformation calculation was the nominal diameter, however, this is not the true value. Therefore, the calculated deformation for the force of 1,5 N was not exact and served only as a starting point for the calculation of the relative deformations with greater forces. Calculated mean deformations for a series of five measurements are shown in Table 3.

Preglednica 3. *Srednje deformacije za različne premere kroglic in različne merilne sile*
Table 3. *Mean deviations for different sphere’s diameters and different measurement forces*

d mm	x - µm										
	F - N										
	1,5	1,6	1,7	1,8	1,9	2	2,1	2,2	2,3	2,4	2,5
0,8	0,035	0,06	0,085	0,1	0,135	0,18	0,22	0,25	0,275	0,32	0,37
1	0,04	0,075	0,1	0,135	0,165	0,205	0,2275	0,2475	0,2675	0,3075	0,33
1,35	0,03	0,0525	0,075	0,1025	0,12	0,145	0,17	0,2075	0,235	0,275	0,305
2	0,05	0,0875	0,105	0,13	0,1575	0,19	0,2325	0,275	0,3	0,32	0,3675
5	0,035	0,0675	0,0975	0,1325	0,16	0,18	0,2125	0,24	0,2675	0,29	0,305

Standardno negotovost tega izračuna lahko izrazimo kot eksperimentalni standardni odmik ([2] in [3]), ki ga izračunamo iz desetih merilnih vrednosti za vsako kroglico in vsako merilno silo. Vrednosti so zbrane v diagramu na sliki 2. Iz diagrama je razvidno, da imamo največ težav prav pri kroglicah majhnega premera, kjer so tudi deformacije največje. Vendar pa je negotovost vedno precej nižja od spremembe deformacije.

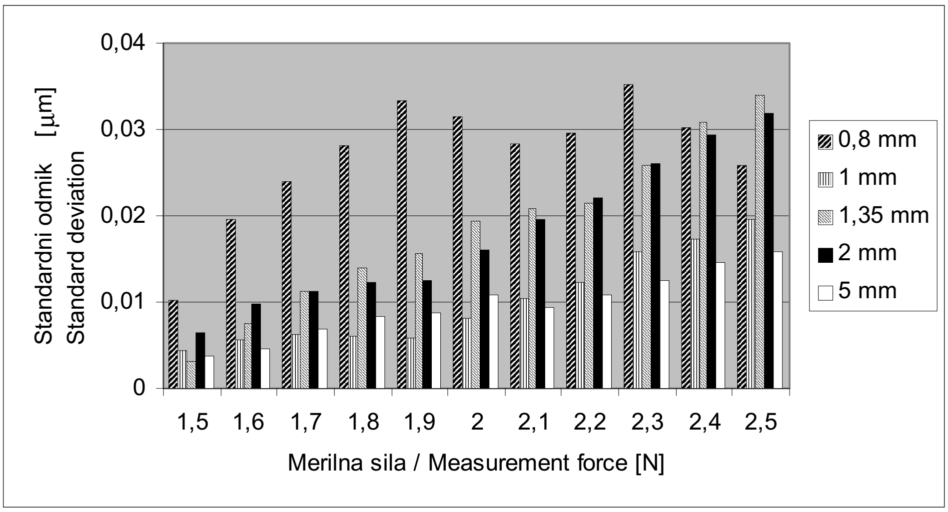
The standard uncertainty for this calculation can be expressed as a standard deviation ([2] and [3]) calculated from ten measurement values for each sphere‘s diameter and each measurement force. The values are collected in the diagram in Figure 2. This diagram shows that most of the problems occur at small diameters where the deformations are the biggest. However, the uncertainty is, in all cases, much lower than the change of the deformation.

3 PRIMERJAVA PRESKUSNIH VREDNOSTI DEFORMACIJ Z IZRAČUNANIMI ODMIKI

Primerjava rezultatov meritev in izračunanih rezultatov kaže, da so predpostavke glede

3 COMPARISON OF THE EXPERIMENTAL AND CALCULATED DEFORMATION DEVIATIONS

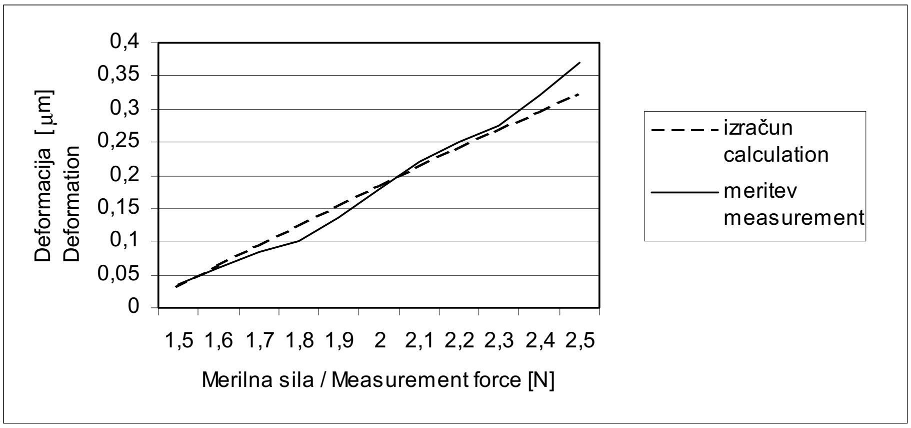
A comparison of the measurements and the calculated values proves that the assumptions



Sl. 2. *Standardni odmiki izmerjenih deformacij*
Fig. 2 *Standard deviations of measured deformations*

negotovosti določanja deformacije, ki smo jih navedli v točki 1.1, realne. Sklepamo lahko tudi, da z analitičnim preračunom ne presežemo določenega deleža skupne standardne negotovosti, ki sme znašati največ 0,2 μm. Slika 3 prikazuje primerjavo za kroglico s premerom 0,8 mm, slika 4 pa za kroglico s premerom 1,35 mm.

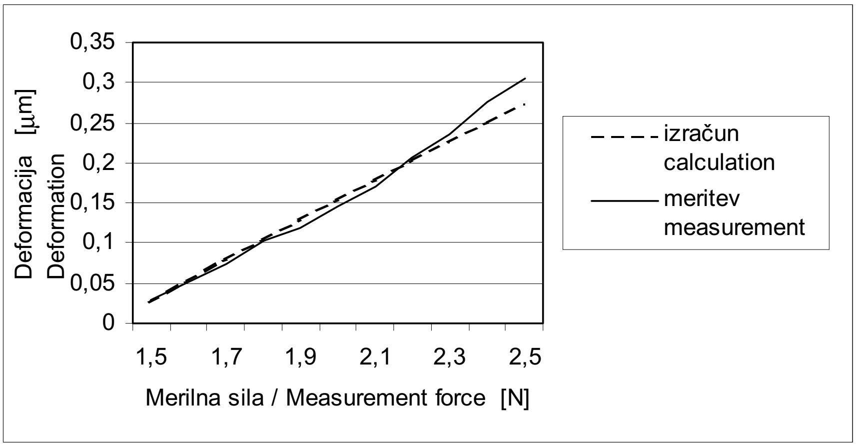
regarding the uncertainty of the deformation determination stated in section 1.1 are realistic. It can also be concluded that the supposed uncertainty contribution of less than 0,2 μm is not exceeded in the analytical calculation. Figure 3 shows a comparison for the sphere's diameter of 0,8 mm and Figure 4 for the diameter of 1,35 mm.



Sl. 3. *Primerjava izračunanih in izmerjenih deformacij za kroglico premera 0,8 mm*
Fig. 3. *Comparison of calculated and measured deformations for the sphere's diameter of 0,8 mm*

Največja razlika, ki se pojavi na obravnavanem območju sile, je 0,05 μm, kar je na ravni negotovosti izračunanih srednjih vrednosti izmerjenih deformacij. Pri kroglicah večjih premerov (npr. 5 mm) se pojavi največja razlika 0,15 μm, vendar pa pri teh kroglicah deformacija ni kritična.

The greatest difference in the whole range is 0,05 μm, which is approximately the level of the uncertainty of the calculated mean values of the measured deviations. The maximum difference for the bigger sphere's diameters (e.g. 5 mm) is 0,15 μm, but the deformation is not critical at these diameters.



Sl. 4. *Primerjava izračunanih in izmerjenih deformacij za kroglico premera 1,35 mm*
Fig. 4. *Comparison of calculated and measured deformations for the sphere's diameter of 1,35 mm*

4 SKLEP

S preskusno določitvijo deformacije pri merjenju premerov majhnih kroglic z metodo mehanskega dvotočkovnega tipanja smo želeli pokazati pravilnost ocene negotovosti izračuna z analitičnimi obrazci. Predpostavke o oceni območij, v katerih lahko pričakujemo prave vrednosti mehanskih lastnosti materialov, so se pokazale kot zelo

4 CONCLUSION

The aim of the experimental determination of the deformation during the measurement of small sphere's diameters with the method of mechanical two-point probing was to show the correctness of the uncertainty estimation of the analytical calculation. Assumptions about estimating intervals in which true values of the material's mechanical properties can be realistične. Vse dobljene razlike med izračunanimi in eksperimentalno določenimi deformacijami so bile znotraj območja standardne negotovosti. Rezultati preskusne analize deformacije in negotovosti določitve te deformacije bodo rabili kot dokaz o pravilnosti izračuna deformacije in ocene deleža merilne negotovosti pri akreditiranih kalibracijskih postopkih.

expected were found to be very realistic. All the differences between the calculated and the experimentally determined deformations were within the standard uncertainty interval. The results of the experimental analysis of the deformation and of the uncertainty of the deformation determination will serve as proof of the correctness of the deformation calculation and the uncertainty component estimation in the accredited calibration procedures.

5 OZNAKE
5 SYMBOLS

merilna sila	F	measurement force
deformacija pri tipanju krogle	x	deformation by the probing a sphere
premer deformiranega polja	$2a$	deformed area diameter
faktor mehanskih lastnosti materialov	C_E	material's mechanical property factor
premer krogle	d	sphere's diameter
modula elastičnosti	E_1, E_2	elasticity moduli
Poissonova količnika	ν_1, ν_2	Poisson's ratia
standardna negotovost	u	standard uncertainty
meritev 1 ... meritev 5	M1...M5	measurement 1 ... measurement 5

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Prilagoditev modela vrednotenja merilne negotovosti pri kalibraciji dolžinskih etalonov na temelju avtomatizacije meritve

Modification of the Model for Measurement Evaluation in a Gauge-Block Calibration Based on Measurement Automation

Bojan Ačko - Adolf Šostar

Prispevek obravnava modele za vrednotenje merilne negotovosti pri kalibraciji dolžinskih etalonov - vzporednih končnih meril po metodi mehanske primerjave dolžin. Prikazana je prilagoditev sedanjega modela, ki ga uporabljamo pri običajnem postopku kalibracije, za razmere meritve pri avtomatizirani meritvi. Z avtomatizacijo meritve je omogočen nadzor nad večino vhodnih veličin v matematičnem modelu meritve, zato je mogoče zmanjšati standardne negotovosti teh veličin in s tem tudi skupno merilno negotovost. Seveda pa ima lahko avtomatizacija tudi nekatere motilne vplive na rezultat kalibracije, zato je pomembno, da pri načrtovanju avtomatizacije vnaprej predpostavimo vse morebitne vplive na merilno negotovost in se na podlagi analize teh vplivov odločimo za ustrezno različico avtomatizacije.

(Ključne besede: etaloni, meritev dolžin, kalibriranje, negotovosti merilne, avtomatizacija)

This paper treats models for evaluating the uncertainty of measurement during the calibration of length standards — gauge blocks based on the mechanical comparative method. A modification of the existing model used in the classic calibration procedure for measurement conditions in the automated measurement is presented. Control over most input values of the mathematical model of the measurement is ensured by the automation, and as a consequence the standard uncertainties of these values and the combined uncertainty can be reduced. However, automation can also have some negative influences on the calibration result. Therefore it is very important that all possible influences on the uncertainty of the measurement are anticipated in advance when the automation is planned, and the method of automation is chosen after these influences are precisely analysed.

(Keywords: length standards, measurements, calibrations, uncertainty of measurements, automation)

0 UVOD

Nacionalni etalon za dolžino v R Sloveniji so vzporedna končna merila, ki so sledljiva na primarni etalon preko kalibracij v evropskih državnih laboratorijih. Etalone iz industrije in kalibracijskih laboratorijev kalibriramo po metodi mehanske primerjave dolžin z nacionalnim etalonom. Najboljša merilna zmogljivost, izražena z merilno negotovostjo, ni primerljiva z zmogljivostmi evropskih laboratorijev, ki kalibrirajo po metodi absolutne interferenčne meritve z laserjem, vendar je trenutno ustrezna glede na zahteve industrije. Naš cilj, ki temelji na predpostavljenem povečevanju zahtev industrije po točnosti, je zmanjšanje negotovosti kalibracij brez uvajanja interferenčnega sistema, ki bi bil za slovensko industrijo predrag. Raziskovalno delo na tem področju je usmerjeno v analizo kritičnih

0 INTRODUCTION

The national standard for length in Slovenia is realised with gauge blocks. These gauge blocks are traceable to the primary standard through calibrations in different European national laboratories. The standards from Slovenian industry and various calibration laboratories are calibrated by mechanical comparison with the national standard. Slovenia's best measurement capabilities are not comparable with those of other European national laboratories, which have interferometric calibration systems, but it is able to deal with the present industrial needs. Our aim is to reduce the uncertainty of length calibrations without having to resort to interferometric systems, which would be too expensive for industry. Our research work in this field is focused on critical uncertainty contributions like prispevkov k negotovosti, kakor so kalibracija opreme, pogoji okolice in vpliv merilnika.

Na podlagi raziskav smo se odločili, da bomo sistem za kalibracijo izboljšali z rekonstrukcijo merilne naprave in odlagalnih površin za temperaturno stabilizacijo etalonov in z avtomatizacijo merilnega procesa. Hkrati z uvajanjem teh izboljšav je treba tudi analizirati in spremeniti modele za vrednotenje merilne negotovosti zaradi optimiranja novega kalibracijskega postopka.

the calibration of the equipment, as well as environmental and human influences.

As a result of our research the calibration system will be improved by the reconstruction of the device and the surfaces for the thermal stabilisation of the gauge blocks and by the automation of the measurement process. In order to optimise the new calibration procedure, models for evaluating the uncertainty of measurements will be analysed and modified during the introduction of the improvements.

1 POSTOPEK VREDNOTENJA MERILNE NEGOTOVOSTI

1 PROCEDURE FOR EVALUATING THE MEASUREMENT UNCERTAINTY

Negotovost vrednotimo po postopku v [1], hkrati pa upoštevamo tudi priporočila EAL za evropske akreditirane laboratorije, ki so podana v [2]. Poglavitni koraki postopka so naslednji:

- Določimo matematični model meritve, ki predstavlja izhodno veličino meritve kot funkcijo vhodnih veličin. Funkcija f mora vsebovati vse veličine, vključno z vsemi povezavami in popravnimi faktorji, ki lahko prispevajo pomembno komponento negotovosti k merilnemu rezultatu. Pravilna določitev matematičnega modela meritve (1) je ključnega pomena za kakovost določitve negotovosti meritve:

The uncertainty is evaluated using the procedure in [1] and by considering the EAL guides for European accredited laboratories given in [2]. The procedure consists of the following basic steps:

- A mathematical model of the measurement, which represents the output value of the measurement as a function of input values, is defined. Function f comprises all the input values including all the corrections and correction factors that could significantly influence the uncertainty of the measurement result. The correct definition of the mathematical model (1) is of essential importance for the quality of the uncertainty evaluation:

$$y = f(x_1, x_2, ..., x_i, ..., x_N) \qquad (1).$$

- Ovrednotimo standardne negotovosti vseh ocen vhodnih veličin $u(x_i)$. Če obstaja povezanost med dvema vhodnima veličinama (veličini med seboj nista neodvisni), moramo v skupni standardni negotovosti $u_c(y)$ upoštevati tudi člene, ki zajemajo kovariance ocen vhodnih veličin. Povezavo izrazimo z enačbo:

- Standard uncertainties $u(x_i)$ of all input values are evaluated. If there is a correlation between two input values (i.e. the values are not independent), parts including covariances of the input value estimations are considered in the combined standard uncertainty $u_c(y)$. The correlation is expressed by equation:

$$s(x_{i,k}, x_{j,k}) = \frac{1}{n-1}\sum_{k=1}^{n}(x_{i,k} - \bar{x}_i)(x_{j,k} - \bar{x}_j) \qquad (2).$$

- Izračunamo standardno negotovost ocene izhodne veličine $u_c(y)$ po enačbi:

- The standard uncertainty of the output-value estimation $u_c(y)$ is evaluated using equation:

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \qquad (3).$$

Če sta vhodni veličini X_i in X_j med seboj odvisni oz. sta v povezanosti, moramo v enačbi (3) upoštevati še njuno kovarianco. Enačba (3) dobi novo obliko:

If the input values X_i and X_j are dependent res. corelated, the covariance is included in equation (3). Equation (3) gets a new form:

$$u_c^2(y) = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i, x_j) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i, x_j) \qquad (4).$$

- Izračunamo razširjeno negotovost meritve:

- The expanded uncertainty of measurement is calculated:

$$U = ku_c(y) \qquad (5).$$

- Faktor k izberemo v odvisnosti od zahtevanega nivoja zaupanja. Pri normalni porazdelitvi ustreza

- The coverage factor k is chosen with respect to the required level of confidence. In a normal distribution the faktor 2 nivoju zaupanja 95,45%, faktor 3 pa nivoju zaupanja 99,73%.

factor 2 corresponds to a level of confidence of 95.45% and the factor 3 to a level of confidence of 99.73%.

2 MODEL VREDNOTENJA NEGOTOVOSTI ZA SEDANJI POSTOPEK KALIBRACIJE

2 MODEL FOR THE MEASUREMENT UNCERTAINTY EVALUATION FOR THE EXISTING CALIBRATION PROCEDURE

2.1 Matematični model meritve

Meritev izvedemo tako, da najprej izmerimo referenčni etalon, nato pa še etalon, ki ga kalibriramo, in primerjamo med seboj izmerjeni vrednosti. Iz primerjave izmerjenih vrednosti izračunamo odstopek mere kalibriranega etalona. Ločljivost meritve je 10 nm. Postopek je opisan v [3] do [5]. Dolžina *l* končnega merila, ki ga kalibriramo, je podana z enačbo (6):

2.1 Mathematical model of measurement

The measurement is performed in such a way that the reference standard (gauge block) is measured first and then the standard to be calibrated is measured. The two measured values are compared and the deviation is calculated. The resolution of the measurement is 10 nm. The procedure is described in [3] to [5]. The length of the gauge block to be calibrated is calculated using equation (6):

$$l = l_e + \delta l - L \cdot (\delta\alpha \cdot \overline{\Delta t} + \overline{\alpha} \cdot \delta t) - \delta l_v \qquad (6).$$

Ta enačba vsebuje vse veličine, ki pomembno vplivajo na rezultat meritve, vključno s popravki temperaturnih raztezkov in izsrednega tipanja končnega merila med meritvijo.

This equation contains all the values that significantly influence the measurement result including the thermal expansion and non-central gauge-block probing corrections.

2.2 Izračun koeficientov občutljivosti

Koeficienti občutljivosti za posamezne standardne negotovosti vhodnih veličin $u(x_i)$ povedo, kako močno bo določena negotovost vhodne veličine vplivala na skupno negotovost meritve. Izračunamo jih kot parcialne odvode funkcije *f* po posameznih vhodnih veličinah. V našem primeru moramo izračunati naslednje koeficiente občutljivosti [3]:

2.2 Sensitivity coefficient calculation

Sensitivity coefficients for single standard uncertainties of the input values $u(x_i)$ indicate the size of the influence of a particular input value's standard uncertainty on the total measurement uncertainty. These coefficients are calculated as partial derivatives of the function *f* over input values. In our case the following sensitivity coefficients are calculated [3]:

$$\begin{aligned}
c_e &= \partial l / \partial l_e = 1 \\
c_{\delta l} &= \partial l / \partial \delta l = 1 \\
c_{\delta\alpha} &= \partial \ell / \partial \delta\alpha = -L \cdot \overline{\Delta t} \\
c_{\overline{\Delta t}} &= \partial \ell / \partial \overline{\Delta t} = -L \cdot \delta\alpha \\
c_{\overline{\alpha}} &= \partial \ell / \partial \overline{\alpha} = -L \cdot \delta t \\
c_{\delta t} &= \partial \ell / \partial \delta t = -L \cdot \overline{\alpha} \\
c_{\delta l_v} &= \partial l / \partial \delta l_v = 1
\end{aligned}$$

2.3 Ocene standardnih negotovosti vhodnih veličin in skupna standardna negotovost meritve

Standardne negotovosti vhodnih veličin smo ocenili na podlagi doseženih pogojev okolice, uporabljene merilne opreme, negotovosti kalibracije referenčnih etalonov in podatkov o lastnostih materialov etalonov. Pogoje okolice smo ovrednotili na podlagi meritev temperature v različnih točkah merilne prostornine, na mizi merilnega instrumenta in na etalonih pred kalibracijo in med njo. Podatke o lastnostih materialov (predvsem nas je zanimala linearna temperaturna razteznost α) smo dobili od nekaterih proizvajalcev končnih meril, podatke o

2.3 Standard uncertainty estimations of the input values and the total measurement uncertainty

The standard uncertainty estimations of the input values were based on the following: the environmental conditions; the measurement equipment used; the calibration uncertainties of the standard gauge blocks and the gauge-block comparator; and the material properties data. The environmental conditions were evaluated from temperature measurements at different points: in the measuring space, on the comparator table and on the gauge blocks, before and during the calibration. Material properties data (especially the linear thermal expansion coefficient α) were obtained from a negotovosti kalibracije referenčnih etalonov pa iz certifikata o kalibraciji. Negotovost zaradi izsrednega tipanja etalona smo ovrednotili na podlagi statistične analize več sto izmerjenih vrednosti.

V preglednici 1 so predstavljene ocene vrednosti posameznih vhodnih veličin, njihove standardne negotovosti, koeficienti občutljivosti, tip statistične porazdelitve za posamezno veličino in skupna standardna negotovost meritve (izračunana po enačbi (3)) za primer kalibracije etalona dolžine 100 mm.

number of gauge-block producers, while the uncertainties of the reference gauge-block calibration were obtained from the calibration certificates. The uncertainty of the non-central gauge-block probing was evaluated by a statistical analysis of many hundreds of measured values.

Estimated values of the input quantities, their standard uncertainties, sensitivity coefficients, type of statistical distributions for a single value, and the total standard uncertainty (calculated using equation (3)) for the case of the 100-mm gauge-block calibration are shown in Table 1.

Preglednica 1. *Standardne negotovosti ocen vhodnih veličin na zgornji meji merilnega območja (100 mm)*
Table 1. *Standard uncertainties of the input value estimations on the upper limit of the measurement range (100 mm)*

Veličina X_i Quantity X_i	Ocenjena vrednost Evaluated value	Standardna negotovost Standard uncertainty	Porazdelitev Distribution	Koeficient občutljivosti Sensitivity coefficient	Prispevek negotovosti Uncertainty contribution
l_e	100 mm	20 nm	normalna normal	1	20 nm
δ_l	0 nm	15,9 nm	normalna normal	1	15,9 nm
$\delta\alpha$	0 °C^{-1}	0,58·10^{-6} °C^{-1}	pravokotna rectangular	-3·10^7 nm°C	-17,4 nm
$\overline{\Delta t}$	0 °C	0,08 °C	normalna normal	-200 nm°C^{-1}	-16 nm
$\overline{\alpha}$	11·10^{-6} °C^{-1}	0,40·10^{-6} °C^{-1}	pravokotna rectangular	-3·10^7 nm°C	-12 nm
δ_t	0 °C	0,02 °C	pravokotna rectangular	-1200 nm°C^{-1}	24 nm
δ_{l_v}	0 nm	5 nm	normalna normal	1	5 nm
				Skupaj: Total:	44,2 nm

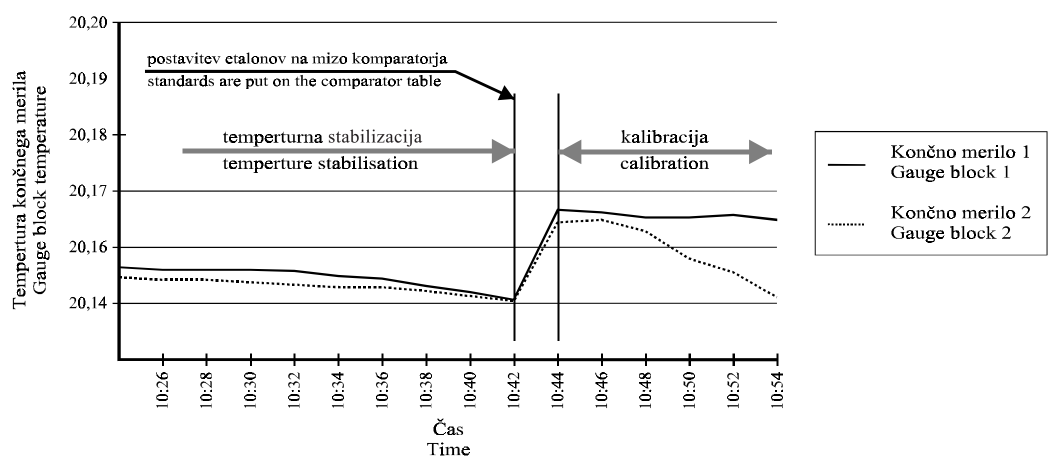
3 KRITIČNE KOMPONENTE NEGOTOVOSTI

Iz preglednice 1 vidimo, da poleg kalibracije etalonov in kompratorja (l_e, δl) bistveno vplivajo na negotovost še komponente δt, $\delta\alpha$ in $\overline{\Delta t}$. Če natančneje pogledamo komponento $\delta\alpha$, ugotovimo, da je prispevek negotovosti velik, ker je velik utežni koeficient $c_{\delta\alpha} = \partial\ell / \partial\delta\alpha = -L \cdot \overline{\Delta t}$, ta koeficient pa je odvisen od povprečnega odstopka temperature etalonov. Povzamemo lahko torej, da so bistveni vplivi na skupno negotovost kalibracije odstopek temperature etalonov, negotovost določitve temperaturnega odstopka, razlika med temperaturama referenčnega in kalibriranega etalona in negotovost določitve te razlike. Problem je predvsem v tem, da med kalibracijo ne moremo meriti temperatur posameznih etalonov, ampak merimo temperaturo mize komparatorja in predpostavljamo, da imata oba etalona enako temperaturo kakor miza. Dodatne težave povzroča

3 CRITICAL UNCERTAINTY COMPONENTS

As we can see in Table 1, besides the calibration of the standards and the comparator (l_e, δl) the components δt, $\delta\alpha$ and $\overline{\Delta t}$ significantly influence the total uncertainty. If we look closely at component $\delta\alpha$ we find that its contribution is significant because its sensitivity coefficient $c_{\delta\alpha} = \partial\ell / \partial\delta\alpha = -L \cdot \overline{\Delta t}$ is big. This coefficient depends on the average gauge-block temperature deviation. Indeed, we found that the significant influences on the total calibration uncertainty were the gauge-block temperature deviation, the uncertainty of temperature deviation evaluation, the temperature difference between the gauge blocks, and the uncertainty of the evaluation of this difference. One problem is that we are not able to measure the temperatures of both gauge blocks. However, we supposed that these temperatures are equal to the temperature of the comparator table, which is measured during the calibration. Additional problems nenaden porast temperature etalonov takoj po postavitvi na merilno mizo. Slika 1 prikazuje rezultate meritev temperature na dveh preskusnih etalonih med temperaturno stabilizacijo, postavitvijo na mizo komparatorja in med meritvijo.

are caused by a rapid gauge-block temperature rise after setting the gauge block on the comparator table. The results of temperature measurements on two test standards during: thermal stabilisation, placement on the table and measurement are shown in Figure 1.



Sl. 1. *Rezultati meritev temperature na etalonih pred kalibracijo in med njo*
Fig. 1. *Results of standard temperature measurements before and during the calibration*

Vidimo, da se pojavi kritični trenutek po postavitvi etalonov na mizo zaradi različnih toplotnih lastnosti materialov mize in površine za temperaturno stabilizacijo ter zaradi postavitve etalonov v navpično lego. Zaradi te temperaturne spremembe začnemo meritev približno tri minute po postavitvi etalonov na mizo komparatorja. Po nekaj minutah se pojavi nov problem. Temperaturi etalonov se začneta razhajati. Referenčni etalon, ki je postavljen bliže merilcu, ohranja temperaturo na približno isti ravni, medtem ko se kalibrirani etalon začne ohlajati. Po približno desetih minutah je razlika že 0,03 K, kar kritično vpliva na rezultat meritve.

It is easy to see that the critical moment is the placement of the standards on the comparator table. The temperature change is caused by the different thermal properties of the thermal stabilisation surface and the comparator table's surface and by turning the gauge blocks into the vertical position. In order to avoid the influence of this temperature change, the measurement begins approximately three minutes after the standards are placed on the table. However, a few minutes later a new problem arises. The gauge-block temperature difference increases. The reference gauge block that is closer to the operator maintains its temperature, while the gauge block being calibrated starts cooling. After about ten minutes the difference is already 0.03 K, large enough to have a critical influence on the measurement result.

4 SPREMEMBA MODELA VREDNOTENJA MERILNE NEGOTOVOSTI

V prejšnjem poglavju smo videli, da so kritični vplivi na negotovost predvsem negotovost kalibracije referenčnih etalonov in spremembe temperature etalonov pred kalibracijo in med njo. Na podlagi izkušenj v zadnjih petih letih, ko smo kalibrirali referenčne etalone v različnih evropskih državnih laboratorijih (PTB Nemčija, JV Norveška, BNM-LNE Francija) in smo natančno analizirali rezultate kalibracij, smo ugotovili, da pomeni pomemben prispevek k negotovosti tudi lezenje (drift) etalonov. Z leti se spreminjata dolžina in oblika etalonov, hkrati

4 MODIFICATION OF THE MODEL FOR MEASUREMENT UNCERTAINTY EVALUATION

In the previous section we have seen that the uncertainty of a calibration is critically influenced by the gauge-block calibration uncertainty and by the gauge-block temperature change before and during the calibration. However, our experience over the last five years, when calibrations of our reference standards have been performed in different European national laboratories (PTB Germany, JV Norway and BNM-LNE France) and when critical analyses of the calibration results have been performed, has shown that gauge-block drift also represents an important contribution to the uncertainty. Gauge-block length and geometry change over a period pa se zaradi uporabe obrabljajo. Zato moramo v matematični model (6) vnesti tudi popravek lezenja:

of a year as the surfaces get worn during application. For this reason the mathematical model (6) needs to be supplemented with a drift correction.

$$l = l_e + \delta l - L \cdot (\delta\alpha \cdot \overline{\Delta t} + \overline{\alpha} \cdot \delta t) - \delta l_v - d \quad (7).$$

Seveda je sprememba matematičnega modela samo prvi korak pri prilagoditvi modela vrednotenja negotovosti. Bistvene so dejavnosti, ki jih izvedemo na temelju analize kritičnih vplivov temperature.

Modification of the mathematical model is, however, only the first step in the modification of the uncertainty evaluation model. The activities that are performed on the basis of the analysis of critical temperature influences are very important.

4.1 Avtomatizacija postopka kalibracije

Nameni avtomatizacije postopka kalibracije so poleg časovne racionalizacije še naslednji:
- izključitev vplivov merilca na meritev (predvsem toplotno sevanje),
- postavitev etalonov v času temperaturne stabilizacije v enak položaj kakor med meritvijo,
- možnost zaščite etalonov pred nečistočami (teh v modelu vrednotenja negotovosti sicer nismo upoštevali, povzročajo pa naključne pogreške),
- manjša možnost mehanskih poškodb etalonov med meritvijo zaradi avtomatičnih pomikov merilne mize.

Avtomatiziran postopek bo potekal brez posegov merilca. Manipulator bo avtomatično postavljal etalone na merilno mizo, poseben krmilni mehanizem pa bo pomikal merilno mizo v položaje, ki jih določa merilni postopek.

Zasnova avtomatizacije, vključno z vsemi potrebnimi algoritmi in določitvijo mehanskih, pnevmatskih in elektronskih komponent, je že končana. V nasprotju s komercialnimi izvedbami avtomatizacije, ki jih ponujajo različni proizvajalci merilne opreme, smo se mi projekta lotili predvsem z vidika zmanjšanja merilne negotovosti in ne z vidika zmanjševanja merilnih časov. Izvedene so bile vse analize merilne negotovosti, ki so zajemale predvsem raziskave sprememb pogojev merjenja.

Z vidika merilne negotovosti je avtomatizacija pomembna zaradi zmanjšanja razlike med temperaturama referenčnega in kalibriranega etalona in zaradi zmanjšanja spremembe temperature po postavitvi etalonov na merilno mizo primerjalnika.

4.1 Automation of the calibration process

In addition to reducing the time of the calibration process the automation is designed to do the following:
- eliminate the operator influences on the measurement (especially thermal radiation),
- ensure the same position of the gauge blocks during the thermal stabilisation and the measurement,
- protect the gauge blocks from dirt (this was not considered in the uncertainty evaluation model, but it can cause random errors),
- decrease the possibility of mechanical damage during the measurement by introducing automated table movements.

The automated process will run without operator interventions. A manipulator will put standards on the measurement table, which will then be moved into specified positions by a special mechanism.

The design of the automated system including all the necessary algorithms and the determination of the necessary mechanical, pneumatic and electronic elements is already finished. In contrast to commercial automation systems offered by various producers of gauge-block comparators, the primary aim of our automation project is to reduce uncertainty rather than reducing the time and costs of calibration. All the uncertainty analyses relating to the change in measurement conditions have already been done.

Concerning measurement uncertainty, automation is important in order to decrease the temperature difference between the reference gauge block and the gauge block being calibrated, and to decrease the temperature change after placing the gauge blocks on the comparator table.

4.2 Merilna negotovost avtomatiziranega postopka

Analiza temperatur pred meritvijo in med njo, ki je temeljila na simuliranju avtomatiziranega merilnega postopka in je obsegala več sto meritev temperatur ob uporabi različnih materialov, virov osvetlitve in pogonskih agregatov (vključno z različnimi vrstami izolacije in odvoda toplotne energije), je pokazala, da se lahko temperaturne razmere znatno izboljšajo. Končni rezultati analize so predstavljeni v preglednici 2.

4.2 Measurement uncertainty of the automated process

A temperature analysis before and during the measurement based on a simulation of an automated process and containing hundreds more temperature measurements for different materials, illumination sources and driving aggregates (including different types of isolations and thermal energy flows) has shown that the thermal conditions can be significantly improved. The final analysis results are presented in Table 2.

Preglednica 2. *Standardne negotovosti ocen vhodnih veličin na zgornji meji merilnega obmoèja (100 mm) po spremembi kalibracijskega postopka*
Table 2. *Standard uncertainties of the input value estimations on the upper limit of the measurement range (100 mm) after modifying the calibration procedure*

Veličina X_i Quantity X_i	Ocenjena vrednost Evaluated value	Standardna negotovost Standard uncertainty	Porazdelitev Distribution	Koeficient občutljivosti Sensitivity coefficient	Prispevek negotovosti Uncertainty contribution
l_e	100 mm	20 nm	normalna normal	1	20 nm
δ_l	0 nm	15,9 nm	normalna normal	1	15,9 nm
$\delta\alpha$	0 °C^{-1}	0,58·10^{-6} °C^{-1}	pravokotna rectangular	-1·10^{7} nm°C	-5,8 nm
$\overline{\Delta t}$	0 °C	0,04 °C	normalna normal	-200 nm°C^{-1}	-8 nm
$\overline{\alpha}$	11·10^{-6} °C^{-1}	0,40·10^{-6} °C^{-1}	pravokotna rectangular	-1·10^{6} nm°C	-0,4 nm
δ_t	0 °C	0,01 °C	pravokotna rectangular	-1200 nm°C^{-1}	-12 nm
δ_{l_v}	0 nm	5 nm	normalna normal	1	5 nm
d	0 nm	7 nm	pravokotna rectangular	1	7 nm
				Skupaj: Total:	31,1 nm

5 SKLEP

Z avtomatizacijo postopka kalibracije končnih meril dosežemo stabilnejše pogoje merjenja in s tem zmanjšamo bistvene vplive na merilno negotovost. Na podlagi simuliranja postopka in analize pogojev (predvsem temperature) smo ugotovili, da se predvsem bistveno zmanjša razlika med temperaturama etalonov in sprememba temperature po postavitvi etalonov na merilno mizo. Skupna merilna negotovost se pri etalonu dolžine 100 mm zmanjša za približno 34%. S takšno negotovostjo kalibracije dosežemo raven najboljših svetovnih kalibracijskih laboratorijev, primerljivi pa postanemo tudi z nekaterimi laboratoriji, ki kalibrirajo po metodi absolutne interferenčne meritve z uporabo primarnega etalona.

5 CONCLUSION

An automated gauge-block calibration process ensures more stable measurement conditions and so the critical influences on measurement uncertainty are therefore minimised. The process simulation and conditions (temperature) analysis have shown that the temperature difference between the standards and the temperature change after placing the standards on the comparator table decrease significantly. The total uncertainty for the 100-mm standard decreases by about 34%. With such an uncertainty a level comparable with that of the world's best laboratories is achieved and the results can also be compared with some laboratories performing calibrations using the absolute interference method with an application of the primary standard of measurement.

6 SIMBOLI
6 SYMBOLS

ocena izhodne veličine meritve	y	measurement output value estimation
ocena vhodne veličine meritve	x_i	measurement input value estimation
standardna negotovost ocene vhodne veličine	$u(x_i)$	standard uncertainty of an input value estimation
skupna standardna negotovost meritve	$u_c(y)$	combined standard uncertainty of measurement
razširjena negotovost meritve	U	expanded uncertainty of measurement
faktor širitve negotovosti	k	coverage factor
kalibrirana dolžina končnega merila	l	calibrated gauge-block length

dolžina referenčnega končnega merila	l_e	reference gauge-block length
izmerjena razlika med referenčnim in kalibriranim končnim merilom	δl	measured difference between the reference and the calibrated gauge block
imenska dolžina končnega merila	L	nominal gauge-block length
povprečna razteznost končnih meril	$\bar{\alpha}$	average linear thermal expansion coefficient of two gauge blocks
razlika linearnih temperaturnih razteznosti končnih meril	$\delta\alpha$	difference between the linear thermal expansion coefficients of two gauge blocks
povprečni odstopek temperature končnih meril od 20 °C	$\overline{\Delta t}$	average temperature deviation of two gauge blocks from 20 °C
razlika temperatur končnih meril	$t\delta$	gauge-block temperature difference
odstopek zaradi izsrednega tipanja končnega merila	δl_v	deviation caused by non-central gauge-block probing
korekcija lezenja končnega merila	d	gauge-block drift correction

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Naprava in postopek za kalibriranje členkastih koordinatnih merilnih naprav

Apparatus and a Procedure to Calibrate Coordinate Measuring Arms

Igor Kovač - Andreas Klein

Razvita je metoda za povečanje absolutne natančnosti prenosnih koordinatnih merilnih naprav z rotacijskimi osmi. Predlagana je povsem nova metoda, ki je zasnovana na kalibracijskih meritvah vzdolž ravne črte, nastavljive v različnih prostorskih smereh. V ta namen smo razvili novo zelo natančno kalibracijsko napravo, s katero je mogoče zbrati verodostojno število pozicijskih merilnih vrednosti, ki jih potrebujemo za izvedbo kalibriranja. Identifikacija parametrov je bila nato izvedena s kalibracijskim programskim paketom RoboCal. S tem prispevkom je pokazano, da s predlaganim postopkom kalibriranja in z uporabo nove zelo natančne kalibracijske priprave lahko izrazito izboljšamo natančnost pozicioniranja členkastih koordinatnih merilnih naprav. To je potrjeno tudi s preskusi.

(Ključne besede: naprave merilne koordinatne, naprave prenosne, kalibriranje, meritve ravnosti)

A technique for increasing the absolute accuracy of portable, coordinate measuring arms with exclusively rotational axes was developed. This new technique is based on calibration measurements along a straight line that is adjusted in various spatial directions. For this reason a special, new, high-precision calibration apparatus was developed to collect a representative quantity of accurate data needed for the successful calibration. Parameter identification was carried out using the RoboCal calibration software. The calibration procedure using the high-precision calibration apparatus can improve the pose accuracy of the coordinate measuring arm drastically. This was also confirmed by our experiments.

(Keywords: coordinate measuring devices, portable devices, calibrations, straightness measurements)

0 UVOD

Prenosne ročno gnane členkaste koordinatne merilne naprave (ČKMN - Coordinate Measuring Arm-CMA) z rotcijskimi osmi so se uspešno uveljavile v merilni tehniki, kjer potrebujemo tridimenzionalne rezultate meritev položaja [1]. Zaradi svoje kinematične strukture odprte verige členkastih mehanizmov ne dosegajo velike togosti in s tem velike absolutne natančnosti pozicioniranja, kakor je to običajno za kartezične koordinatne merilne naprave (KKMN - Coordinate Measuring Machine CMM). Vendar pa že sama struktura mehanizma, majhna teža, velika prilagodljivost, prenosljivost in dobra priročnost ČKMN omogočajo, da te naprave uporabimo na povsem novih področjih geometrijskega merjenja. Da bi s pridom izkoristili vse prednosti in pozitivne lastnosti teh naprav, obenem pa njihovo uporabo razširili tudi na področje, na katerem je potrebna večja absolutna natančnost merjenja, je treba absolutno natančnost pozicioniranja sedanjih naprav ČKMN izboljšati.

Najpomembnejša lastnost vsake merilne naprave je njena zmožnost natančnega pozicioniranja. Za naprave z rotacijskimi osmi pomeni ponovljivost poze

0 INTRODUCTION

Portable, manually driven, coordinate measuring arms (CMAs) with exclusively rotational axes have been successfully introduced into many measuring applications where three-dimensional geometrical data are required [1]. This is true that an open kinematic chain with more axes cannot ensure such high rigidity and accuracy of the mechanical structure as in common Cartesian coordinate measuring machines (CMMs); however, structural compactness, low weight, good flexibility, portability and good dexterity allow CMAs to be applied to completely new areas. To take advantage of these positive characteristics and to expand their use to measuring applications where higher measuring accuracy is demanded, the absolute accuracy of the positioning has to be increased.

To obtain an insight into the characteristics of devices, particularly devices with rotational axes, the most important feature is pose repeat-

(PP glede na standard ISO 9283; poza - skupni izraz za pozicijo in orientacijo) glavni natančnostni podatek. Ta vrednost pove, kakšna je zmožnost naprave pri ponavljajočem se prihajanju v isto pozo v nespremenjenih razmerah premikanja in okolice. Preskusi, izvedeni na prototipu merilne naprave ČKMN , kažejo, da je z uporabo posebnih materialov in z ustrezno konstrukcijsko rešitvijo mogoče doseči razmeroma dobro ponovljivost tudi pri napravah z odprto kinematično verigo [2]. Meritve natančnostnih lastnosti različnih ČKMN potrjujejo domnevo o prevladujočem vplivu sistematičnih pogreškov. Tako pomeni ponovljivost tisto mejno vrednost, ko začnejo prevladovati naključni pogreški, če so okoliščine nespremenjene. S tem določajo meritve ponovljivosti mejo izboljšanja absolutne natančnosti poze (AP glede na standard ISO 9283), ki jo lahko dosežemo s postopki kalibracije in kompenzacije sistematičnih deležev pogreškov.

Absolutna natančnost pozicioniranja ČKMN je odvisna predvsem od natančnosti izdelave in od verodostojnosti modela, ki je uporabljen za preračun dejanske poze. Za zagotovitev kakovosti izdelave in za natančno identifikacijo parametrov modela ČKMN, so potrebne natančne meritve in napredne metode modelno zasnovane identifikacije parametrov [3]. Ti postopki in metode so zajeti v tehniki, ki jo imenujemo kalibriranje mehanizmov in jo poznamo s področja robotike kot robotsko kalibriranje [4].

V robotiki se je mnogo avtorjev ukvarjalo s postopki kalibracije in kompenzacije ([5] do [7]). Rezultati preskusov v robotiki na mehanskih strukturah z rotacijskimi osmi kažejo, da ti postopki omogočajo izboljšavo absolutne natančnosti mehanizma blizu meje ponovljivosti. S praktičnega vidika pomeni postopek kritično točko pri zmožnosti merilne naprave, ki jo uporabljamo za kalibriranje. Ta mora zbrati potrebne podatke poz v določenem prostoru v ustreznem nivoju natančnosti. Kalibracijski programski paket je razvit tako, da lahko sodeluje s poljubno kalibracijsko merilno napravo. Ker ustrezne naprave za kalibriranje členkastih koordinatnih merilnih naprav ni, smo se odločili, da zanje razvijemo novo zelo natančno kalibracijsko pripravo in oblikujemo ustrezen postopek modelno zasnovane identifikacije parametrov in s tem vplivamo na občutno povečanje natančnostnih lastnosti ročnih večstopenjskih členkastih merilnih naprav, ki so mehansko podobne členkastim robotom.

1 NOVA ZELO NATANČNA KALIBRACIJSKA NAPRAVA

Sedanje ČKMN kalibriramo in testiramo zelo različno. Za kalibriranje in testiranje ČKMN glede natančnostnih lastnosti v prostoru lahko uporabimo metodo s posebeno kalibracijsko oziroma testno šablono ali pa metodo s kroglami na palici ([8] in [9]). Nadalje lahko uporabimo metodo kalibriranja z uporabo artefaktov [10]. Preučevali in testirali smo

ability (RP according to ISO 9283). This value characterises the device’s capability to attain the same pose n-times under the same conditions. Experiments on CMAs show that the use of special materials and the choice of convenient construction solutions offer the possibility of achieving a relatively good repeatability performance, even for devices with an open kinematic chain structure [2]. Accuracy measurements carried out on different CMAs confirmed the mostly systematic character of the remaining sources of error. In this context, repeatability represents a limitation, where stochastic deviations under constant environmental conditions become dominant. Therefore, the repeatability measurement determines the limitation of pose-accuracy (AP according to ISO 9283) improvement by means of the compensation of systematic error parameters, i.e. calibration.

Absolute positioning accuracy depends mostly on the quality of the manufactured CMAs and how well the model used for the pose calculation matches with reality. To ensure quality of manufacturing and to accurately identify CMA model parameters, advanced measuring procedures and model-based parameter-identification methods are required [3]. These procedures and methods are summarised in the techniques called device calibration, known in robotics as robot calibration [4].

Many authors have studied calibration and compensation procedures in robotics ([5] to [7]). The results of experiments on robot mechanism structures with rotational axes show that this provides us with the possibility to improve absolute accuracy performance nearly up to the repeatability limit. From the practical point of view, the critical point of this procedure is the capability of the measuring device used for the calibration to collect all the needed positional data in space with the demanded accuracy level, whereas the calibration software can cooperate with any measuring device. Therefore, we decided to design and develop a new high-precision calibration apparatus, and formulate an appropriate advanced model-based parameter-identification procedure for the calibration of CMAs in order to lead to significant improvements in the accuracy characteristics of such manually driven multi-axis measuring devices which have many similarities to robots.

1 NEW HIGH-PRECISION CALIBRATION APPARATUS

Existing CMAs are calibrated and tested very differently. A special calibration and testing jig or an adapted ball-bar approach for establishing the degree of volumetric accuracy may be used ([8] and [9]). Another calibration method involves a procedure using different artefacts [10]. Calibration with a Cartesian CMM was also studied; however, the tudi možnost kalibriranja z uporabo KKMN. Vendar zaradi velikega raztrosa merilnih rezultatov, katerih vzrok je elastičnost sistema KKMN kot posledica reakcijskih sil, ki se pojavijo ob premikanju merilne naprave ČKMN, merilni rezultati niso uporabni [11].

Na podlagi raziskav na tem področju smo ugotovili, da ustrezno rešitev ponuja samo robustna mehanska oprema za merjenje in vodenje vrha ČKMN vzdolž referenčne črte, ki jo je mogoče v prostoru poljubno usmerjati. Za potrditev te domneve smo izvedli preskus na sedanjem dolžinskem primerjalniku [12]. Z uporabo primerjalnika, ki je fiksno nameščen v klimatizirani kabini, smo uspešno izvedli meritve ponovljivosti in natančnosti prototipa ČKMN vzdolž ravne črte v treh različnih vodoravnih legah [13]. Ker omejeno število vodoravnih črt ne da verodostojnih rezultatov, potrebnih za oceno natančnosti naprave v celotnem področju gibanja, smo se odločili za razvoj nove zelo natančne kalibracijske priprave za testiranje in kalibriranje členkastih merilnih naprav z rotacijskimi osmi, ki jo je mogoče nagibati pod različnimi koti v prostoru.

Podatek, ta je ključen pri razvoju nove kalibracijske priprave, je podan z mejo pozicijske natančnosti, ki jo mora kalibracijska priprava doseči. Ta meja je bila definirana na temelju meritev ponovljivosti na sedanjem prototipu ČKMN. Preskus, ki je bil izveden na sedanjem dolžinskem primerjalniku v klimatiziranem prostoru v nespremenjenih razmerah, je pokazal, da znaša ponovljivost v najbolj ugodnem delu delovnega prostora r = 2,5 μm za statistično verjetnost $\pm 2\sigma$ glede na standard ISO 9283 [13]. Nadalje smo raziskali vse možne vzroke, ki lahko povzročajo odstopanja pri samih kalibracijskih meritvah. V ta namen smo izvedli veliko število različnih poskusov in simuliranj. Ugotovili smo, da so celotna odstopanja sistema najbolj povezana s spremembami v okolici, z učinkovanjem vplivov notranjih in zunanjih sil in momentov ter z odstopki geometrijske nenatančnosti posameznih elementov [14].

Celoten sistem je sestavljen iz premega nosilca s podporno konstrukcijo, sistema vležajenih sani, pogonskega sistema in merilnega sistema, ki je nameščen ločeno glede na premi nosilec. Glavna naloga sistema premega nosilca je natančno vodenje sani glede na zahteve orientacijskega odstopanja vzdolž ravne črte v prostoru. V ta namen je izbran votel keramični nosilec dolžine L=2000 mm s površinami, obdelanimi v tolerančnem območju premosti manjše od 1 μm/m. Računska simuliranja, ki so bila izvedena na izbranem nosilcu, so pokazala, da odstopanja od premosti zaradi vpliva lastne teže nosilca in zaradi vpliva zunanjih sil ne presegajo vrednosti 1 μm oziroma kota 0,5 kotnih sekund [15].

Ker pa konstrukcijska rešitev upošteva tudi merjenja v navpični smeri, je pogonskemu sistemu sani dodana tudi protiutež. Nameščena in vodena je na posebnih vodilih znotraj keramičnega nosilca in

measuring results did not prove to be useful since considerable variation in the results appeared, this was caused by the deflection of the CMM system as a consequence of reaction forces caused when moving the CMA [11].

From the above investigations in this area it was clear that only robust mechanical equipment for measuring and guiding of CMAs along any reference line adjustable in various spatial directions can offer a promising high-precision solution. To confirm this supposition, an existing high-precision length comparator was used [12]. Using this fixed high-precision length comparator in a climatic chamber, repeatability and accuracy measurements of the CMA were successfully carried out along some horizontal straight lines [13]. While a limited number of horizontal lines cannot give representative results for an assessment of a complete device, we decided to design and develop a new high-precision calibration apparatus for testing and calibrating CMAs, which can be adjusted in various spatial directions.

When starting to design the new calibration apparatus we set the limits of positional accuracy that the calibration apparatus should achieve. This limit was based on repeatability measurements made on an existing CMA. The experiment, which was made on a high-precision length comparator in the stable environment of a climatic chamber, showed that the repeatability in the most advantageous workspace amounts to r = 2.5 μm for a statistical probability of $\pm 2\sigma$ according to ISO 9283 [13]. Another important point was to establish all the possible sources of deviation. Consequently, many experiments and simulations were made to determine the deviations which are mainly associated with changes in the environmental conditions, with internal and external sources of forces and moments, and with geometrical deviations of individual elements [14].

The whole system consists of a line gauge beam with a support arrangement, a sled-bearing system, a drive system and a measuring system located separately from the line gauge beam. The main task of the line-gauge-beam system is to guide the sled exactly within the demanded limits with respect to deviations in orientation along a straight line. A hollow ceramic beam length of L = 2000 mm with surfaces manufactured to a tolerance of 1 μm/m was chosen. Simulations showed that the straightness deviation under its own weight and under external forces did not exceed a value of 1 μm or an angle of 0.5 arc seconds [15].

Since it should also be possible to measure in the vertical direction, a counterweight was added to the sled-bearing drive system. It was located and guided on separate shafts inside the ceramic beam and preko pogonskega sistema povezana s sanmi. Vodila protiuteži so nameščena povsem neodvisno od keramičnega nosilca in tako ne vplivajo na deformacijo keramičnega nosilca.

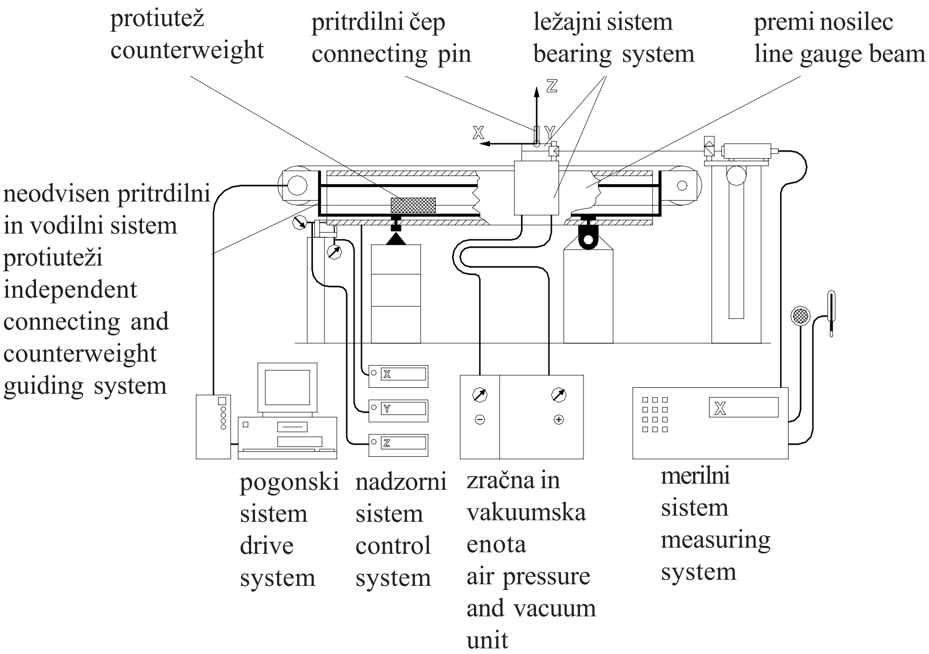
Vležajenje sani je izvedeno z zračnim ležajem tipa L z dodatnim vakuumskim delom, ki poveča togost ležaja, zaradi majhne in priročne konstrukcije je taka rešitev tudi primerna za povezavo s ČKMN. Izvedba konstrukcije tipa L omogoča pritrditev podpor nosilca v Bessel-ovih točkah in s tem možnost premikanja sani vzdolž celotne dolžine nosilca. Pri ČKMN s petimi osmi je za prosto premikanje vzdolž ravne črte v prostoru potrebnih šest prostostnih stopenj. Problem ene manjkajoče rotacije smo rešili z dodatnim rotacijskim vakuumsko prednapetim zračnim ležajem, na katerega je nameščen priključni čep za pritrditev ČKMN.

Merilni del sistema v grobem sestavljata laserski interferometer, ki je namenjen za merjenje položaja v smeri X in nadzorni sistem, ki ga sestavljajo merilniki pomikov premega nosilca v smereh Y in Z. Edina naloga tega sistema je zaznati premike, če se pojavijo, ki jih povzroča obremenjevanje kalibracijske priprave med samim merjenjem s strani ČKMN. Da se tem vplivom kar najbolje izognemo, smo pozicijski merilni sistem postavili na samostojen in neodvisen podstavek. Ker objekt, ki ga merimo, povzroča sile, te lahko deformirajo celoten nosilec in podporno konstrukcijo, je glavna prednost neodvisno postavljenega pozicijskega merilnega sistema, da deformacije ne vplivajo na rezultat pozicijske meritve. Celotna naprava je prikazana na sliki 1.

connected through a drive system with the sled. These separate shafts allow for the complete separation of the counterweight guide from the ceramic beam and thus avoid any deflection of the ceramic beam.

For the sled-bearing system we decided to use an L-type sled with a preloaded vacuum-air bearing, which is very rigid, small, light and convenient for connecting to CMAs. Due to its L-type construction it was possible to support the line gauge beam in the Bessel-points and in spite of the supports allow the sled-bearing system to make free movement along the whole beam length. For CMAs with five axes for free movement along any straight line in space with constant orientation, one degree of freedom is missing. To solve this problem we added an additional high-precision rotational preloaded vacuum-air bearing equipped with a connecting pin for connection with a CMA.

The measuring part of the system consists of a laser interferometer to measure longitudinal distance in the X direction and a control system, which contacts the line-gauge-beam surfaces in the Y and Z directions. The only task of this system is to measure displacements, if any occur, resulting from the loading of the high-precision calibration apparatus by the CMA. To achieve the best performance of the whole high-precision calibration apparatus we decided to locate the position measuring system separately from, and independently of, the line-gauge-beam system. Since the object to be measured causes forces which deflect the whole beam and the support-construction, the main advantage of a separately located position-measuring system is that deflections have no influence on the position-measuring results. The whole arrangement is presented in Fig. 1.



Sl. 1. *Celotna postavitev nove kalibracijske naprave, nastavljive v različnih prostorskih smereh*
Fig. 1. *Complete arrangement of the new calibration apparatus, oriented in various spatial directions*

Za določitev razširjene negotovosti meritve smo razvili poenostavljen vendar verodostojen teoretični model kalibracijske priprave za primer nadzorovanih pogojev okoliščin. V izračunih so negotovosti meritev razporejene v pozicijske in orientacijske. Najbolj neugodne rezultate preračuna smo dobili pri pozicijskem odstopanju v smeri *Y*. Kadar je merilni sistem nagnjen za okoli 50 stopinj, je podpora 2 zelo visoka. Teoretični odstopek v smeri *Y* lahko v ekstremnem primeru znaša na vrhu merilnega področja tudi Sb_{yex} = 0,024 mm. V takem primeru je neizogiben poseben dodaten merilni sistem, ki meri odstopanja v smereh *Y* in *Z*. V bolj ugodnih primerih pa teoretičen preračun na poenostavljenem vendar verodostojnem modelu da boljše rezultate razširjene negotovosti meritve. V smeri *X* znaša U_x = 0,00218 mm, v smeri *Y* U_y = 0,00271 mm in v smeri *Z* U_z = 0,00336 mm. Vrednosti pri orientacijskem delu pa so: U_{Rx} = 7,1 kotne sekunde za rotacijo okoli osi *X*, U_{Ry} = 1,2 kotne sekunde okoli osi *Y* in U_{Rz} = 0,9 kotne sekunde za rotacijo okoli osi *Z* [20].

Za potrditev teoretičnih postavk in preračunov modela in za določitev eksperimentalne negotovosti meritve zelo natančne kalibracijske naprave, so potrebne različne meritve [16]. Najboljšo oceno glede negotovosti lahko naredimo na podlagi meritev premosti vodenja sani kalibracijske naprave, obremenjene s ČKMN. Za merjenje premosti smo uporabili avtokolimator in elektronske libele. Dodatno smo z merilniki pomikov v nekaterih značilnih točkah nosilca merili tudi pozicijaska odstopanja v smereh *Y* in *Z*.

Meritve so bile izvedene v laboratorju v nadzorovanih razmerah. Pri tem sta bili kalibracijska priprava in ČKMN postavljeni na skupno granitno mizo. Tako so bile izpolnjene vse zahteve glede nespremenjene medsebojne lege in stabilnosti obeh sklopov naprav. Pri meritvi je bila ČKMN v smeri *X* postavljena na sredino glede na kalibracijsko napravo in 622 mm oddaljena v smeri *Y*. Med samo meritvijo sta bili obe napravi medsebojno povezani. S tem je bila zelo natančna kalibracijska naprava tudi dejansko obremenjena. Prva merilna lega je bila izbrana v sredini nosilca. Sani smo nato pomaknili vzdolž nosilca in izvedli meritev na vsakih 100 mm. Pomiki so bili narejeni najprej v negativno smer *X* in nato v pozitivno smer *X* od enega konca nosilca do drugega, meritev pa končali v prvotni začetni točki. Po več ko petih ponovitvah meritve vzdolž celotne dolžine nosilca, so bile kotne vrednosti merjene z avtokolimatorjem in z elektronskimi libelami v diferencialnem vklopu statistično obdelane in na sliki predstavljene kot odstopanja srednje vrednosti premosti. Merilni sestav za merjenje premosti in kotnih odstopanj, obremenjen s ČKMN, je prikazan na sliki 2.

We developed a theoretical model to determine the expanded uncertainty of the measurement for a simplified but corresponding model of the high-precision calibration apparatus under controlled environmental conditions. In the calculation the uncertainties of the measurement were divided into positional and orientational parts. The most unfavourable results of the calculation of the positional part were obtained in the *Y* direction. When the measuring equipment is extremely inclined and support number 2 must be very high, the calculated deviation in the *Y* direction can be about Sb_{yex} = 0.024 mm in the extreme case at the top of the measuring area. In such a case a separate measuring system to measure this deviation would be indispensable. However, in less unfavourable cases the theoretical calculations performed on the simplified but corresponding model gave results for the expanded uncertainty of measurement in the *X* direction U_x = 0.00218 mm, in the *Y* direction U_y = 0.00271 mm, in the *Z* direction U_z = 0.00336 mm; and for the orientational part U_{Rx} = 7.1 arc seconds around the *X* axis, U_{Ry} = 1.2 arc seconds around the *Y* axis, and U_{Rz} = 0.9 arc seconds around the *Z* axis [20].

To confirm these theoretical suppositions and calculations and to verify the actual uncertainty of the measurement of the high-precision calibration apparatus, we carried out various measurements [16]. The best survey of uncertainty characteristics can be made by straightness measurements of the preloaded vacuum-air-bearing system loaded with a CMA. The straightness was measured with an autocollimator and with electronic inclinometers. In some characteristic positions the displacements were measured with length indicators, which contact the line-gauge-beam surfaces in the *Y* and *Z* directions.

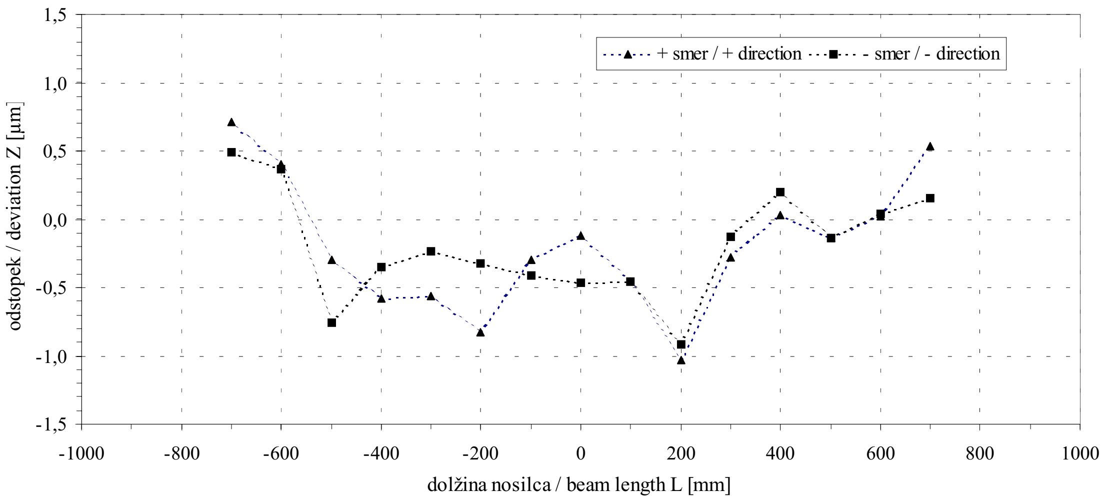
The measurements were carried out in a laboratory under constant environmental conditions where the high-precision calibration apparatus and the CMA were placed on the same granite table. In this way all the requirements for a constant and stable relationship between the two base coordinate systems were fulfilled. The CMA was put in the central area of the length measurement direction and 622 mm away from the beam centre line. During the measurement both devices were coupled together. In this case the CMA represented a load on the high-precision calibration apparatus. The first measuring position was chosen to be in the middle of the beam. The sled-bearing system loaded with the CMA moved along the beam and stopped every 100 mm. Movements occurred first in the negative *X* direction to one side of the beam then in the positive *X* direction on the other side and finally back to the previous initial position. After more than five repetitions of the same measuring procedure along the whole beam length, the angular changes measured with an autocollimator and with electronic inclinometers using differential switching were statistically processed and presented as mean values of the straightness deviations. The measuring set-up for straightness and angle deviation measurements when loaded with the CMA is presented in Fig. 2.

Sl. 2. *Ureditev merilnega mesta za merjenje odstopkov premosti in kotnih odstopanj, pri čemer so sani obremenjene s ČKMN*

Fig. 2. *Layout of the measuring set-up for straightness and angle deviation measurements when loaded with the CMA*

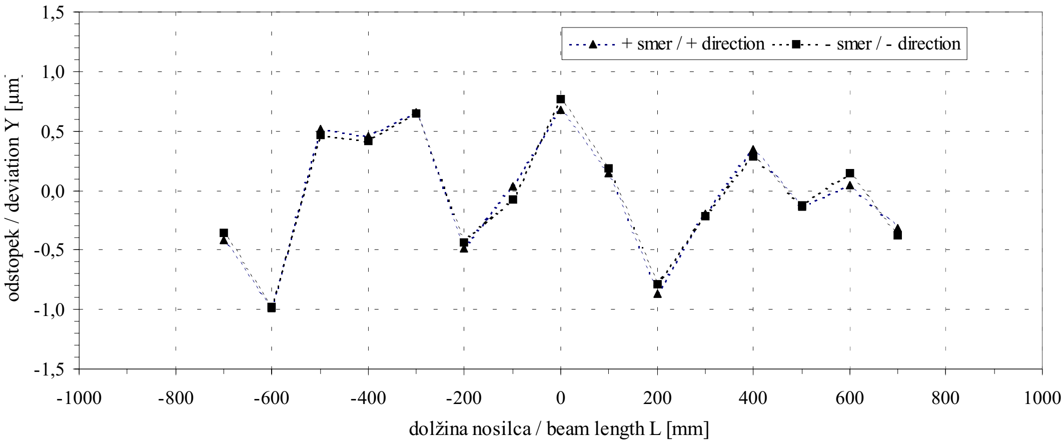
Rezultati odstopanj premosti kalibracijske naprave v smeri *Z*, ko je leta obremenjena s ČKMN, so prikazani na sliki 3. Standardni odklon rezultatov meritev z avtokolimatorjm v smeri Z v vseh pozicijah ne presega vrednosti za 2σ = 0,7 µm. Rezultati meritev v smeri *Y*, ki so prikazani na sliki 4, so zelo podobni. Standardni odklon 2σ za meritve v smeri *Y* ne presega vrednosti 0,6 µm. Rezultati srednjih vrednosti meritev kotnih odstopkov β vzdolž osi *X*, ki so bili merjeni z elektronskimi libelami v diferencalnem vklopu, so prikazani na sliki 5. Med meritvami smo preverjali tudi pomike nosilca na več ključnih mestih. Opazne so bile samo zelo majhne (v našem primeru zanemarljive) spremembe pozicije zaradi upogibanja nosilca pod bremenom sani. Drugih omembe vrednih pomikov v drugih smereh nismo zaznali.

The results for the straightness deviation of the high-precision calibration apparatus in the *Z* direction when connected to the CMA as an external load are presented in Fig. 3. The standard deviation of the results obtained by the autocollimator in the *Z* direction in all positions was not larger than 2σ = 0.7 µm. The situation for the results in the *Y* direction, presented in Fig. 4, was very similar. For the *Y* direction the standard deviation 2σ was not larger than 0.6 µm. The results for mean values of the angular deviations β, measured along the *X* axes with electronic inclinometers using differential switching, are presented in Fig. 5. During the measurement we checked the displacements of the beam gauge at several key locations. Only bending changes at the expected level (in our case negligible) were noted, and no large displacements in the other directions were observed.

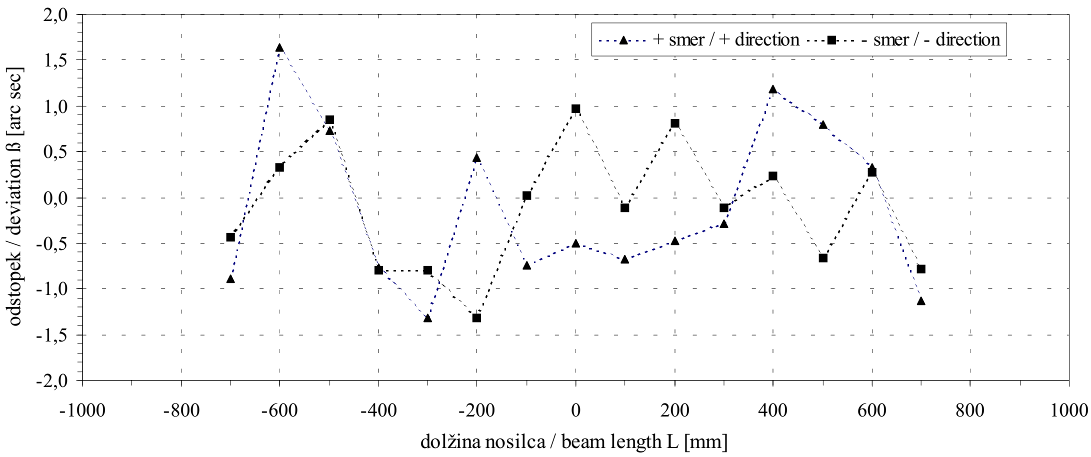


Sl. 3. *Rezultati meritev premosti v smeri Z*

Fig. 3. *Results of straightness measurements in the Z direction*



Sl. 4. *Rezultati meritev premosti v smeri Y*
Fig. 4. *Results of straightness measurements in the Y direction*



Sl. 5. *Rezultati meritev kotnih odstopanj okoli osi X*
Fig. 5. *Results of angular deviation measurements about the X axis*

Za konec smo celotno zelo natančno kalibracijsko napravo postavili na podpore in nagnili keramični nosilec za kot $\alpha = 50^{o}$. Ker smo v tej legi pričakovali opazne elastične deformacije zaradi obremenjevanja z zunanjimi silami in momenti naprave, ki jo merimo, smo pri preskusu posebno poudarili meritvi pomikov v smereh *Y* in *Z*. Preskus je pokazal, da čvrsta pritrditev podpor na betonsko podlago in toga pritrditev zamenljivih delov podpor sestavljajo razmeroma stabilno strukturo, tako da vrednosti pomikov nikjer ne presežejo meje 2 μm z upoštevanjem navedenih pogojev obremenjevanja.

Rezultati meritev zelo natančne kalibracijske naprave so pokazali, da so teoretični izračuni in pričakovanja pravilna in resnična. Tako lahko novo natančno kalibracijsko napravo predlagamo kot primeren referenčni merilni sistem za kalibracijska merjenja naprav s členkasto kinematično strukturo, kakor so na primer merilni roboti ali preostale ročne členkaste merilne naprave.

Finally, we put the whole high-precision calibration apparatus on supports and in a position inclined by $\alpha = 50$ degrees. Since, here, significant elastic deformations through changeable loading from the device to be measured can appear, we measured displacements caused through loading with the CMA, particularly in the *Y* and *Z* directions. Because of the solid fixing of the supports to the concrete base and the rigid connection of the exchangeable support parts, we were successful in keeping these values under the 2 μm level for the stated loading conditions.

The experiments on the real high-precision calibration apparatus showed that the theoretical expectations were successfully achieved. Thus the new high-precision calibration apparatus can be taken as an appropriate reference measuring system for calibration measurements of devices with unconventional kinematic structures, such as measuring robots, or in particular, manually driven CMAs.

2 KALIBRACIJSKE MERITVE

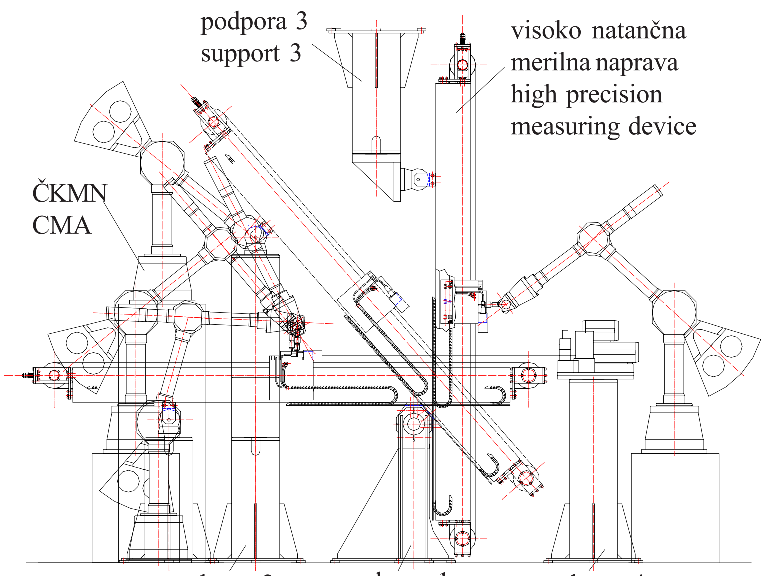
Za uspešno in kakovostno izvedbo kalibriranja z razvito kalibracijsko napravo in predlaganim postopkom potrebujemo določeno število kalibracijskih meritev. Te meritve naj bodo izvedene v več različnih pozah in izbrane tako, da merilna naprava CMA zavzame vedno različno konfiguracijo mehanizma. Med premikanjem v naslednjo pozo je priporočljivo, da se vrtijo vse osi členkov.

Pri kalibracijskih meritvah smo zelo natančno kalibracijsko napravo prek opisanih podpor pritrdili na betonsko podlago. ČKMN smo postavili na isto podlago in jo priključili prek priključnega čepa na kalibracijsko pripravo. Višino smo spreminjali tako, da smo ČKMN postavili neposredno na betonsko podlago ali pa jo položili na podstavek. Iz praktičnega gledišča jo je bolj primerno postaviti v različne lege ob kalibracijski pripravi, kakor pa nasprotno. Koordinate X in Y in vrtenje okoli osi Z tako preprosto spreminjamo s premikanjem oziroma vrtenjem baznega koordinatnega sistema ČKMN (s podstavkom ali brez njega) na betonski podlagi. Konstrukcija kalibracijske priprave omogoča le vrtenje nosilca okoli osi Y in s tem možnost nastavljanja kota nagiba. Določen nagib dosežemo tako, da na prvi podpori zasučemo os in s tem nagnemo celotni nosilec. Z vstavitvijo dodatnih zamenljivih delov na drugem podstavku pritrdimo nosilec v nasprotni podporni točki. V ekstremnem primeru je kalibracijska priprava postavljena tudi navpično (sl. 6).

2 CALIBRATION MEASUREMENT

For a successful and quality calibration with the proposed apparatus and procedure, a certain number of calibration measurements are needed. These measurements should be performed in many different poses and be chosen so that the CMA always takes a different mechanical configuration. During the movement to another measuring pose it is recommended that all joints rotate.

To take into account all the above demands, the high-precision calibration apparatus with robust supports was placed and fixed to a concrete base. The CMA was positioned on the same base and connected through a connecting pin to the high-precision calibration apparatus. The CMA was placed directly on the base or lifted to a support. From a practical point of view it is more convenient to place the CMA at different locations around the high-precision calibration apparatus than to make it possible for this robust measuring device to be adapted for any possible measuring arrangement. Therefore the X and Y coordinates and the rotation about the Z axes can be easily changed through the movement and rotation of the CMA base coordinate system with (or without) its support on the concrete base. On the other hand, the construction of the high-precision calibration apparatus allows adjustments of the measuring and guiding beam system in various spatial directions. A desired inclination can be reached by turning the whole line-gauge-beam system about the horizontal axes of the first support and by insertion of additional exchangeable support parts into the second support. In an extreme case the high-precision calibration apparatus can also be placed in the vertical position (Fig. 6).



Sl. 6. *Zelo natančna kalibracijska naprava in ČKMN v različnih konfiguracijah in različnih legah za opravljanje kalibracijskih meritev v različnih položajih*

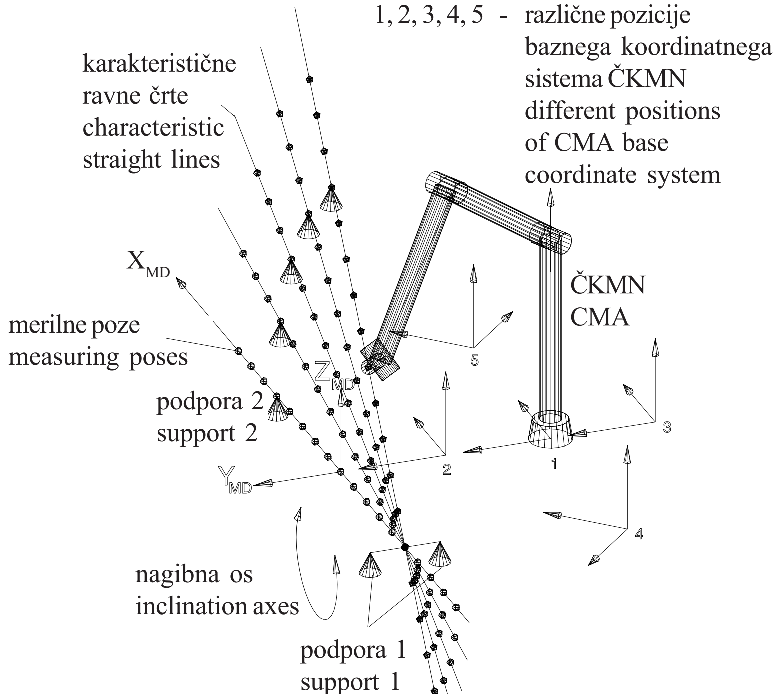
Fig. 6. *High-precision calibration apparatus and a CMA in different configurations and locations to carry out calibration measurements in different positions*

V primeru meritev v različnih vodoravnih legah, lahko višino ČKMN spreminjamo z vstavitvijo zamenljivih delov podstavka. V našem primeru smo jo postavili na granitno mizo ob kalibracijski napravi. Pomikanje ČKMN v naslednjo lego na granitni mizi in sprememba nagiba nosilca sta izvedeni ročno. Tako smo upoštevali razmerje med še razumno ceno in togostjo naprave.

Potek kalibracijskih meritev je prikazan na sliki 7. Pri tem smo izvajali meritve vzdolž različno nagnjenih ravnih črt, nastavljenih na kalibracijski napravi, spreminjali pa smo tudi lego in kot ČKMN glede na kalibracijsko napravo (sl. 7). Glede na opisan postopek smo zbirali podatke meritev razdalj, dobljenih z uporabo laserskega interferometra vzdolž nosilca v smeri *X* pri predpostavki, da se med meritvijo orientacija nosilca ne spreminja. Obenem smo zbirali tudi kotne vrednosti posameznih členkov ČKMN. Z namenom, da nadziramo morebitna odstopanja pravokotno na keramični nosilec v smereh *Y* in *Z*, smo pozicijska odstopanja merili z merilniki pomikov, ki so bili nameščeni na neodvisna stojala.

If measurements at different horizontal positions are needed the CMA support can be varied through exchangeable support parts or in our experimental case by placing the CMA on a stable granite table. Movement of the CMA to another location and readjustment of the inclination in our case was made manually, while a reasonable relationship between system robustness and the cost of the device was taken into account.

For the calibration measurements some characteristic straight lines that were adjusted in various spatial directions by different CMA base coordinate positions and rotations were chosen (Fig. 7). From these calibration measurements, laser interferometer distances along the line gauge beam at constant orientation carried out on the high-precision calibration apparatus and encoder angle values measured by the CMA were collected. In order to observe possible deviations orthogonal to the line gauge beam in the *Y* and *Z* directions, the displacement of the line gauge beam was measured with length indicators placed on separate stands.



Sl. 7. *Nekaj značilnih ravnih črt, nastavljenih v različnih prostorskih smereh pri različnih legah in usmeritvah ČKMN, ki jih uporabljamo pri kalibracijskih meritvah*

Fig. 7. *Some characteristic straight lines adjusted in various spatial directions by different CMA base coordinate positions and rotations used for calibration measurement*

3 RAZPOZNAVANJE PARAMETROV

Razpoznavanje parametrov je bilo izvedeno z uporabo kalibracijskega programa RoboCal, ki je bil razvit na Fraunhoferjevem inštitutu za proizvodne sisteme in konstrukcijsko tehnologijo (IPK) [17]. Ta

3 PARAMETER IDENTIFICATION

Parameter identification was carried out using the RoboCal calibration software that was developed by the Fraunhofer Institute Production Systems and Design Technology (IPK) [17]. This soft-programski paket omogoča razpoznavanje parametrov, ki pripadajo naslednjim podmodelom mehanizma: kinematični model, model pogona in model elastičnih deformacij [18]. Model pogona je sestavljen iz pogona posameznih členkov. RoboCal omogoča modeliranje sklenjenih kinematičnih verig znotraj posameznega pogona (ročični in drsni mehanizmi, paralelogrami), medtem ko je s programom mogoče modelirati celovite mehanske strukture z razklenjeno kinematično verigo, s pričetkom na podlagi in koncem na prirobnici (zaporedni mehanizem). Če to primerjavo razvijemo za naš primer, opazimo, da kalibracijska priprava in ČKMN v bistvu ustvarjata zaprto kinematično verigo (vzporedni mehanizem). Potemtakem ni mogoče izvesti razpoznave modela elastičnih deformacij, ker si preračun bremena zaradi obremenitve posameznih členkov zamišlja, da imamo opravka s prostim koncem kinematične verige.

3.1 Modeliranje

Preostala podmodela ČKMN sta kinematični model in model pogona. Kinematični model je popoln in primerljiv s kinematičnim modelom členkastega robota. Zatorej bomo oznako "zaporedno zapestje" uporabili za opis zadnjih dveh osi ČKMN in rotacijskega zračnega ležaja kalibracijske priprave. Oznaka "tarča" opisuje lokacijo, kamor je pritrjeno odbojno zrcalo laserskega interferometra. Model pogona opisuje razmerje med vrednostmi merilnega sistema v členku in relativnim kotom med posameznimi deli enega segmenta glede na drugega. Odnos je zapisan s stalnim prestavnim razmerjem, dodana pa je Fourierjeva aproksimacija, ki ponazarja morebitno odstopanje prestavnega razmerja. Zaradi zgornjih razlogov (preračun bremena si zamišlja prosti konec kinematične verige), se zračnost v zgibih ne razpozna. Izbira poz, v katerih naj bo opravljena meritev, prav tako pripada postopku modeliranja. Izbira vzorca poz predpisuje neko odvisnost, ki na ta način lahko pokrije podobno odvisnost zaradi parametra modela. Ta odvečnost povzroči defekt modelnega Jacobiana. Elementi te matrike so izpeljani iz položajev tarče glede na parametre modela. Najbolj primerno je, da odvečnost zaznamo in ji sledimo z uporabo razstavitve modelnega Jacobiana po singularnih vrednostih.

3.2 Funkcijska vrednost

V vsaki merjeni pozi i beremo vrednosti h iz merilnih sistemov posameznih členkov ČKMN in vrednosti iz meritve z laserskim interferometrom. S kalibracijo razpoznamo parametre modela p, ki minimizirajo vsoto vseh razdalj (Euklidove norme), ki jih dobimo kot razliko med položaji tarče M in pripadajočimi izračunanimi položaji T:

ware enables the identification of parameters that belong to the three submodels of the mechanism: the kinematic model, the actuator model and the model of elastic deformations [18]. The actuator model is composed of the actuators of the joints. RoboCal enables the modelling of closed kinematic chains within the individual actuators (crank-and-slider mechanism, parallelogram), whereas the kinematic model of the overall mechanism forms an open kinematic chain that starts at the base and ends at the flange (serial mechanism). Compared with this, the entity of the precision calibration apparatus and the CMA forms a closed kinematic chain (parallel mechanism). Consequently, there is no identification of the model of elastic deformations because the calculation of the load due to the dead weight of the links assumes that there is a free end to the kinematic chain.

3.1 Modelling

The two remaining submodels of the CMA are the kinematic model and the actuator model. The kinematic model is complete and comparable to the kinematic model of an articulated robot. Accordingly, the notion Ain-line wrist will be used to describe the entity of the last two axes of the CMA and the rotating vacuum-air bearing of the measurement device. The notation Atarget describes the location that the laser interferometer is aiming at. The actuator model describes the relation between the joint encoder reading and the angular position of the links relative to each other. The relation is described by the constant gear ratio plus a Fourier approximation describing the gear runout. For the above reasons (the calculation of load assumes a free end to the kinematic chain), there is no identification of the joint backlash. The selection of measurement poses belongs to the modelling, too. A pose pattern describes a dependency and thus may cover a similar dependency that is due to a model parameter. This redundancy causes rank deficiency of the model Jacobian. The elements of this matrix are the derivations of the target positions with respect to the model parameters. In a convenient way, redundancy can be detected and traced using the Singular Value Decomposition (SVD) of the model Jacobian.

3.2 Merit function

At each measurement pose i, the joint encoder values h of the CMA and the output of the laser interferometer are read. The calibration identifies the model parameters p that minimise the sum of all distances (i.e. Euclidean norms) that remain between each measured target position M and its corresponding computed position T:

$$\min_{p \in \Re^n} \left\{ \left\| M - T(p,h) \right\|^2 \right\}$$

3.3 Optimizacija modela

Metoda razstavitve po singularnih vrednostih (RSV) je bila uporabljena na modelnem Jacobianu ČKMN z uporabo različnih kompletov poz. Za razpoznavanje večine modelnih parametrov sta potrebni vsaj dve različni postavitvi kalibracijske naprave glede na merilno napravo CMA. Rezultati, ki so prikazani na naslednjih slikah, so dobljeni iz meritev v dveh različnih legah: pri prvi legi je kalibracijska naprava postavljena vodoravno, v drugi legi pa je kalibracijska priprava nagnjena za kot, ki znaša okoli 50° relativno glede na prvotno vodoravno lego. Parametri lahko postanejo medsebojno odvisni zaradi izbire mernih poz. Informacija meritve je tridimenzionalna. Poleg interferometrskih razdalj vzdolž osi merjenja lahko določimo tudi premike pravokotno na os merjenja. V primerjavi s pričakovano natančnostjo merilne naprave CMA so te vrednosti zanemarljivo majhne. Za izboljšanje natančnosti poze ta informacija zadostuje. V nasprotnem primeru obstaja možnost, da iz kalibracijske naprave razberemo petdimenzionalno merilno informacijo (zanemarimo vrednosti rotacije pravokotno na rotacijsko os vakuumsko prednapetega zračnega ležaja). Z uporabo tridimenzionalne informacije, se izkaže, da sta dva kinematična parametra v zaporedju od tretjega k četrtemu členku izrazito odvisna od preostalih kinematičnih parametrov in ju v razpoznavi ni. Če pogledamo še parametre pogona, vidimo, da majhen kot rotacije posameznih členkov pomikov povzroči koeficient sinusa pri Fourierjevi aproksimaciji, ki je odvisen od prestavnega razmerja.

3.3 Model optimization

SVD was applied to the model Jacobian of the CMA using different pose sets. At least two different configurations of the calibration apparatus with respect to the CMA are necessary in order to identify most of the model parameters. The results presented here are based on two configurations: in the first configuration, the calibration apparatus is oriented horizontally, and in the second configuration it is inclined by about 50 degrees relative to the previous position. Parameters may become dependent on each other due to the measurement set-up. The measurement information is three-dimensional. Not only is the displacement along the axis of the measurement device determined, the displacements orthogonal to this axis are also known to be negligible, compared to the expected pose accuracy of the CMA. For pose accuracy improvement, this information is sufficient. Otherwise, the calibration apparatus has the potential to serve for five-dimensional measurement information (negligible rotations orthogonal to the axis of the rotating vacuum-air bearing). With 3D information, two kinematic parameters in the sequence from the third to the fourth joint strongly depend on other kinematic parameters and thus are absent from a reliable identification. Concerning the actuator parameters, the small rate of joint movement makes the sine-coefficient of the Fourier approximation dependent on the gear ratio.

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     |                                                          25 %
     |                                                           |
 2.1-|
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3.29-|
     |000000000000000000000000X 10.3
3.52-|
     |00000000000000000000000000000000X 13.8
3.76-|
     |000000000000000000000000000000000000000000000000000000000X 24.1
   4-|
     |00000000000000000000000000000000X 13.8
4.23-|
```

Sl. 8. *Porazdelitev rezultatov pred kalibriranjem v vodoravni legi (srednja vrednost: 3,4mm, standardno odstopanje: 0,59mm, največja razlika: 4,0mm)*

Fig. 8. *Distribution of residuals prior to calibration in horizontal position (mean: 3.4mm, standard deviation: 0.59mm, maximum: 4.0mm)*

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  1.1-|
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      |0000000000000000X  6.9
 1.59-|
      |0000000000000000X  6.9
 1.75-|
      |0000000000000000000000000000000000000000X 17.2
 1.91-|
      |00000000000000000000000000000000X 13.8
 2.07-|
      |00000000000000000000000000000000X 13.8
 2.23-|
      |000000000000000000000000000000000000000000000000X 20.7
 2.39-|
```

Sl. 9. *Porazdelitev rezultatov pred kalibriranjem v nagnjeni legi (srednja vrednost: 1,8mm, standardno odstopanje: 0,40mm, največja razlika: 2,3mm)*

Fig. 9. *Distribution of residuals prior to calibration in inclined position (mean: 1.8mm, standard deviation: 0.40mm, maximum: 2.3mm)*

```
        |                                                         25 %
        |                                                          |
 0.0082-|
        |0000000000000000X  6.9
 0.0111-|
        |
  0.014-|
        |000000000000000000000000X 10.3
 0.0168-|
        |000000000000000000000000X 10.3
 0.0197-|
        |0000000000000000000000000000000000000000X 17.2
 0.0226-|
        |000000000000000000000000X 10.3
 0.0255-|
        |0000000000000000000000000000000000000000000000000000000000| 27.6
 0.0284-|
        |0000000X  3.4
 0.0313-|
        |0000000X  3.4
 0.0341-|
        |0000000X  3.4
  0.037-|
        |0000000000000000X  6.9
 0.0399-|
```

Sl. 10. *Porazdelitev rezultatov po kalibriranju v vodoravni legi (srednja vrednost: 0,024mm, standardno odstopanje: 0,0072mm, največja razlika: 0,040mm)*

Fig. 10. *Distribution of residuals after calibration in horizontal position (mean: 0.024mm, standard deviation: 0.0072mm, max: 0.040mm)*

```
         |                                                         25 %
         |                                                          |
 0.00923-|
         |0000000X  3.4
  0.0178-|
         |0000000X  3.4
  0.0264-|
         |00000000000000000000000000000000000000000000000000000000X 24.1
   0.035-|
         |0000000000000000000000000000000000000000X 17.2
  0.0436-|
         |00000000000000000000000000000000X 13.8
  0.0522-|
         |0000000000000000000000000000000000000000X 17.2
  0.0608-|
         |0000000000000000X  6.9
  0.0693-|
         |0000000X  3.4
  0.0779-|
         |
  0.0865-|
         |0000000000000000X  6.9
  0.0951-|
         |0000000X  3.4
   0.104-|
```

Sl. 11. *Porazdelitev rezultatov po kalibriranju v nagnjeni legi (srednja vrednost: 0,048mm, standardno odstopanje: 0,021mm, največja razlika: 0,10mm)*

Fig. 11. *Distribution of residuals after calibration in inclined position (mean: 0.048mm, standard deviation: 0.021mm, max: 0.10mm)*

3.4 Rezultati

Rezultati razpoznavanja kinematičnih parametrov so prikazani na slikah 8 do 11. Kakovost identifikacije parametrov razberemo iz statistične analize razlik, to je analize razlik med merjenimi in izračunanimi položaji tarče. To je postopek po IRIS-DIS 9283 [19]. S slik 8 in 9 sta razvidni porazdelitvi razlik pred kalibriranjem glede na lego kalibriranja. Tako slika 7 kaže rezultate merilne naprave v vodoravni legi in slika 9 pri nagibu 50°. V vodoravni legi znaša največja razlika okoli 4 mm in je skoraj dvakrat večja kakor v nagnjeni legi. Porazdelitev razlik po kalibriranju prikazujeta sliki 10 in 11. V vodoravni legi znaša največja razlika okoli 0,04 mm. S tem je izboljšava s kalibriranjem za faktor 100 očitna. V nagnjeni legi je uspešnost kalibriranja prav tako očitna, vendar le za faktor 20. Povsem jasno je, da je obremenitev segmentov v obeh primerih povsem različna. Iz tega lahko sklepamo, da je vzrok razlike v faktorjih posledica elastičnih deformacij.

4 PREVERJANJE

Z namenom, da potrdimo pravilnost rezultatov razpoznavanja kinematičnih parametrov, smo izvedli eksperimentalno preveritev na prototipu ročno vodene členkaste koordinatne merilne naprave z rotacijskimi osmi. V ta namen smo parametre razpoznavne na podlagi postopka kalibriranja vnesli v kinematični model prototipa ČKMN. Nato smo merilno napravo ponovno priključili na kalibracijsko napravo. Tokrat smo kalibracijsko napravo uporabili kot referenčni merilni sistem, s katerim smo testirali absolutno natančnost ČKMN na temelju meritev premosti v različnih legah in v različnih smereh v prostoru. Merilni postopek je bil zelo podoben postopku pri kalibracijskih meritvah. Meritve so bile izvedene pri štirih različnih nagibih. Pri vsakem nagibu je bila ČKMN postavljena različno glede na referenčni merilni sistem. S tem smo povečali število različnih poz merjenja. Poze so bile izbrane v drugih položajih kakor pri kalibracijskih meritvah. S tem smo zagotovili resničnost postopka preverjanja. Rezultati meritve preverjanja so prikazani na sliki 12. Oznake H, IN15, IN30 in IN50 pomenijo, da je bila naprava postavljena v vodoravno lego (H), nagnjeno za 15° (IN15), 35° (IN35) oziroma za 50° (IN50). V vsaki legi smo spreminjali položaj merilne naprave CMA relativno glede na referenčni merilni sistem. Lege označene s P1, P2, P3,P4 in P5, ki smo jih dodali oznakam H, IN15, IN30 in IN50 pomenijo, da je bil bazni koordinatni sistem ČKMN v P1 oddaljen za okoli 500 mm od merilne točke na referenčnem merilnem sistemu. Oznaka P3 pomeni isto pozicijo

3.4 Results

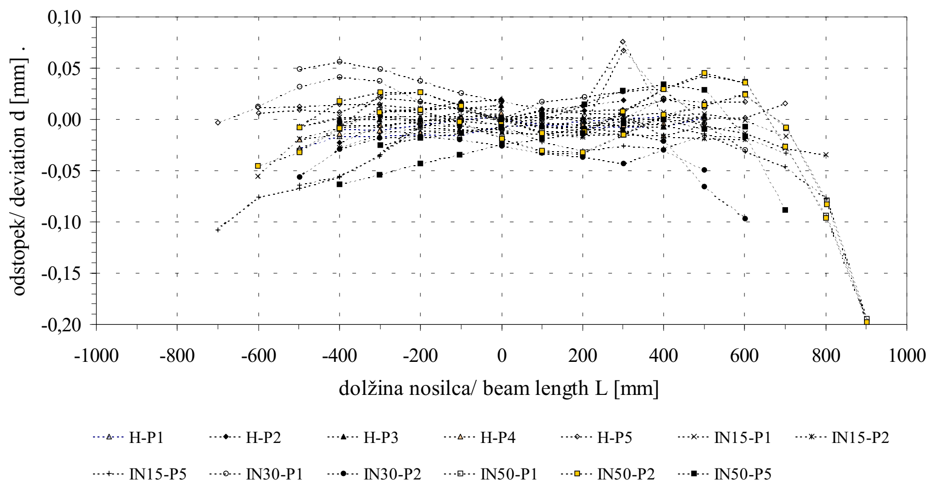
The results for the identification of the kinematic parameters are shown above. The quality of the parameter identification can be seen from the statistical analysis of the residuals, i.e. the analysis of the remaining differences between the measured and the calculated target positions. This is the procedure according to IRIS-DIS 9283 [19]. For both configurations, Figures 8 and 9 show the distribution of the residuals prior to calibration. Fig. 8 corresponds to the horizontal orientation of the measurement device and Fig. 9 to an inclination of about 50 degrees. In the former case, the maximum residuals are about 4mm and thus almost twice as large as in the latter one. The distribution of the residuals after calibration is shown in Figures 10 and 11. In the horizontal case, the maximum residuals are about 0.04mm. Thus calibration has improved this value by a factor of 100! In the inclined case, calibration decreases the maximum residuals by only a factor of 20. Obviously, the load distribution is different in the two cases, so elastic behaviour may be responsible for this observation.

4 VERIFICATION

To confirm the results of the identification of kinematic parameters we carried out experimental verification on a prototype of a manually driven coordinate measuring arm with exclusively rotational axes e.g. a CMA. For this purpose we put the parameters identified from the calibration procedure into the kinematic model of the existing prototype CMA and connected it to the high-precision calibration apparatus. In this case the high-precision calibration apparatus was used as a reference measuring system to check the absolute accuracy of the CMA on the basis of straightness measurements oriented in various spatial directions. The measuring procedure was very similar to the procedure in the calibration measurement. The measurements were made in four different inclinations. In each inclination the CMA was placed differently in relation to the reference measuring system to expand the variability of poses. The measuring poses were chosen a little bit differently from the calibration poses to ensure a credible verification procedure over the desired measuring area of the CMA. The results of this verification measurement are presented in Fig. 12. Notations: H, IN15, IN30 and IN50 mean that the reference measuring system was placed into the horizontal level (H), and then inclined for about 15 degrees (IN15), 35 degrees (IN35) and finally by 50 degrees (IN50). At each level we changed the position of the CMA relative to the reference measuring system. Positions marked by P1, P2, P3, P4 and P5, which were added to the previous denotations H, IN15, IN30 and IN50, mean that the base coordinate system of the CMA was initially positioned about 500 mm from the measuring point on the reference measuring system

ČKMN, le da je bila prva os zasukana za okoli 45° in oznaka P4 pozicijo, zasukano okoli prve osi za 45° relativno glede na referenčni merilni sistem. Oznaki P2 in P5 pomenita meritve v legi, ki je bila oddaljena 730 mm oziroma 400 mm od merilne točke na referenčnem merilnem sistemu. Te oznake veljajo pri vseh nagibih. Rezultati meritev, izvedenih na prototipu ČKMN, ki jih prikazuje slika 12, zajemajo rezultate, ki upoštevajo samo izboljšavo na podlagi kinematičnih parametrov.

(P1). Notation P3 represents the same position of the CMA where the first axis was turned by about +45 degrees and P4 the position turned by about 45 degrees relative to the reference measuring system. The notations P2 and P5 represent measurements in positions which were first 730 mm and secondly 400 mm away from the measuring point on the reference measuring system. The notation is valid for all measuring inclinations. Additionally, we should mention that the result of experiments carried out on a prototype of the CMA presented in Fig. 12 includes only kinematic parameters.



Sl. 12. *Rezultati natančnosti razdalje, ki so bili izvedeni na prototipu ČKMN, kalibrirane s programskim paketom RoboCal in merjenem na zelo natančni kalibracijski pripravi, ki je bila uporabljena tudi kot referenčni merilni sistem za testiranje absolutne natančnosti ČKMN na podlagi meritev natančnosti razdalje.*

Fig. 12. *Results for distance accuracy carried out on a prototype of the CMA calibrated with RoboCal software and measured on a high-precision calibration apparatus which was also used as a reference measuring system to check the absolute accuracy of the CMA on the basis of distance accuracy measurements.*

Pri ekstremno stegnjeni konfiguraciji mehanizma so razvidna odstopanja v navpični smeri (sl. 12). Ta odstopanja se ujemajo s teoretično predpostavko o vplivu elastičnih deformacij. Enako opažanje je razvidno pri meritvi, označeni s H-P5 pri +300 mm. V tej legi sta bili zadnji osi orientacijskega dela ČKMN v singularnem položaju. Odstopanja v tej poziciji so povezana z notranjimi silami in momenti, povezanimi s singularnim položajem in imajo za posledico elastično deformiranje konstrukcije.

From Fig. 12, in the extremely stretched arm configuration, noticeable deviations in the vertical direction were apparent, which confirm the theoretical supposition of the influence of elastic behavior. The same observation was also evident in the measurement marked with H-P5 at +300 mm. In this position the last two axes of the orientational part of the CMA were found to be in a singularity, where deviations in position as a consequence of elastic structural deformations caused by internal forces and moments occurred.

5 SKLEP

Rezultati kalibriranja in njihovo preverjanje so pokazali, da z razvito kalibracijsko pripravo in s predlaganim postopkom lahko izvedemo zelo natančno kalibriranje členkastih koordinatnih merilnih naprav na podlagi meritev vzdolž ravne črte, nastavljive v različnih

5 CONCLUSION

The calibration results and their verification show that the developed apparatus and proposed procedure can perform the calibration of CMAs with high precision on the basis of measurements along straight lines adjusted in prostorskih smereh. Izvedeno kalibriranje je izboljšalo natančnost poze ČKMN za faktor 100 (vodoravna postavitev) oziroma za faktor 20 (nagnjena postavitev). Na ta način je pokazano, da je mogoče absolutno natančnost členkastih koordinatnih merilnih naprav, namenjenih za geometrijska merjenja, uspešno izboljšati. Nadaljnje raziskave bodo najverjetneje ostredotočene na preučevanje elastičnih vplivov. Pri tem bomo iskali vzroke različnega obnašanja mehanizma pri vodoravnih in nagnjenih položajih. Prav tako je tudi vredno omeniti, da ni omejitev za uporabo kalibracijske priprave in postopka tudi za kalibriranje merilnih robotov z rotacijskimi osmi.

various spatial directions. The calibration performed improved the pose accuracy of the CMA by factors of 100 (horizontal position) or 20 (inclined position). In this way the absolute accuracy of CMAs intended for geometrical measurements can be successfully increased. In order to find the reason for the different behaviour in horizontal and inclined positions, further studies should concentrate on the elastic behaviour of the CMA. It is also worth mentioning that there are no limitations to the use of the apparatus and procedure for the calibration of measuring robots with rotational axes.

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Raziskave difuzije skozi stik PVD prekrito orodje iz kermeta/obdelovanec

An Investigation of the Diffusion Across a PVD-Coated Cerment Tool/Workpiece Interface

Mirko Soković - Ladislav Kosec - Leszek A. Dobrzański

Upoštevajoč omejitve pri izboljšanju mehanskih lastnosti rezalnih orodij, obstajajo nadaljnje možnosti za izboljšanje učinkovitosti orodja le na podlagi zmanjšanja termokemijske obrabe, ki je posledica poteka difuzije. To je mogoče doseči z izbiro ustrezne kombinacije med osnovnim materialom orodja in prevleko PVD (fizikalno nanašanje v vakuumu), ki kar se da upočasni potek difuzijske obrabe, ali vsaj ne poslabša mehanskih lastnosti podlage – osnovnega materiala orodja.

V tem prispevku je raziskovana difuzija skozi stik PVD prekrito orodje iz cermeta na obdelovanec. Za študij termo-kemijske obrabe cermetov na temelju Ti(C,N), prekritih s prevleko TiN (PVD) ali TiZrN (PVD) kot difuzijsko pregrado, je uporabljena metoda difuzijskih členov.

(Ključne besede: prevleke PVD, cermeti, procesi difuzijski, procesi termokemični, obraba)

Taking into account the limitations that exist when it comes to improving the mechanical properties of cutting tools, further possibilities to improve tool performance might be found in reducing the thermochemical wear, which is a result of a diffusion process. This reduction is possible if we choose a favorable combination of substrate and PVD (Physical Vapour Deposition) coating in which the process of diffusion wear is slowed down as much as possible or is not detrimental to the mechanical properties of the substrate, which is the basic material of the tool.

In this work the diffusion across a coated cermet tool/workpiece interface was studied. Recently, the diffusion-couple method was used to study the thermochemical wear of Ti(C,N)-based cermets coated with TiN (PVD) and TiZrN (PVD) coatings as a diffusion barrier.

(Keywords: PVD coatings, cermets, diffusion processes, thermochemical processes, wear)

0 UVOD

Nove usmeritve pri razvoju karbidnih trdin vključujejo tudi kermete kot rezalne materiale, ki so bili predmet številnih razprav v preteklih letih, tako v objavah kakor tudi na konferencah ([1] do [4]). Kljub veliki odpornosti kermetov proti obrabi in majhni nagnjenosti k adheziji, prevleke prav tako poudarijo prednosti teh rezalnih materialov.

Večina objav na področju obrabe kermetov ([5] do [8]) se ukvarja s termomehansko obrabo medtem ko so termokemijski procesi na dotiku med orodjem in obdelovancem manj temeljito raziskani. Še posebej primanjkuje podatkov o mehanizmih obrabe prekritih orodij iz kermeta.

V vsakem tribološkem dotiku pri odrezovanju materialov pomeni prevleka na orodju zaščitno plast proti zelo visokim temperaturam in dotikalnim pritiskom. Temperature rezanja nad 650 °C so značilne

0 INTRODUCTION

New trends in hard-metal development include the use of cermets as cutting materials. These materials have been the subject of many discussions in recent years, in publications and at conferences ([1] to [4]). Despite the high wear resistance of cermets and their low adhesive tendency, coatings can offer certain advantages to these cutting materials.

The majority of the publications in the field of cermet wear ([5] to [8]) deal with thermomechanical wear, while the thermochemical processes at the contact between the tool and the workpiece have been less thoroughly researched. In particualr, there is not enough data about the wear mechanisms of coated cermet tools.

In every tribocontact in the cutting of materials the coating on the tool is a protective layer against the very high temperatures and contact pressures. Machining with HSS tools at temperatures above pri obdelavi z orodji iz HSS, medtem ko so temperature nad 1000 ^{o}C značilne za obdelavo pri velikih hitrostih in obdelavo v trdo jekel in zlitin z orodji iz karbidnih trdin ali kermetov, prekritih s prevlekami CVD oz. PVD. Pri teh visokih dotikalnih temperaturah difuzijo atomov materiala orodja v odrezek spremlja občuten padec mikrotrdote, korozijske odpornosti, odpornosti proti obrabi ter trdnosti orodja.

Obsežni testi so bili opravljeni z namenom, da bi določili zmožnosti in omejitve pri uporabi kermetov kot rezalnih materialov ([9] in [10]). Rezultat procesa difuzije elementov orodja in obdelovanca skozi vmesnik je sprememba sestave mejne plasti orodja, ki povečuje možnost mehanske poškodbe rezalnega robu. V primeru odrezovanja s prekritim orodjem opazimo ta pojav po daljšem času uporabe v primerjavi z neprekritim orodjem.

650^{o}C is not possible, and temperatures above 1000^{o}C are common in the high-speed and heavy-duty machining of steels and alloys with CVD-or PVD-coated carbides or cermets. At these high contact temperatures the chemical dissolution of the tool material into the chip on an atomic scale is accompanied by a rapid decrease in the microhardness, corrosion resistance, wear resistance and the strength of the tool.

Extensive tests were carried out in order to determine the performance capabilities and operating limits of cermet cutting materials ([9] and [10]). The result of the diffusion of an element from the tool and the workpiece through the interface is a change in the composition of the boundary layers of the tool, which increases the possibility of mechanical damage to the cutting edge. In the case of cutting with coated tools these phenomena occur after a longer time of service in comparison to uncoated ones.

1 EKSPERIMENTALNO DELO

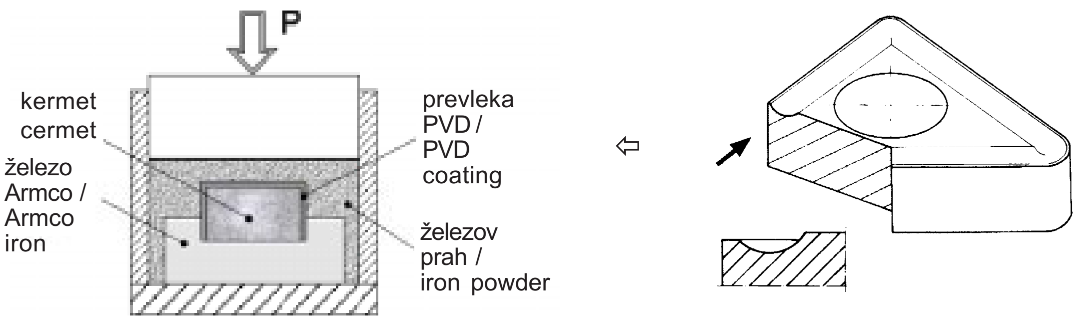
1.1 Priprava difuzijskih členov

Vzorci za analizo pojavov na dotiku orodje/obdelovanec so bili sestavljeni iz dela rezalne ploščice iz kermeta, prekrite s prevleko PVD (debeline 3 µm), ploščice iz železa Armco in tehnično čistega prahu železa (sl. 1) [10].

1 EXPERIMENTAL WORK

1.1 Preparation of Diffusion Couples

The samples for the analysis of the phenomena in the tool/workpiece contact were taken from a part of a PVD-coated cermet cutting insert (the thickness of the coating was 3 µm), an Armco-iron insert and technically pure iron powder, Figure 1 [10].



Sl. 1. *Struktura difuzijskega člena*
Fig. 1. *Composition of the diffusion couple*

Dufuzijski členi so bili narejeni tako, da so v neposrednem dotiku, povzročenem s silo, trdna ploščica iz železa Armco ali železov prah s kermetom, prekritim s TiN (PVD) ali prevleko TiZrN (PVD) oz. z neprekritim kermetom.

Razlog za takšno obliko sklapljanja vzorcev je bil v tem, da so deli kermeta, izrezani iz realnih ploščic, zaradi svoje oblike na cepilni ploskvi neprimerni za pripravo standardnih difuzijskih parov. Kljub temu je bil v tem primeru tesen dotik med vsemi elementi difuzijskega člena (premera 15 mm) dosežen z uporabo pritisne sile 250 kN. Zaradi te obremenitve se je del ploščice iz kermeta zaril v zelo mehko ploščico iz železa Armco, medtem ko se je železov prah tesno oprijel

Diffusion couples were made by bringing into contact a solid plate of Armco iron or iron powder and the use of force to make an intimate and strong contact between the partners with TiN (PVD)-coated cermet, TiZrN (PVD)-coated cermet, and uncoated cermet.

The reason for this kind of coupling of the samples was in that some parts from the cermet, cut out from real insert shapes, were unsuitable for the preparation of normal diffusion couples. Nevertheless, in this way a tight contact between all the elements was obtained since in the making of the diffusion couples (diameter 15 mm) a pressure of 250 kN was applied. Under this load a part of the cermet was pressed into the very soft Armco-iron insert while the iron powder was tightly compacted. This made profilirane površine kermeta, kakor se zahteva za difuzijske teste. Višina stisnjenih vzorcev je bila v mejah od 10 do 12 mm.

1.2 Opis pojavov

Po končani pripravi difuzijskih členov je bil opravljen postopek difuzijskega žarjenja v cevni peči, v atmosferi H_2, pri temperaturi 1000 ± 3 ^oC. To je privedlo do sintranja poprej stisnjenega železovega prahu. Čas žarjenja je bil 1 ura za polovico vzorcev. Da bi ugotovili učinek časa segrevanja na debelino reakcijske plasti, je bil čas žarjenja v cevni peči za drugo polovico vzorcev podaljšan na 24 ur.

Železov prah vsebuje kisik v obliki oksidov na površini prahastih delcev. V danih razmerah (1000 ^oC, H_2) se železov oksid razgradi in nastane vodna para. Železov oksid oz. vodna para sta bila glavna (edina) vira kisika, potrebnega za oksidacijo prevlek TiN (PVD) in TiZrN (PVD) oz. kermetov v raziskovanih difuzijskih členih. Izmed vseh elementov, vsebovanih v "difuzijskem paru" kermet/železo: Ti, W, Mo, Ni, Co in Fe ima titan največjo privlačnost do kisika, s katerim tvori vrsto različnih oksidov (TiO, Ti_2O_3, Ti_3O_5, Ti_4O_7 in TiO_2). Prosta energija nastanka titanovega ali cirkonijevega nitrida je veliko bolj negativna kakor proste energije nastanka vseh preostalih spojin (npr. WC, MoC, TiC, TiN or ZrN) [11]. Zaradi tega v navzočnosti kisika te spojine oksidirajo, še posebej Ti (pa tudi Zr). Med naštetimi elementi ima najmanjšo privlačnost do kisika Ni. Zaradi tega je kermet material, v katerem se pojavlja t.i. selektivna oksidacija.

Med omenjenimi oksidi titana sodi TiO_2 v skupino n-polprevodnikov (s presežkom kovinskih ionov), medtem ko sta TiO in Ti_2O_3 amfoterna prevodnika (kovinska prevodnika). TiO_2 raztaplja WO_3 tako kakor NiO in kakor kažejo meritve, izmed preostalih elementov tudi železove okside. Ko je nastala plast titanovega oksida se proces oksidacije upočasni, stopnja oksidacije se sedaj vodi s stopnjo difuzije elementov skozi titanov oksid. Ker je koncentracija titana v plasti TiN in/ali v kermetu veliko večja od koncentracije preostalih elementov ter je njegova privlačnost do kisika znatno večja v primerjavi s preostalimi (z izjemo Zr), v glavnem oksidira titan. Nikel, kot veliko bolj plemenita kovina v tej kombinaciji, se nabira in bogati na strani kermeta, kar se izkaže v povečanju koncentracije niklja in opazi kot "svetla" (bela) ali plast "C" – mejna plast "prizadetega" rezalnega materiala (sl. 2).

2 ANALIZA DIFUZIJSKEGA ČLENA

Kakor je razvidno s slik 2 (a) in (b) pri danih pogojih se je oblikovala široko vplivana difuzijska

the contact with the profiled cermet surface very tight, as required for the diffusion tests. The height of the pressed pieces was between 10 and 12 mm.

1.2 Description of the phenomena

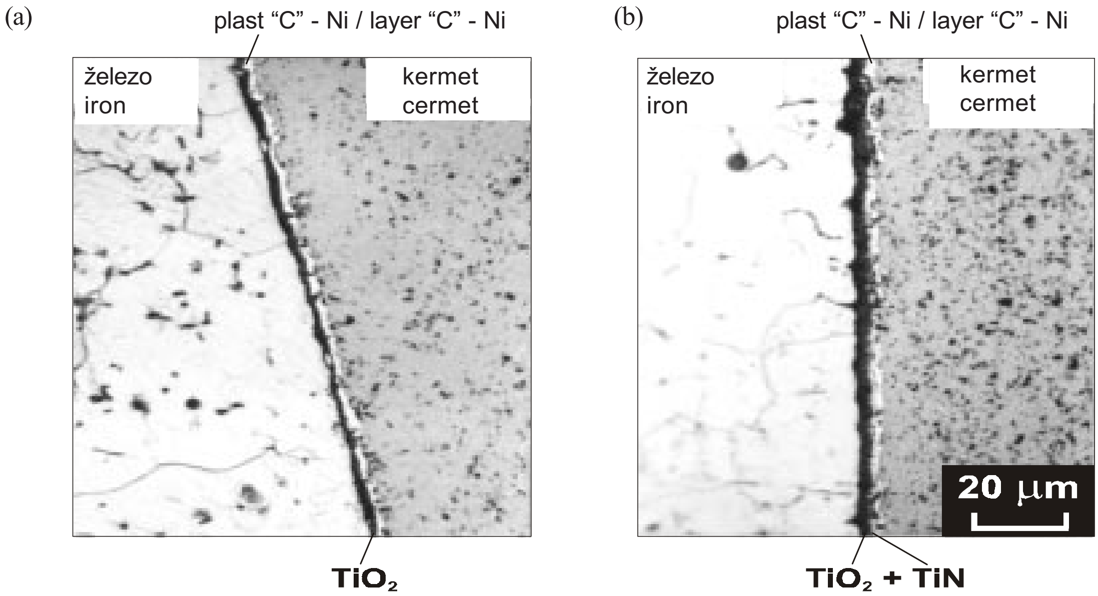
After preparing the diffusion couples the process of diffusion annealing was carried out in a tube furnace in a H_2 atmosphere at a temperature of 1000 ± 3 ^oC. This led to sintering of the previously compacted iron powder. The annealing time was 1 hour for half of samples. In order to establish the effects of heating time on the width of the reaction layer, for other samples the time of their heating in the tube furnace was prolonged to 24 hours.

Iron powder contains oxygen in the form of oxides on the surface of the powder particles. Under certain conditions (1000 ^oC, H_2) the iron oxides reduce and water vapor is formed. Iron oxides or water vapor were the main source of oxygen for the oxidation of TiN (PVD) and TiZrN (PVD) coatings or the cermets in the studied diffusion couples. Among all the elements contained in the cermet/iron diffusion couple Ti, W, Mo, Ni, Co and Fe — it is the titanium that has the highest affinity for oxygen, forming a series of different oxides — TiO, Ti_2O_3, Ti_3O_5, Ti_4O_7 and TiO_2. The free energy of formation of titanium and zirconium oxides is much more negative than the free energy of formation of all the compounds present in the diffusion couples, for example WC, MoC, TiC, TiN or ZrN [11]. Therefore, in the presence of oxygen these compounds oxidize, especially the Ti and the Zr. Among the elements present the lowest affinity to oxygen is found with the nickel. Thus, cermet is a material in which so-called selective oxidation takes place.

TiO_2 belongs to the group of n-type semiconductors (with a surplus of metallic ions) whereas TiO and Ti_2O_3 are amphoteric conductors (metallic conductors). TiO_2 dissolves WO_3 as well as NiO and, as measurements show, from among the other elements, also iron oxides. Once a layer of titanium oxide has been formed, the process of oxidation slows down as the rate of oxidation is now controlled by the rate of diffusion of elements through the titanium oxide. Since the concentration of titanium in the TiN and/or cermet layer is much higher than the concentration of the other elements and its affinity to oxygen is considerably higher than the affinity of the others (except Zr), it is mainly the titanium that oxidizes. Nickel, as a much more precious metal in this combination, accumulates and gets richer on the cermet side, which can be seen in the increase of nickel concentration and the occurrence of "bright" (white) or layer "C" – boundary layer of the "affected" tool material, Figure 2.

2 ANALYSIS OF THE DIFFUSION COUPLE

As is evident from Figure 2 (a) and (b), under the given conditions a wide diffusion-affected zone



Sl. 2. *Optični posnetek prereza difuzijskih členov: (a) neprekrit cermet/železo Armco (temna plast - titanov oksid, svetla plast - nikelj) in (b) cermet, prekrit s prevleko JOSTiN[R]/železo Armco (temna plast - titanov oksid + TiN, svetla plast - nikelj).*

Fig. 2. *Optical micrograph of the diffusion couples of: (a) uncoated cermet/Armco iron (dark layer - titanium oxide, bright layer - nickel) and (b) JOSTiN[R] coated cermet/Armco iron (dark layer - titanium oxide + TiN, bright layer - nickel).*

cona v kermetu, na dotiku med neprekritim ali prekritim kermetom/železom. Z EMPA (elektronska analiza na mikro vzorcih) črtno analizo je bilo ugotovljeno, da je zaradi difuzije Ti nastala mejna plast bogata predvsem z Ni.

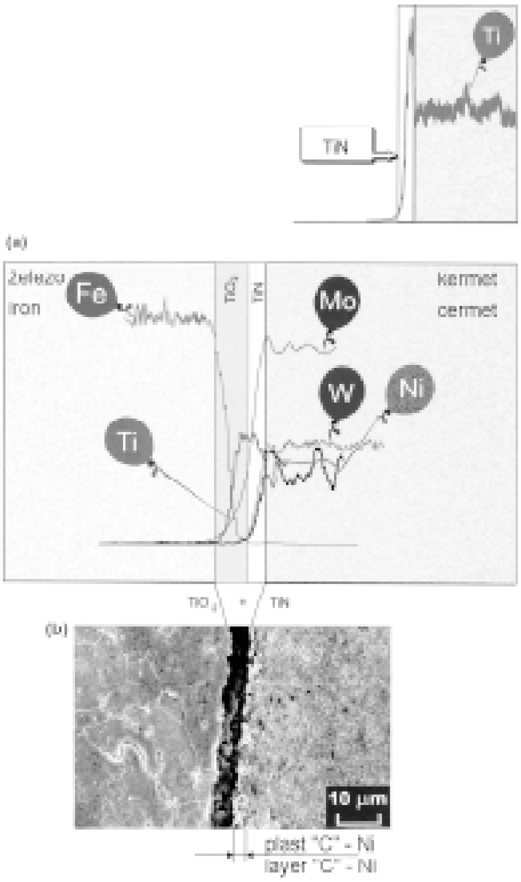
Najprej je bila narejena analiza difuzijskega člena, sestavljenega iz železa Armco in prekritega kermeta s prevleko TiN (PVD). Slika 3 prikazuje SEM (vrstična elektronska mikroskopija) mikroposnetek prečnega prereza difuzijskega člena in ustrezne rezultate polkvantitativne analize EMPA. Po enournem žarjenju na 1000 °C plast TiN oksidira in nastane oksid, najverjetneje TiO_2, medtem se en del oksida nastane tudi na račun oksidacije titana iz kermeta. Zaradi oksidacije titana se kemijska sestava kermeta vzdolž meje s titanovim oksidom spremeni. Prav za titanovim oksidom je bilo opaženo močno zmanjšanje koncentracije titana v kermetu, kar kaže na to, da je bil titan porabljen v oksidacijskem postopku in pri rasti oksidacijskega pasu. Profil koncentracije opozarja na določeno stopnjo spojitve nekaterih drugih elementov v titanovem oksidu, še posebej volframa in molibdena. Hkrati se je zgodila delna prerazporeditev niklja v tem delu kermeta.

V difuzijskem členu, ki je sestavljen iz železa Armco in prekritega kermeta s prevleko TiZrN (PVD), po enournem žarjenju na 1000 °C plast PVD popolnoma oksidira. Slika 4 kaže mikroposnetek SEM prečnega prereza skozi omenjeni difuzijski člen ter rezultate polkvantitativne analize EMPA. Vzdolž oksida ima kermet podobno mikrostrukturo kakor v prejšnjem primeru (sl. 3). Povečan je znesek faze,

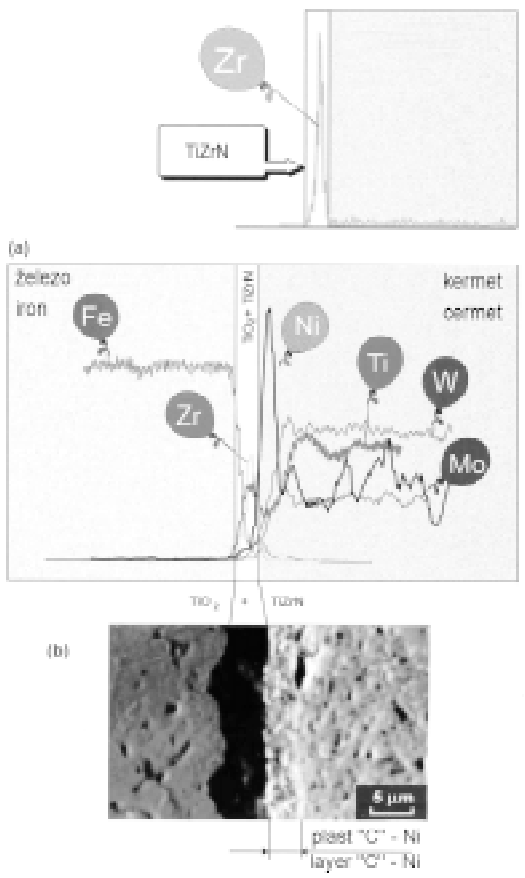
was created in the cermet in the contact between the uncoated or coated cermet/iron. With the EMPA (Electronic Micro Probe Analysis) line analysis it was found that due to diffusion of Ti the created boundary layer is rich in Ni.

First, a thorough analysis of the diffusion couple consisting of Armco iron and TiN (PVD)-coated cermet was made. Figure 3 shows a SEM (Scanning Electron Microscopy) micrograph of the cross-section through the diffusion couple and the corresponding results of the semi-quantitative EMPA analysis. After a one-hour annealing at 1000 °C the TiN layer oxidized to form an oxide, most probably TiO_2, while one part of the oxide was formed as a result of the oxidation of titanium from the cermet. Due to the oxidation of titanium the chemical composition of the cermet along the boundary with the titanium oxide changes. Immediately behind the titanium oxide a very much reduced concentration of titanium in the cermet occured, which shows that the titanium was consumed in the oxidation process and the growth of the oxidation belt. The concentration profiles point to a certain degree of fusibility of some of the other elements in the titanium oxide, especially tungsten and molybdenum. At the same time a partial redistribution of the nickel takes place in this part of the cermet.

In the diffusion couple, consisting of Armco iron and TiZrN (PVD)-coated cermet, after a one-hour annealing at 1000°C the PVD layer totally oxidized. Figure 4 shows an SEM micrograph of the cross-section through the mentioned diffusion couple and the results of the semi-quantitative EMPA analysis. Along the oxide the cermet has a similar microstructure as in the previous case (Fig. 3), however, there is an increase in



Sl. 3. *Polkvantitativne analiza EMPA difuzijskega člena kermet, prekrit s TiN/železom Armco (a) in ustrezen posnetek SEM (b); ($t_ž$ = 1^h, 1000 °C).*
Fig. 3. *Semi-quantitative EMPA analysis of the TiN-coated cermet/Armco iron diffusion couple (a) and corresponding SEM micrograph (b); (t_{an} = 1^h, 1000 °C).*



Sl. 4. *Polkvantitativna analiza EMPA difuzijskega spoja kermet, prekrit s TiZrN/železom Armco (a) in ustrezen posnetek SEM (b); ($t_ž$ = 1^h, 1000 °C).*
Fig. 4. *Semi-quantitative EMPA analysis of the TiZrN-coated cermet/Armco iron diffusion couple (a) and corresponding SEM micrograph (b); (t_{an} = 1^h, 1000 °C).*

bogate z nikljem ter faze, bogate z volframom in molibdenom. Posredno to tudi podpira ugotovitev o pojavu selektivne oksidacije kermeta pod oksidom in tako to območje postaja revno s titanom ([12] in [13]).

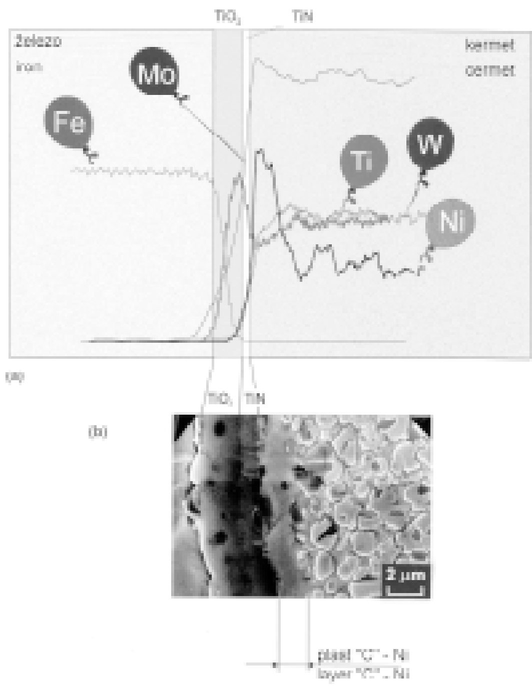
Da bi ugotovili vpliv časa segrevanja na debelino reakcijske plasti, je bil, za nekaj vzorcev difuzijskih členov, čas segrevanja v cevni peči podaljšan za 24 ur. Pričakovano je bilo, da se bo debelina reakcijske plasti bistveno povečala. Debelina plasti titanovega oksida je približno enaka, ne glede na to, ali je žarjenje pri 1000 °C trajalo 1 uro ali 24 ur, kar podpira zamisel o preventivnem delovanju atmosfere na mejno površino. Rezultati polkvantitativne analize EMPA tega difuzijskega člena ter ustrezni mikroposnetek SEM so prikazani na sliki 5.

Difuzijski člen železo Armco/neprekriti kermet je bil žarjen na enak način, pri 1000 °C 1 uro. V tem primeru (sl. 2a) se na dotiku prične selektivna oksidacija kermeta takoj. Primarno oksidira titan, medtem ko je v titanovem oksidu vzdolž meje z

the portion of the phase rich in nickel and the phase rich in tungsten and molybdenum. Indirectly, this too is a supporting statement for the selective oxidation of the cermet under the oxide taking place and this part becoming poor in titanium ([12] and [13]).

In order to establish the effects of heating time on the width of the reaction layer the heating time in the tube furnace was prolonged to 24 hours for some of the diffusion couple samples. It was expected that the thickness of the reaction layer would increase significantly. The thickness of the titanium oxide layer is approximately the same, irrespective of whether the annealing at 1000 °C lasted 1 hour or 24 hours, which supports the idea of prevented access of the atmosphere to the boundary surfaces. The results of the semi-quantitative EMPA analysis of this diffusion couple and the corresponding SEM micrograph are presented in Figure 5.

The Armco iron/uncoated cermet diffusion couple was annealed in the same way at 1000 °C for 1 hour. In this case (Fig. 2a) selective oxidation of the cermet in the contact started happening right away. Primarily it was the titanium that oxidized, while in the



Sl. 5. *Polkvantitativna analiza EMPA difuzijskega spoja kermet, prekrit s TiN/železom Armco (a) in ustrezen SEM posnetek (b); ($t_ž$ = 24^h, 1000 ^{o}C).*
Fig. 5. *Semiquantitative EMPA analysis of the TiN-coated cermet/Armco iron diffusion couple (a) and corresponding SEM micrograph (b); (t_{an} = 24^h, 1000 ^{o}C).*

železom še nekaj raztopljenega železa in na meji s kermetom nekaj raztopljenega W in Mo. Vzdolž oksida se drugi elementi v kermetu bogatijo v fazo, bogato z nikljem in fazo, bogato z volframom in molibdenom.

Rezultati raziskav potrjujejo, da je *plast "C"* (mejna plast prizadetega rezalnega materiala) v vseh primerih skrajno bogata z Ni, hkrati pa v tem področju ni opaznega zmanjšanja deleža Ti, ki prodira skozi prevleko, oksidira in se nalaga na prevleko na strani železa Armco.

Oksidacija in pas titanovega oksida preprečujeta normalno napredovanje difuzije med čistimi partnerji: kermet, prevleka in železo. Nastanek oksidacijske plasti je verjetno bolj realen pojav pri odrezovanju kakor verjetnost, da bo ostala površina rezila neoksidirana pri tako visoki temperaturi (800 to 1000 ^{o}C). To je razlog, da difuzijski poskusi, opravljeni na takšen način, kažejo bolj realno sliko dogodkov v vmesniku *prekrito orodje PVD/obdelovanec* kakor v primeru *statičnih difuzijskih preskusov v vakuumu* brez oksidacije.

3 SKLEPNE UGOTOVITVE

Rezultat difuzije elementov iz orodja in obdelovanca skozi vmesnik je sprememba sestave mejne plasti orodja, ki povečuje možnost mehanskih poškodb rezalnega robu. V primeru odrezovanja s prekritim orodjem te pojave opazimo po daljšem času

titanium oxide along the boundary with the iron there was still some dissolved iron, and on the boundary with the cermet, some dissolved W and Mo. Along the oxide, other elements in the cermet became enriched in the phase rich in nickel and the phase rich in tungsten and molybdenum.

The results of our investigation confirm that layer "C" (boundary layer of the affected tool material) is in every case, extremely rich in Ni, while at the same time in this area we observed a significant drop in the content of Ti, which diffuses through the coating, oxidizes and deposits itself on the coating on the Armco-iron side.

Oxidation and the occurrence of a belt of titanium oxides prevent the normal progress of diffusion between the pure partners: cermet, coating and iron. The formation of an oxidation layer is probably a more realistic phenomenon in cutting than the probability that the surface of the cutter would remain unoxidized at such a high temperature (800 to 1000 ^{o}C). That is why the diffusion experiments carried out in this way show a more realistic picture of the events in the PVD-coated tool/workpiece interface than in the case of static diffusion experiments in vacuum where oxidation was not present.

3 CONCLUSIONS

The result of the diffusion of the elements from the tool and the workpiece through the interface is a change in the composition of the boundary layers of the tool, which increases the possibility of mechanical damage to the cutting edge. In the case uporabe v primerjavi z neprekritim orodjem. Prevleke PVD so difuzijska ovira za atome kisika iz atmosfere, C in Fe iz obdelovanca kakor tudi Ti, Ni, W, Mo in Co ter C iz orodja v material obdelovanca ([10] do [13]).

Obravnavani primer žarjenja difuzijskih členov je razkril nekaj informacij o pojavih, ki se pojavljajo pri odrezovanju železnih zlitin z orodji iz kermeta, prekritih s prevlekami PVD. Opisani poskusi se lahko nanašajo na realni postopek odrezovanja zaradi podobnosti kakor so visoka temperatura, na katero se segreje rezalni rob lokalno ter oksidacijska atmosfera, ki v primeru suhega rezanja v celoti obdaja površino orodja. Neprimerna izbira rezalnih parametrov, ki lahko povzročijo nenavadno visoke temperature rezalnega orodja, so lahko razlog za razgradnjo prevleke PVD, glede na mehanizme, sprožene s spremembami ali pomanjkljivostmi, opisanimi v tem prispevku. Med temi lahko omenimo: spremembe v kemijski sestavi, mikrostrukturne spremembe, napake v novo nastali oksidni plasti (pore, razpoke), notranje napetosti in krhkost. Mehanska nestabilnost oksida na prevleki PVD (nenehno odstranjevanje med odrezovanjem) pospešuje nadaljnjo oksidacijo prevleke PVD in s tem njeno razgradnjo ter povečano obrabo orodja.

of cutting with coated tools these phenomena occur after a longer time of service compared to uncoated ones. PVD coatings are a diffusion barrier to oxygen atoms from the atmosphere, C and Fe from the workpiece as well as for Ti, Ni, W, Mo and Co and C from the tool to the workpiece material ([10] to [13]).

The studied example of annealing diffusion couples has revealed some information on the phenomena that take place in cutting iron alloys with cermet tools coated with PVD coatings. The described experiments can be related to the real process of cutting as there are some similarities such as high temperature, to which the cutting edge heats up locally, and the oxidation atmosphere, which in the case of dry cutting fully surrounds the surface of the tool. Careless selection of cutting parameters, which can cause unusually high temperatures of the cutting tool, may be a reason for the degradation of the PVD coating, according to the mechanisms triggered by the changes or weaknesses described in this contribution. Among these we can mention: changes in the chemical composition, microstructure changes, defects in the newly formed oxide layer (pores, cracks), internal stresses, and brittleness. The mechanical instability of the oxide on the PVD coating (permanent removal during cutting) further accelerates the oxidation of the PVD coating, causing its degradation and increased tool wear.

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Optimiranje dinamične uravnoteženosti krilca

Optimization of the Dynamic Balance of an Aileron

Mihael Mesarič - Franc Kosel

V prispevku je podana uporaba kriterija dinamične uravnoteženosti krilca, ki zagotavlja preprečitev vihranja[1] krila na letalih splošne kategorije. Na podlagi kriterija je bila z uporabo paketa za računalniško podprto konstruiranje Pro/ENGINEER določena potrebna masa balansirne uteži krilca letala. Rezultati dobljeni na modelu so bili eksperimentalno potrjeni. Z gradientno metodo optimizacije so bile določene izmere in namestitev balansirne uteži, da bi minimizirali maso krilca.

(Ključne besede: krilca letalska, uravnoteženje dinamično, metode optimiranja, paketi programski)

This paper deals with the use of the aileron balance criterion as one of the criteria for providing freedom from wing flutter on general-category airplanes. Based on this criterion and using the Pro/ENGINEER computer-aided-design software, the required mass of the balance weight was obtained. The results from the model were confirmed by our experiments. By using the gradient-optimisation method, the optimum size and position of the balance weight with respect to the minimisation of the aileron mass were achieved.

(Keywords: aileron, dynamic balance, optimization methods, computer software)

0 UVOD

Pri zasnovi letal je zaradi lahke gradnje treba analizirati tudi možnost nastanka aeroelastičnih pojavov ([1] do [5]). Tako je za letala splošne kategorije pri postopku pridobivanja ustreznih dovoljenj treba med drugim pokazati, da v uporabnem območju hitrosti letenja ne pride do vihranja krila. Vihranje je nestabilno samovzbujano nihanje deformabilnega telesa, ki je posledica aerodinamičnih in vztrajnostnih obremenitev ter vpliva elastičnih deformacij. V splošnem lahko vihranje krila razdelimo na oblike, ki zajemajo [3]:

- torzijsko in upogibno nihanje krila,
- gibanje krilca in torzijsko nihanje krila,
- gibanje krilca in upogibno nihanje krila.

Zapletenost pojava je spodbujala k iskanju poenostavljenih metod dokazovanja primernosti zasnove, da v uporabnem območju hitrosti letala ne pride do vihranja ([6] in [7]). Za letala splošne kategorije, z največjo hitrostjo strmoglavljenja V_D < 133,7 m/s (260 kt) so poenostavljeni kriteriji za preprečitev pojava vihranja krila, obrata krilc in divergence krila podani v [7] in temeljijo na statističnih analizah, preskusih modelov v vetrovniku ter na analitičnih raziskavah aeroelastičnosti na poenostavljenih modelih.

Za preprečitev pojava vihranja krila moramo biti pozorni na naslednje tri parametre: dinamično

[1] Pogosto se za vihranje uporablja tudi tujka “flutter”.

0 INTRODUCTION

During the airplane-design process it is necessary to investigate the possibility that aeroelastic phenomena may occur as a result of a lightweight structure ([1] to [5]). In order to certify the airplane in the general category it is necessary to demonstrate that the airplane is free of flutter in its operational speed range. Flutter is an unstable self-sustained oscillation of an elastic body that comprises aerodynamic, elastic and inertial forces. In general there are three kinds of wing flutter [3]:

- torsional–flexural flutter,
- torsional aileron flutter,
- flexural aileron flutter.

The complexity of the flutter phenomenon has prompted efforts to find simplified methods for establishing freedom from flutter in the operating speed range of the airplane ([6] and [7]). Reference [7] is intended to serve as a guide to small-airplane designers (dive speed V_D < 133.7 m/s i.e. 260 kt) in the areas of prevention of flutter, aileron reversal and wing divergence. The data in [7] rely upon statistical studies, wind-tunnel tests of models and simplified analytical studies.

The prevention of wing flutter is achieved by paying careful attention to three parameters: aileuravnoteženost krilc, torzijsko prožnost krila in mrtvi hod krilc.

- Kriterij za dinamično uravnoteženost krilca je razmerje med masnim deviacijskim momentom I_{OY} glede na tečajno os krilca in vzporednico z osjo trupa letala, ki poteka skozi vozel prve upogibne lastne oblike nihanja krila ter osnim masnim vztrajnostnim momentom krilca okrog tečajne osi I_Y. Mejna vrednost parametra I_{OY}/I_Y je odvisna od največje dovoljene hitrosti strmoglavljenja letala V_D.
- Parameter torzijske prožnosti krila je odvisen od hitrosti letala V_D. Izračunamo ga iz porazdelitve zasuka krila obremenjenega z enotskim torzijskim momentom.
- Ohlapnost krilca ob drugem zadržanem krilcu ne sme preseči dane vrednosti.

V prispevku se bomo omejili na izpolnitev kriterija dinamične uravnoteženosti krilca, pri čemer bomo optimirali izmere in lego uteži za uravnoteženje krilca, da bi minimizirali maso krilca.

ron balance, wing torsional flexibility and aileron free play.

- The aileron balance criteria are obtained from the aileron product of inertia I_{OY} about the wing's fundamental bending-node line and the aileron-hinge line as well as the aileron's mass moment of inertia I_Y about its hinge line. A limit for the parameter I_{OY}/I_Y is set as a function of the dive speed V_D.
- A torsional flexibility parameter for the wing is established as a function of V_D. It is calculated from the wing-twist distribution per unit of applied torque.
- The total free play of each aileron with the other aileron clamped to the wing must not exceed the specified maximum.

This paper deals with achieving the aileron balance criteria and presents the optimisation of the size and position of the required balance weight in order to minimise the aileron weight.

1 DINAMIČNO URAVNOTEŽENJE KRILCA

1 DYNAMIC BALANCE OF THE AILERON

Gibalno enačbo krilca zapišemo [8] v obliki:

The equation of motion of the aileron is given [8] as:

$$H_a + H_{Fa} = I_Y \ddot{\delta}_a - 2I_{OY}\left(rq + \dot{p}\right) \quad (1),$$

kjer so H_a - moment aerodinamične obremenitve okrog tečajne osi, H_{Fa} - moment krmilne sile, I_Y - masni vztrajnostni moment krilca okrog tečajne osi ter *p, q r* - kotne hitrosti krilca okrog vzdolžne, prečne in navpične osi letala. Z δ_a je označen odklon krilca, z I_{OY} pa masni deviacijski moment glede na tečajno os *Y* in vzporednico z osjo trupa letala, ki poteka skozi vozel prve upogibne lastne oblike nihanja krila (sl. 1). Iz gibalne enačbe (1) je razvidno, da dobimo zaradi vztrajnosti krilca, pri kombiniranem vrtenju okrog prečne in navpične osi oziroma pri kotnem pospešku okrog vzdolžne osi letala, moment, ki odklanja krilce. Pri upogibnem nihanju krila, se dinamično neuravnoteženo krilce odklanja, tako da zmanjšuje aerodinamično dušenje in s tem spodbuja nastanek vihranja pri manjših hitrostih leta. Povezavo med gibanjem krilca in odklonom krilca zmanjšamo, če zmanjšamo vrednost masnega deviacijskega momenta I_{OY}, kar je torej pogoj za dinamično uravnoteženje krilca.

Masno središče samega krilca je običajno precej za tečajno osjo. Krilce lahko dinamično uravnotežimo tako, da pomaknemo tečajno os krilca nazaj oziroma dodamo balansirno utež. Balansirna utež je običajno nameščena na podaljšku na sprednjem zunanjem robu krilca, ali je pri aerodinamično čistejših izvedbah vgrajena v sprednji rob krilca. Pri namestitvi balansirne uteži moramo izpolniti trdnostne zahteve, podane v predpisih.

where H_a and H_{Fa} are the aerodynamic and control moments about the hinge line, respectively, and I_Y is the mass moment of inertia of the aileron about its hinge line. The values *p, q* and *r* represent the angular velocity of the aileron in roll, pitch and yaw, respectively. δ_a describes the aileron deflection, whereas I_{OY} is the aileron product of inertia about the wing's fundamental bending-node line O and the aileron-hinge line Y (Figure 1). Equation (1) reveals that during a simultaneous pitching and yawing motion or during angular acceleration of the airplane about its longitudinal axis, inertia forces induce a hinge moment that deflects the aileron. During bending vibration of the wing, the aerodynamic damping of the wing is reduced due to the deflection of the dynamically unbalanced aileron and this initiates the flutter at lower airspeeds. As a consequence of equation (1), lowering the value of the aileron product of inertia I_{OY} reduces the inertial coupling between the aileron motion and deflection. Therefore, the aileron product of inertia can be regarded as a criterion of the dynamic balance of the aileron.

The centre of gravity of the aileron generally lies well behind the hinge line. The aileron can be dynamically balanced by shifting the hinge line aft or by adding a balance weight. This balance weight is usually placed on a special arm sticking out in front of the control surface or it is integrated into the leading edge of the aileron in an aerodynamically cleaner design. Strength requirements for the balance-weight attachment must also be fulfilled.

Na preprečevanje vihranja ugodno vpliva povečanje masnega vztrajnostnega momenta krilca okrog tečajne osi. Zato je kot poenostavljeni kriterij za preprečitev vihranja na letalih splošne kategorije v [7] definirano razmerje med masnim deviacijskim in vztrajnostnim momentom krilca I_{OY}/I_Y. Vrednost razmerja je odvisna od največje hitrosti strmoglavljenja letala in je dobljena na podlagi:

- statističnih analiz geometrijskih, vztrajnostnih in elastičnih lastnostih letal, pri katerih se je med letom pojavilo drhetnje, in na temelju uporabljenih metod za odpravo vihranja,
- omejenega števila preskusov poltogih modelov v vetrovniku,
- analitičnih raziskav aeroelastičnosti na dvodimenzionalnem modelu.

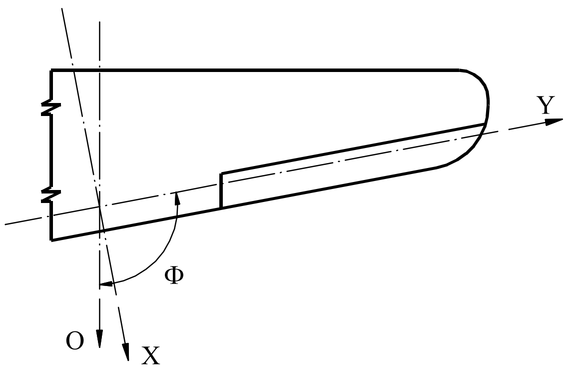
V primeru, da tečajna os ni pravokotna na vzdolžno os letala (sl. 1), dobimo masni deviacijski moment glede na osi *Y* in *O* z naslednjo transformacijo:

The prevention of flutter is also helped by an increase in the mass moment of inertia of the aileron about its hinge axis. Hence, the ratio between the aileron product of inertia and the mass moment of inertia I_{OY}/I_Y is defined as simplified flutter-prevention criteria in [7]. The value of the ratio depends on the design dive speed and it is obtained on the basis of:

- a statistical study of the geometric, inertia and elastic properties of those airplanes that have experienced flutter in flight, and the methods used to eliminate the flutter;
- limited wind-tunnel tests conducted with semi-rigid models;
- analytic studies based on a two-dimensional model.

If the aileron-hinge axis is not perpendicular to the longitudinal axis of the airplane (Fig. 1) the mass product of inertia with respect to the *Y* and *O* axes is calculated using the transformation given below:

$$I_{OY} = I_{XY} \sin\Phi - I_{YY} \cos\Phi \quad (2).$$



Sl. 1. *Definicija tečajne osi Y in osi O, vzporedne z osjo trupa letala, ki poteka skozi vozel prve upogibne lastne oblike nihanja krila*

Fig. 1. *Definition of hinge line Y and the wing's fundamental bending-node line O*

2 REZULTATI IN RAZPRAVA

Optimalne izmere in lego balansirne uteži smo določili za krilce lahkega letala splošne kategorije, za katerega lahko uporabimo kriterij dinamične uravnoteženosti krilca podan v [7]. Glavne izmere krilca, narejenega iz armirane plastike, so prikazane na sliki 2. Tečajna os je pravokotna na vzdolžno os letala, globina krilca pa se klinasto zmanjšuje proti koncu krila. Balansirna utež je vgrajena v sprednji rob krilca, pri čemer znaša notranji premer zaokrožitve sprednjega roba krilca 12 mm.

Za določitev ustreznega masnega deviacijskega in vztrajnostnega momenta krilca smo uporabili paket za računalniško podprto konstruiranje Pro/ENGINEER. Sprva smo preračunali vrednosti za krilce brez uteži in jih primerjali z izmerjenimi.

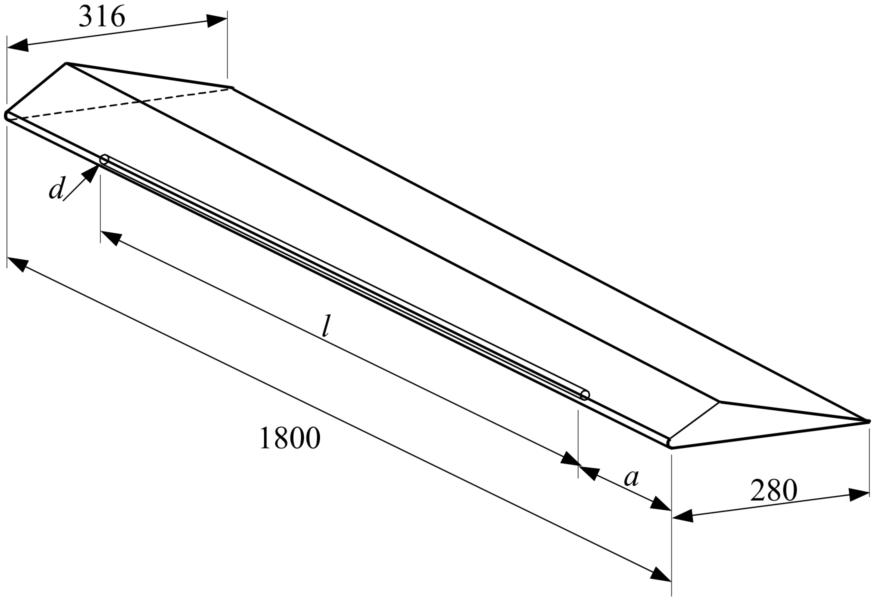
Glede na podatke o gostoti posamezne plasti armirane plastike in pene [9] smo s

2 RESULTS AND DISCUSSION

The optimum size and position of the balance weight was determined for the aileron of a general-category airplane for which the use of the aileron balance criteria given in [7] is adequate. The main dimensions of the aileron, which is made of fibre-reinforced material, are presented in Figure 2. The hinge axis is perpendicular to the airplane's longitudinal axis and the aileron chord is tapered towards the wing tip. The balance weight is integrated into the aileron's leading edge, with an inner diameter of 12 mm.

The corresponding mass product and moment of inertia of the aileron were determined using the Pro/ENGINEER computer-aided-design software. As a first step, the values for the aileron without the balance weight were determined and compared to the measured values.

With the available density data for an individual layer of fibre-reinforced composite and foam [9], and us-



Sl. 2. *Glavne izmere levega krilca*
Fig. 2. *Main dimensions of left aileron*

programom določili maso strukture krilca, ki znaša 1,369 kg. Maso nanesene barve smo ocenili kot razliko do mase krilca brez uravnotežne palice, ki znaša 1,745 kg. Predpostavili smo, da je barva enakomerno porazdeljena po površini krilca. Nato smo primerjali izračunane in izmerjene vrednosti lege masnega središča (preglednica 1). Lego masnega središča krilca brez uravnotežne palice smo določili z merjenjem sile v podpori in z obešanjem krilca [9]. Pri merjenju sile v podpori smo uporabljali napravo Zwick Z050 s sondo za merjenje sile do 100 N, tip KAP-S K1 0,05N proizvajalca System Technik GmbH. Z obešanjem, kakor je prikazano na slikah 3*a* in 3*b*, smo določili lego masnega središča vzdolž razpona krilca y_t ter po globini krilca x_t. Navpično razdaljo med masnim središčem in tečajno osjo z_t pa smo določili z obešanjem krilca okrog tečajne osi in zadnjega roba krilca [9].

Vrednosti masnih vztrajnostnih momentov krilca smo določili na podlagi meritev periode lastnega nihanja krilca. Najprej smo določili masni vztrajnostni moment I_{X_T} okrog osi X_T, ki je vzporedna

ing the software, the mass of the aileron structure was found to be 1.369 kg. The mass of the paint represents the difference between the measured mass of the aileron without the balance weight (1.745 kg) and the calculated mass of the aileron structure. It was assumed that the paint is distributed evenly over the aileron surface. Thereafter, the calculated position of the aileron's centre of gravity was compared with the measurements (Table 1). The centre of gravity of the aileron without the balance weight was experimentally determined by measurements of the force at the support and by the hanging aileron [9]. Measurements of the support force were conducted on a Zwick Z050 Universal Testing Machine using a KAP-S K1 0.05N force transducer manufactured by System Technik GmbH. Figures 3*a* and 3*b* represent estimations of the centre-of-gravity position of the aileron along the span y_t and along the chord x_t. The vertical distance between the hinge line and the centre of gravity z_t was established by hanging the aileron about its hinge line and trailing edge [9].

The experimental determination of the corresponding mass moments of inertia is based on a measurement of the period of the free oscillation of the aileron. At first the mass moment of inertia I_{X_T} about the X_T axis was determined.

Preglednica 1. *Primerjava izračunanega in izmerjene lege masnega središča*
Table 1. *Comparison between the calculated and measured position of the centre of gravity*

	Izračunano Calculated	Izmerjeno Measured	Odstopanje Deviation
x_t - za šarnirno osjo x_t - behind hinge line	45,6 mm	46,7 mm	2,4%
y_t - od širšega roba krilca y_t - from wider aileron edge	882,2 mm	881,8 mm	0,05%
z_t - pod šarnirno osjo z_t - below hinge line	37,0 mm	37,7 mm	1,9%

z osjo X (sl. 1) in poteka skozi masno središče krilca. Pri tem smo krilce položili na trikotno podporo na razdalji l od stranice, na katero je bila pritrjena vzmet togosti k (sl. 4*a*). Uporabili smo dve različni vzmeti, ki sta bili vedno natezno obremenjeni, njuno togost pa smo pomerili na napravi Zwick Z050 [9]. Na podlagi merjenja periode nihanja smo masni vztrajnostni moment okrog osi X_T izračunali po enačbi:

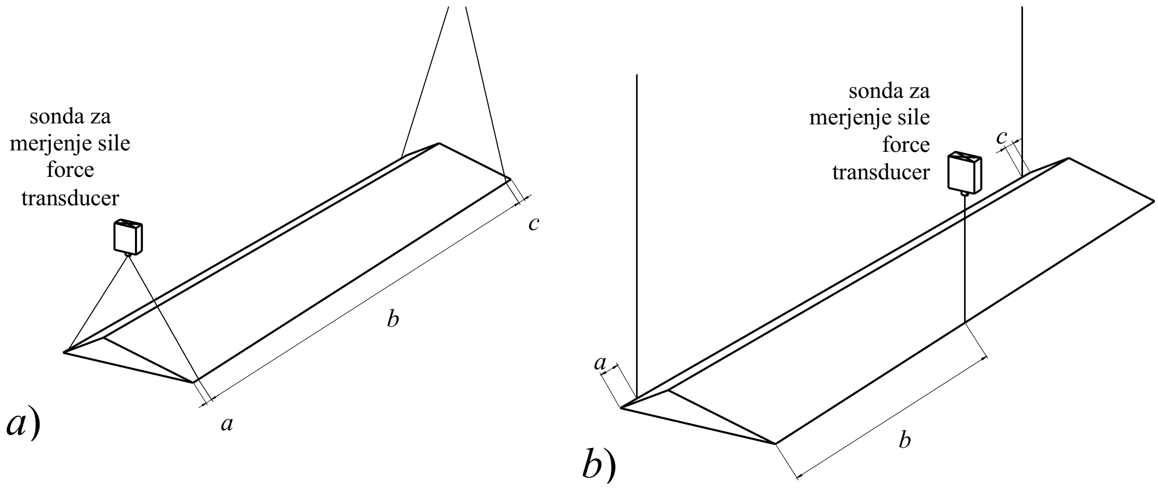
The X_T axis is parallel to the X axis (Figure 1) and goes through the aileron's centre of gravity. The aileron was supported at a distance l from the side where a spring with stiffness k was attached (Figure 4*a*). Two different tensionally loaded springs were used, the stiffness of the springs was experimentally established on the Zwick 050 [9]. Using the measured values of the period of the oscillations, the mass moment of inertia about the X_T axis was calculated with the equation given below:

$$I_{X_T} = kl^2 \left(\frac{T_0}{4\pi} \right)^2 - ml_{MS}^2 \quad (3),$$

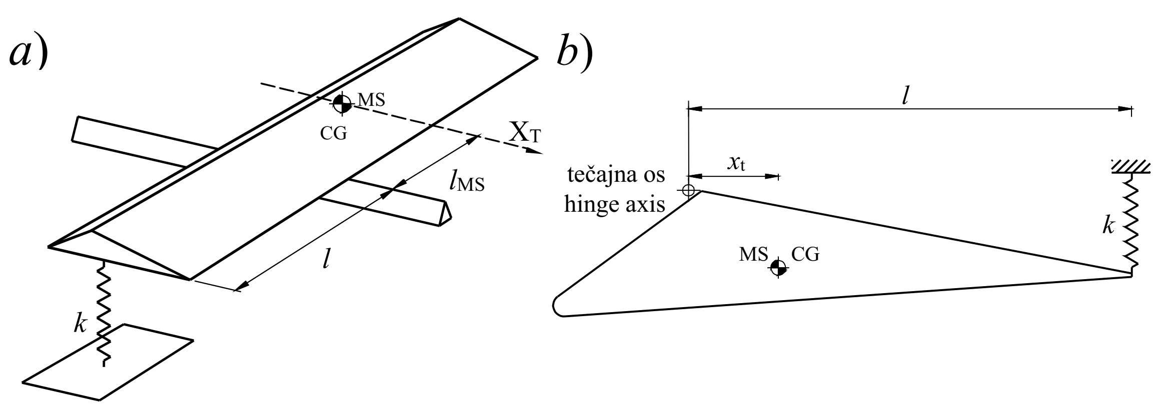
kjer je l_{MS} razdalja med masnim središčem MS in trikotno podporo. Za določitev masnega vztrajnostnega momenta krilca okrog tečajne osi smo vzmet pritrdili na zadnji rob krilca (sl. 4*b*). Iz izmerjenega časa periode nihanja smo prek izraza:

where l_{MS} is the distance between the aileron's centre of gravity and the support. In order to determine the mass moment of inertia about the hinge line, the spring was attached at the aileron's trailing edge (Fig. 4*b*). Using the measured values of the period of the oscillations, the mass moment of inertia about the hinge axis was evaluated with:

$$I_Y = kl^2 \left(\frac{T_0}{2\pi} \right)^2 \quad (4)$$



Sl. 3. *Določitev lege masnega središča po razponu (a) in globini (b) krilca z merjenjem sile v podpori*
Fig. 3. *Determination of the position of the centre of gravity along the aileron span (a) and chord (b) by measurement of the support force*



Sl. 4. *Določitev masnega vztrajnostnega momenta krilca okrog osi X_T (a) ter okrog tečajne osi (b)*
Fig. 4. *Determination of the aileron mass moment of inertia about X_T axis (a) and hinge axis (b)*

Preglednica 2. *Primerjava izračunane in izmerjene vrednosti masnega vztrajnostnega momenta*
Table 2. *Comparison between the calculated and measured values of the mass moment of inertia*

		Izračunano Calculated	Izmerjeno Measured	Odstopanje Deviation
I_{X_T}	okrog osi X_T about axis X_T	0,4871 kgm^2	0,5146 kgm^2	5,6%
I_Y	okrog šarnirne osi *Y* about hinge axis *Y*	0,0195 kgm^2	0,0197 kgm^2	1,0%

Preglednica 3. *Masa in izmere simetrično nameščene in optimalne jeklene balansirne uteži*
Table 3. *Mass and size of symmetrically placed and optimum balance weight made of steel*

Jeklena balansirna utež Balance weight made of steel	masa uteži mass of weight	dolžina uteži *l* length of weight *l*	premer uteži *d* diameter of weight *d*	masa krilca aileron mass
simetrično nameščena symmetrically placed	1,140 kg	1234 mm	12 mm	2,885 kg
optimalna lega optimum position	1,045 kg	1129 mm	12 mm	2,790 kg

izračunali masni vztrajnostni moment I_Y okrog tečajne osi *Y*. Primerjava med izračunanimi in izmerjenimi vrednostmi masnih vztrajnostnih momentov je podana v preglednici 2.

Ugotovljeno odstopanje izračunanih vrednosti lege masnega središča in masnih vztrajnostnih momentov od izmerjenih vrednosti je manjše od 3%, kar potrjuje kakovostne vhodne parametre in ponuja možnost določitve potrebne balansirne uteži. Nekoliko večje je le odstopanje med izmerjeno in izračunano vrednostjo masnega vztrajnostnega momenta I_{X_T}, kar pripisujemo večji masi stranic krilca.

Glede na načrtovano največjo dovoljeno hitrost leta iz diagrama v [7] razberemo, da mora biti parameter dinamične uravnoteženosti krilca $I_{OY}/I_Y < 1{,}75$. S programom smo tako določili izmere in maso simetrično nameščene jeklene balansirne uteži (preglednica 3).

V nadaljevanju smo s paketom Pro/ENGINEER po gradientni metodi optimirali izmere in lego balansirne uteži z namenom, da bi minimizirali potrebno maso. Pri optimizaciji jeklene balansirne uteži smo najprej spreminjali dolžino *l*, premer *d* ter oddaljenost uteži *a* od stranice krilca, ki je bližje koncu krila (sl. 2). Balansirna utež ima obliko valja, zato se mora pri povečanju premera os uteži pomakniti proti sredini krilca, tako da utež nalega na notranji površini spodnje in zgornje skodele krilca (sl. 5). Optimalne izmere in masa jeklene palice so podane v preglednici 3.

Balansirna utež je postavljena tako, da se dotika stranice krilca, ki je bliže koncu krila (a = 0 mm). S tako namestitvijo uteži se najbolj zmanjša vrednost masnega deviacijskega momenta. Optimalni premer balansirne uteži je 12 mm, s čimer je os uteži najbolj oddaljena od tečajne osi. V primeru

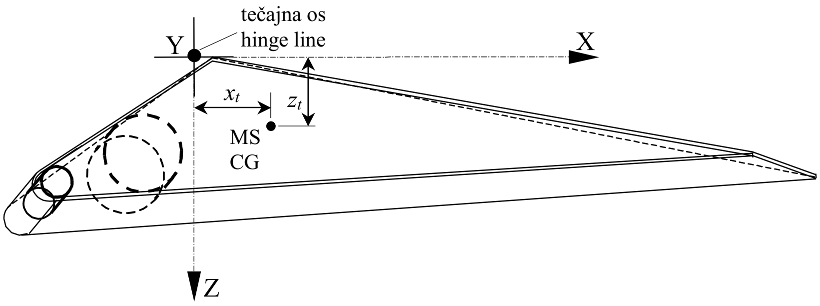
A comparison between the calculated and measured values of the mass moments of inertia is given in Table 2.

We observed that the position of the centre of gravity and the values of the mass moment of inertia of the aileron obtained with the software are in good agreement with the measured values, the deviation being only 3%. The difference between the calculated and measured value of the mass moment of inertia I_{X_T} is somewhat larger, probably as a result of the higher mass of the two sides of the aileron.

The limiting value of the parameter of dynamic balance of the aileron I_{OY}/I_Y is obtained from the diagram in [7] according to the design dive speed, and must not exceed 1.75. Using the software, the corresponding size and mass of the balance weight placed at the leading edge, and symmetrically with respect to the aileron span, was determined and is given in Table 3.

Subsequently, the optimisation of the size and position of the balance weight with respect to the minimisation of the mass was performed with the Pro/ENGINEER software, by applying the gradient-optimisation method. The first part of the optimisation process for the balance weight, which was made of steel, was the variation of the length *l*, the diameter *d* and the distance *a* between the balance weight and the outward side of the aileron. The balance weight has a cylindrical form. If its diameter is enlarged, the balance weight is placed further aft so that its surface touches the inner surface of the aileron's skin (Figure 5). As a result of the optimisation we obtained a balance weight made of steel with the dimensions given in Table 3.

To achieve the best position, the balance weight has to be aligned with the outer side of the aileron (a = 0 mm). In this way the value of the product of inertia of the aileron is mostly reduced. Furthermore, the diameter of the balance weight must be 12 mm, since in this case the largest distance



Sl. 5. *Vpliv premera balansirne uteži na namestitev znotraj krilca*
Fig. 5. *Effect of balance-weight diameter on its position inside the aileron*

povečanja premera je treba balansirno utež premakniti proti tečajni osi, kar zmanjšuje masni vztrajnostni moment krilca in ugoden prispevek balansirne uteži k masnemu deviacijskemu momentu krilca.

Tudi v primeru dodatnega parametra, notranjega polmera balansirne uteži smo dobili enak rezultat optimiranja balansirne uteži, vgrajene v krilce. Maso balansirne uteži smo zmanjšali za 8,3%, maso celotnega krilca pa za 3,3%. Masno središče dinamično uravnoteženega krilca leži x_t = 7,2 mm za tečajno osjo.

Tudi v primeru svinčene balansirne uteži je optimalni premer 12 mm ter namestitev na skrajni zunanji konec krilca. Zaradi večje gostote je potrebna dolžina palice manjša (770 mm), kar ugodno vpliva na masni deviacijski moment I_{OY}. V primerjavi s simetrično nameščeno balansirno utežjo je v tem primeru masa uteži zmanjšana za 11%, celotnega krilca pa za 4,4%. Masno središče dinamično uravnoteženega krilca s svinčeno utežjo leži 8,2 mm za tečajno osjo.

Glede na to, da kriterij dinamične uravnoteženosti krilca vsebuje masni deviacijski moment, je optimalna lega balansirne uteži na skrajnem sprednjem in zunanjem koncu krilca pričakovana. Z optimizacijo smo za obravnavani primer poiskali še optimalno razmerje med dolžino in premerom uteži.

3 SKLEPI

Krilca v veliki meri vplivajo na vihranje krila zato moramo pri snovanju letala uporabiti rešitve, ki preprečujejo samovzbujana nihanja krila v uporabnem hitrostnem območju. Pri letalih splošne kategorije je eden od poenostavljenih kriterijev preprečevanja vihranja parameter dinamične uravnoteženosti krilca. Oblika krilca in lega tečajne osi sta zasnovana glede na aerodinamično učinkovitost krmila in velikost krmilnih sil. Krilce tako dinamično uravnotežimo z dodatno maso. Zato je pametno poiskati optimalne

between the balance weight and the hinge line is achieved. If the diameter of the balance weight is enlarged it must be placed further aft. As a consequence, the mass moment of inertia as well as a favourable contribution of the balance weight to the product of inertia would be reduced.

After including another parameter, i.e. the inner radius of the balance weight, the same optimum size and position of the weight were obtained. After the optimisation, the mass of the balance weight and of the whole aileron were reduced by 8.3% and 3.3%, respectively. The centre of gravity of the dynamically balanced aileron lies x_t = 7.2 mm aft of the hinge line.

With the balance weight made of lead, the same optimum diameter of 12 mm and placement at the outer end of aileron were obtained. Due to higher density, the necessary length of the balance weight was shorter (770 mm), which had a positive effect on the product of inertia I_{OY}. Compared to the symmetrically placed balance weight, the masses of the balance weight and of the whole aileron in this case were reduced by 11% and 4.4%, respectively. The centre of gravity of the dynamically balanced aileron with the balance weight made of lead lies x_t = 8.2 mm aft of the hinge line.

Since the product of inertia is included in the aileron balance criteria the placement of the balance weight of the outmost outward and forward position inside the aileron is expected. However, with optimisation the ideal relation between the length and diameter of the balance weight was achieved for our case.

3 CONCLUSIONS

The aileron greatly influences the occurrence of wing flutter. Therefore, during the airplane design, appropriate measures have to be taken in order to achieve freedom form flutter in the operational speed range. For general-category airplanes one of the simplified criteria for demonstrating freedom from flutter is the aileron balance criterion. Since the aileron shape and its hinge-line position are determined with respect to the aerodynamic effectiveness of the control surface and the magnitude of control forces, a balance weight must be added in order to dynamically balance the aileron. Hence, it is of primary interest to the engineer to optimise izmere in lego balansirne uteži, da bi minimizirali maso krilca.

Pri delu smo uporabili paket za računalniško podprto konstruiranje, ki ne ponuja samo možnosti za iskanje primerne zasnove, v našem primeru dinamične uravnoteženosti krilca, ampak tudi z metodami optimiranja določit optimalno zasnovo glede na dano ciljno funkcijo in kriterije. Pravilnost modela smo potrdili s preskusom, z optimiranjem izmer in lege pa smo maso balansirne uteži zmanjšali za 8,3 % oziroma 11 odstotkov. Nadaljnjo možnost za zmanjšanje mase krilca daje sočasno optimiranje krilca glede na dinamično uravnoteženost in nosilnost.

the size and the position of the balance weight in order to minimise the weight.

In our work the computer aided design software we used not only offers the possibility of finding a feasible solution but also an optimum design with respect to the goal function and restrictions. The accuracy of the model was confirmed by experiments. As a result of the optimisation of the size and position of the balance weight, its mass was reduced by 8.3% and 11%. A further reduction of the aileron mass could be achieved by simultaneous optimisation of the aileron with respect to the aileron balance criteria and structural strength.

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Poročila
Reports

Študij strojništva spodbuja ustvarjalnost
Studying Mechanical Engineering Improves Creativity

Dandanes se v svetu vedno bolj brišejo ločnice med strogo znanstvenimi in empiričnimi metodami raziskovanja. Tudi uporaba sodobne informacijske tehnologije se seli na do nekdaj samo za človeka rezervirana področja ustvarjalnosti. Eksperimentiranje na področju umetne inteligence odpira nove dimenzije našega obstoja in zato je lahko samo majhen korak od znanosti do umetnosti.

Smo verjetno ena redkih generacij strojnikov, ki se redno srečujemo vsako leto, kjer se nam odpirajo zanimivi pogledi na naše skoraj tridesetletne poklicne poti. Človek ne bi verjel, kaj vse strojniki v življenju počnemo oziroma s čim vse se ukvarjamo. To dejstvo vsekakor kaže na izredno široko podlago, ki smo jo s tem študijem pridobili, saj je očitno v nas spodbudil izredno pestre in ustvarjalne smeri delovanja. Sam sem namreč diplomiral leta 1974 pri prof. dr. Janezu Pekleniku in to s področja skupinske tehnologije in klasifikacijskih sistemov obdelovancev. V diplomski nalogi sem se srečal z računalniško obdelavo podatkov, kar je zaznamovalo mojih nadaljnjih 20 let dela na področju informatike. Dolgoletno poglabljanje v informatiko in zmožnosti računalnika je rodilo zanimiv ljubiteljski projekt, ki ga razvijam že prek 15 let. Vedno sem bil namreč prepričan, da je sodobna računalniška tehnologija z ustrezno programsko opremo zmožna veliko več, kakor samo "premetavati" suhoparne podatke. Govor je o razvoju računalniških programov za ustvarjanje grafičnih slik po generativni metodi.

Metoda je v svetu poznana pod imenom "generative art" in se uvršča na področje umetne ustvarjalnosti znotraj širokega področja raziskav umetne inteligence. Generative art je sodobna računalniška metoda za razvoj idej in ustvarjanje novih rešitev na vseh področjih človekovega delovanja. Ne nanaša se samo na področje likovne umetnosti ampak jo preskušajo tudi v arhitekturi, urbanizmu, industrijskem oblikovanju, glasbi, poeziji itn. V bistvu metoda posnema evolucijske procese v naravi, in to od genetskega zapisa, rojstva in rasti do izbrane zrelosti. V praksi so to genetsko zasnovane programske kode, ki tako kakor se dogaja v naravi, ustvarjajo vedno drugačne in neponovljive oblike. Izrednega pomena pri vsem tem pa je trenutek časa zagona generativnega procesa, saj takrat oblikovani genski zapis usodno vpliva na končni rezultat.

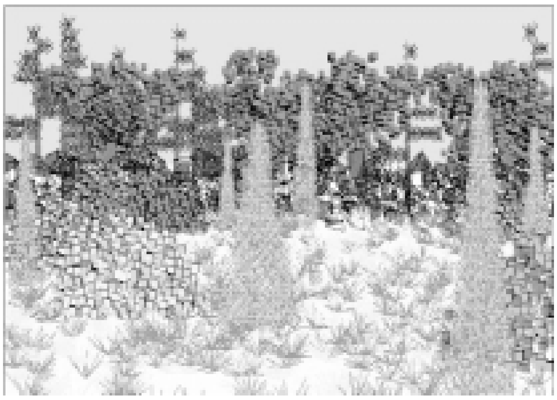
Metodo preskušam na področju ustvarjanja slik. Od prvih poskusov na računalniku C64 je nastala vrsta programov, ki ustvarjajo abstrakcije in stilizirane

Nowadays there are no longer any major differences between the scientific and the empirical approaches to research. The application of new types of information technology has begun to conquer some areas that were until now exclusively reserved for the human being. Experiments in the field of artificial intelligence are opening up a new dimension in our role as a thinking being and make it clear that science and art are very close to each other.

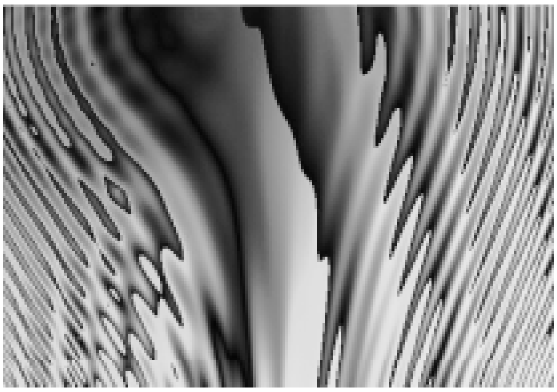
Meeting the generation of people I studied with every year is a good occasion to look at how we have developed professionally. It is difficult to believe how different the jobs are that we are doing and what we are interested in. This fact demonstrates the very high capacity for creativity that comes with the study of mechanical engineering. I took my degree in 1974, under Prof. Janez Peklenik, in the area of group technology and classificatory systems. While preparing my diploma I met the computer and this was tremendously import for my future life. For more than 20 years I was engaged in developing and programming computer applications for production and business-information systems. Being deeply engaged in those characteristics of the computer that surpass man's abilities I developed an original project for computer graphics that found its place in the large field of generative art research.

The generative approach is a part of artificial creativity, which itself forms a part of the area of artificial intelligence research. It is a method for developing ideas and for creating new solutions in all fields of human creativity. It does not refer only to plastic art but also to experiments in architecture, industrial design, music, poetry, etc. This new approach copies evolutionary processes from nature, including the role of the DNA code in developing an organism. In fact, there are genetically designed programs that realize, as nature does, an endless sequence of always different, unique and unpredictable solutions. The starting moment of the genetic process and its time value are very important and have a lot of influence on the final image.

I have experimented with this method of producing visual art. I began on the very popular C64 and to date I have developed a lot of programs that generate pure abstractions and stylized images



Sl. 1
Fig. 1



Sl. 2
Fig. 2

podobe iz narave. Pri razvoju programov obstajata dva osnovna koncepta, in sicer pragmatični in algoritemski tip programov. Pri prvem tipu z uporabo pragmatičnih programskih instrukcij dosežem nepredvidljivost in neponovljivost vendar v okviru pričakovanega (slika 1), pri drugem tipu pa z uporabo instrukcij z matematičnimi algoritmi dosežem popolna presenečenja in praktično ne morem niti približno napovedati likovnega videza končnega rezultata (slika 2). Vsi moji programi so napisani v programskem jeziku GWBASIC in delujejo v DOS okolju brez uporabe sodobnih programov za grafično oblikovanje. Več primerov je mogoče videti na moji spletni strani: www.soban-art.com .

Projekt ima stične točke tudi s strojništvom oziroma strojegradnjo. Generativna metoda se v svetu veliko uporablja za izdelavo vzorcev v industriji tekstila, keramike, drugih talnih oblog in dekorativnih materialov ter v industrijskem oblikovanju predmetov, kjer so vse bolj iskane izvirne oblike. Hiperprodukcija novih in nenavadnih rešitev vsekakor postavlja sodobno številsko krmiljeno (NC) tehnologijo pred nove izzive hitre zadovoljitve naročnika po unikatnem predmetu.

Bogdan Soban

Op.: Prispevek je bil pripravljen na pobudo prof.dr. Janeza Kopača.

of nature. There are two basic concepts of generative programming: the pragmatic and the mathematical approaches. With the pragmatic approach I reach the unpredictability of variety of the defined motif (Fig. 1). Using the mathematical approach means to reach the unpredictability of the motif and the variety of it (Fig. 2), and it is absolutely impossible to anticipate the result. All my programs are developed in the GWBASIC programming language and run in the DOS environment without the need for any graphic programming tool. More examples can be seen on my web page: www.soban-art.com .

The project is related to mechanical engineering. Around the world the results of the generative approach are applied in the production of textile materials, ceramics, materials for floor lining and other decorative materials. Objects with an original design are more and more appreciated. Using this new method to design all these objects means the rapid production of ideas to be realized with modern NC technology.

Bogdan Soban

Note: Contribution was prepared on the initiative of Prof.Dr. Janez Kopač.

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Strokovna literatura

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Personal Events

Osebne vesti

Personal Events

Trimo raziskovalne nagrade

Boris Pukl

Doktorsko delo:
OBRATOVALNA TRDNOST MEHANSKIH ZVEZ DELOV IZ JEKLA IN ALUMINIJEVIH ZLITIN
Mentor: prof.dr. Matija Fajdiga
Somentorja: prof.dr. Vatroslav Grubišić
prof.dr. Jože Vižintin
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V strojništvu, še zlasti pri gradnji vozil, letal in druge transportne tehnike, jeklene materiale čedalje bolj pogosto nadomeščajo z lahkimi zlitinami, predvsem na osnovi aluminija ter s plastičnimi in kompozitnimi materiali. Zaradi številnih dobrih lastnosti in relativnih prednosti v primerjavi s klasičnimi materiali (razmeroma majhna teža in visoka trdnost, odpornost proti koroziji, dobre tehnološke lastnosti, možnost ponovne predelave itn.) aluminijeve zlitine v zadnjem času nadomeščajo jekla tudi pri izdelavi različnih tehnološko zahtevnih in visoko obremenjenih konstrukcijskih elementov.

Za gradnjo modernih konstrukcij, ki so praviloma grajene iz različnih gradiv (jeklo, aluminijeve zlitine, les, umetni materiali, kompoziti in podobno), je še posebno pomembno, kako se obnašajo zveze delov iz različnih gradiv. Zato se raziskovalci že vrsto let trudijo zagotoviti dovolj parametrov za načrtovanje in razvoj takšnih zvez in za spremljanje stanja takih konstrukcij v eksploataciji.

Poseben pomen imajo zveze aluminijevih zlitin in jekla. Eden najpomembnejših problemov pri zvezah delov iz jekla in aluminijevih zlitin je nosilnost dotika obeh gradiv, preko katerega se prenašajo dinamične obremenitve. Izkušnje v svetu so pokazale, da je najbolj problematičen prenos upogibnih momentov iz aluminijeve zlitine na del iz jekla. Tak primer nastopa povsod tam, kjer so dinamično obremenjene konstrukcije iz aluminijeve zlitine naslonjene in podprte z jeklenimi podporami. Ali je to naleganje aluminijevega platišča na jekleno pesto kolesa na vozilu ali pa je to aluminijeva sendvič (izolirana) strešna konstrukcija, odprta na jekleno konstrukcijo. Problemi imajo enake zakonitosti. Pri inženirskem delu je želeno napovedati utrujenostne poškodbe v nalegu obeh delov in trajanje takšne zveze do porušitve. Pri spremljanju obratovanja je želeno napovedati, kdaj je obremenitev kritično poškodovala zvezo obeh delov.

Raziskave so pokazale, da v odvisnosti od vrste materiala in površinske obdelave ter od parametrov preskusov nastopata dve obliki porušitve: porušitev v polju izven območja spoja in porušitev v območju zunanjega roba spoja. V ozkem pasu zunanjega roba spoja, širine od 0,7 do 1 mm, nastopajo različne poškodbe in utrujenostne razpoke, ki kažejo vse značilnosti vpliva torne obrabe. Poroznost in napake v strukturi ter lastnosti materiala močno vplivajo na dinamično zdržljivost ter na obnašanje materiala v spoju in način porušitve. Pomemben vpliv na dinamično oz. obratovalno trdnost in na mehanizem porušitve imajo površinska obdelava ter velikost in zaporedje amplitud obremenitev.

Aleš Lavrič

Magistrsko delo:
KARAKTERIZACIJA PROCESA PROIZVODNJE KOMUTATORJEV
Mentor: prof.dr. Igor Emri
Fakulteta za strojništvo, Univerza v Ljubljani

V sodobni masovni proizvodnji je zagotavljanje stalne kakovosti izdelkov ob sočasnem povečevanju produktivnosti eden od najpomembnejših dejavnikov uspešnega poslovanja. Dober primer izdelka velikoserijske proizvodnje je komutator, katerega nosilni del je izdelan iz polimernega materiala na osnovi fenolnih smol. V njegovem proizvodnem procesu nastopa množica fizikalnih parametrov in človeški dejavnik, ki z različno intenziteto vplivajo na lastnost materiala in na kakovost končnega izdelka. Kakovost komutatorja je vezana predvsem na zagotavljanje optimalnih lastnosti vgrajenega polimernega materiala. Analiza vpliva človeškega faktorja in vpliva tehnoloških ter fizikalnih parametov na material in na končni izdelek je pokazala, da je vpliv človeškega dejavnika na produktivnost prevladujoč.

V nagrajenem delu je z vidika zagotavljanja kakovosti izdelkov obravnavana problematika proizvodnje komutatorjev. Slednji so sestavljeni iz bakrene kletke in nosilnega srednjega dela, ki zagotavlja trdnost in geometrijsko stabilnost izdelka. Nosilni del je izdelan iz kompozita na osnovi fenolnih smol s postopkom injekcijskega brizganja. Razvoj novih generacij komutatorjev gre v smeri vedno večjih obratovalnih hitrosti, predvsem za gradnjo nove generacije neslišnih gospodinjskih aparatov. Komutatorji bodo imeli izredne obratovalne pogoje, ki bodo zahtevali izjemno natančno geometrijo in homogenost srednjega dela komutatorja. Obe lastnosti sta pogojeni s kakovostjo polimernega materiala in temperaturno-mehanskimi-vlažnostnimi pogoji, ki jim je bil material izpostavljen pred proizvodnim procesom in med njim. Zagotavljanje visoke kakovosti izdelkov zahteva razumevanje vedenja polimernega materiala pred, med proizvodnim procesom in tudi pozneje v uporabi.

Primož Vrenk

Diplomsko delo:
RAZVOJ IN RAZISKAVE LAHKIH GRADBENIH PLOŠČ ZA IZKORIŠČANJE SONČNE ENERGIJE
Mentor: doc.dr. Sašo Medved
Fakulteta za strojništvo, Univerza v Ljubljani

Osnovna naloga zgradbe je, da nas ščiti. V sodobnih zgradbah moramo uporabnikom zagotoviti optimalne bivalne pogoje tudi z energijo. Med pomembne dejavnike bivalnega ugodja štejemo temperaturo v prostoru ter vlažnost, gibanje in sestavo zraka. Vse te parametre uravnavamo s strojnimi instalacijami, ki so velik porabnik energije. Prav energija je velik strošek, zato je mogoče z zmanjšanjem njene rabe doseči prihranke.

Velik vpliv na strošek energije ima kakovost izolacije objekta in uporaba sončne energije npr. za ogrevanje in pripravo tople vode. Z izolacijo objekta ne dosežemo samo manjših toplotnih izgub, ampak tudi enakomerno razporeditev temperature v notranjosti zgradbe.

Notranji viri energije (lokalna ogrevala) nam dajejo določen delež potrebne energije za ogrevanje, vendar imajo slabost v tem, da temperatura v prostoru zelo niha in zato se zmanjša ugodje v prostoru, v katerem se uporabljajo. Hkrati ti viri tudi onesnažujejo okolje, čemur se želimo izogniti.

Sončno energijo lahko izkoriščamo neposredno in posredno. Prvi način se izkorišča predvsem pozimi in v prehodnih obdobjih za ogrevanje zraka v notranjosti stavbe ali poleti za ogrevanje vode (bazen). Če želimo bolj izkoriščati neposredno ogrevanje notranjega zraka mora imeti stavba več steklenih površin, kar poveča toplotne izgube skozi tako steno. Uporaba sončne energije se lahko izkaže kot zelo koristna tudi poleti za ogrevanje vode, za kar se uporabljajo posredni sistemi. Velik razvoj so danes dosegli tudi velikopanelni solarni sistemi (sončna streha), ki se vedno več tudi uporabljajo.

Ker uporaba sončne energije ne povzroča onesnaževanja okolja, bi se bilo treba osredotočiti na to, da bi jo v čim večji meri izkoriščali in tako tudi pripomogli k zmanjšanju stroškov energije. Osredotočiti bi se morali predvsem na iskanje in razvoj primerne nove tehnologije, namenjene široki uporabi in cenovno ugodni.

Magisteriji, diplome

MAGISTERIJI

Na Fakulteti za strojništvo Univerze v Mariboru sta z uspehom zagovarjala svoji magistrski deli, in sicer:

dne 7. januarja 2002: **Josip Tavčar**, delo z naslovom: “Primerjava diferencialne optične absorpcijske spektroskopije in točkovnih metod merjenja” in

17. januarja 2002: **Jasenko Perenda**, delo z naslovom: “Mehanska samoojačitev debelostene cevi”.

S tem sta navedena kandidata dosegla akademsko stopnjo magistra tehničnih znanosti.

DIPLOMIRALI SO

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

dne 25. januarja 2002: Martin FAJT, Tomaž HLADNIĆ, Klemen KOLENC, Boštjan ŽEN.

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

dne 31. januarja 2002: Tomaž-Drago ČOPAR, Simon GRADIŠNIK, Igor PALIR, Anton PERNAT, Viljem PUŠNIK.

*

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

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dne 15. januarja 2002: Janez DOLENC, Refik FOČIĆ, Boris PLOS, Aleš TORKAR.

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

dne 31. januarja 2002: Justin BOŽIČ, Benjamin GONC, Ismet MAŠIĆ, Janez ZABUKOVNIK.

*

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

dne 31. januarja 2002: David EKART, Boris MATKO.

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Instructions for Authors

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 urejevalniku 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:
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- 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.

Sprejem člankov in avtorske pravice

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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.

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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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