

Kalibracija koordinatnih merilnih naprav v laboratorijskih razmerah

Calibration of Coordinate Measuring Devices in the Laboratory Conditions

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Prispevek obravnava problematiko sledljivosti meritev v trikoordinatni merilni tehniki. Prikazan je predlog nove metode za kalibracijo trikoordinatnih merilnih naprav, ki se od sedanjih metod razlikuje predvsem po boljši sledljivosti. Meritve, ki jih predvideva metoda, se izvajajo hkrati z laserskim interferometrom in končnimi merili - etalonimi. Pomembno je, da je za vsa uporabljena merila mogoče zagotoviti sledljivost na primarni etalon za dolžino. Postopek je povsem prirejen načelu delovanja koordinatne merilne naprave, omogoča pa tudi natančno analizo vplivov geometrijskih odstopkov naprave na merilni pogrešek. Preizkušena je v laboratoriju za tehnološke meritve, narejena pa je tudi primerjava z znanimi metodami na podlagi rezultatov preskusne kalibracije. Ugotovili smo, da je ponovljivost rezultata kalibracije boljša kakor pri podobni metodi, ki je izpeljana iz postopka za nadzor obdelovalnih strojev.

Ključne besede: naprave merilne trikoordinatne, kalibracija naprav, sledljivost, etaloni, interferometri laserski

The aim of the paper is to emphasise the problem of the traceability of measurement in the three-coordinate measuring technique. A proposal for a new method for the calibration of three-coordinate measuring machines is introduced in the paper. In contrast to the existing calibration methods, the introduced method is totally traceable. Measurements used in the new method are performed simultaneously with a laser interferometer and gauge blocks - standards of measurement. It is very important that traceability to the primary standard for length can be assured for both measuring devices. The method is completely adopted to the operational principle of the coordinate measuring machine and assures exact analysis of the influences of geometrical deviations on the measuring error. It was tested in the laboratory for production measurement. The test included comparison with the existing calibration methods. It was found that the repeatability of calibration results was much better as with the existing method, which was developed from the method for the machine tool check.

Keywords: coordinate measuring devices, calibration of devices, traceability, gauge blocks, laser interferometer

0 UVOD

Sledljivost meritev, ki jo zagotavljamo s kalibracijo merilnih naprav in etalonov, je osnova za kakovost merilnega rezultata. V trikoordinatni tehniki problem sledljivosti še ni rešen, saj še ne obstaja splošna metoda kalibracije, ki bi ustrezala vsem meroslovnim zahtevam. Dandanes so v rabi predvsem postopki kalibracije posameznih koordinatnih osi in tipalnega sistema koordinatne merilne naprave (KMN), ki pa ne zagotavlja sledljivosti meritve v treh koordinatah. Razviti sta tudi dve metodi kalibracije, ki sta vezani na konkretno merilno probleme. Kalibracijska metoda, ki je predstavljena v članku, je nov način reševanja sedanje problematike. Poleg tega, da zagotavlja sledljivost meritev, ima tudi dobro analizno zmožnost in je prirejena načelu merjenja s koordinatno merilno napravo.

0 INTRODUCTION

Traceability of measurement, which is assured by means of calibration, is a basic condition for quality measurement results. The problem of traceability in the coordinate measuring technique has not yet been solved because there exist no universal calibration of Coordinate Measuring Method (CMM) components that would fulfil all metrological requirements. The methods for calibration of CMM components, which are mostly used at present, do not assure traceability of coordinate measurements. Therefore, two calibration methods for solving specific measuring problems have been developed. The calibration method presented in the paper uses a new concept for solving the existing problem. It assures traceability of the calibration and is able to analyse influences on the measuring error. The method is completely adapted to the operational principle of the coordinate measuring machine.

1 KALIBRACIJA TRIKOORDINATNIH MERILNIH NAPRAV

Zaradi raznolikosti pogojev uporabe in merilnih nalog je zagotavljanje sledljivosti zelo zahtevna naloga. Kalibracija KMN po definiciji v [3] in [4] je velik problem, saj še nikomur ni uspel razviti univerzalne kalibracijske metode. Obstaja sicer vrsta metod (tudi standardiziranih) za kalibracijo posameznih komponent oziroma koordinatnih osi [6], vendar je iz rezultatov delnih kalibracij zelo težko sklepati o merilnem pogrešku in negotovosti pri merjenju trikoordinatnega objekta (npr. valja, ravnine, krogla itn.). Obstajata tudi dva postopka za zagotavljanje sledljivosti trikoordinatnih meritov [1], [2] in [6], vendar je eden (primerjalni postopek) namenjen le za manj zahtevne meritve, drugi (navidezna oz. virtualna KMN) pa je zelo zahteven, dolgotrajen in vprašljiv glede sledljivosti etalona.

2 NEGOTOVOST MERITVE IN STOPNJA ZAUPANJA

Uradna definicija izraza "negotovost meritve" po [3] je naslednja:

Negotovost meritve je parameter, pridružen merilnemu rezultatu, ki karakterizira raztres vrednosti, ki bi jih lahko smiselno pripisali merjeni veličini.

Omenjeni parameter je lahko npr. standardni odmik (ali njegov mnogokratnik) ali pa polovična širina intervala z določenim nivojem zaupanja.

Negotovost meritve združuje v splošnem veliko komponent. Nekatere od teh komponent lahko ovrednotimo z uporabo statističnih porazdelitev rezultatov serij meritov - karakterizira jih eksperimentalni standardni odmik (tip A ovrednotenja negotovosti meritve). Druge komponente, ki jih prav tako karakterizira standardni odmik, pa ovrednotimo z uporabo predpostavljenih verjetnostnih porazdelitev po izkušnjah ali drugih informacijah (tip B ovrednotenja negotovosti meritve).

Osnova za oceno negotovosti je matematični model meritve, ki podaja zvezo med merjeno veličino Y in vhodnimi veličinami X_1 do X_N :

1 CALIBRATION OF THREE-COORDINATE MEASURING MACHINES

Calibration of the CMMs is a very complex problem because of different operating conditions and measuring tasks. It is very difficult to calibrate CMMs in accordance with the definition in [3] and [4] since an universal calibration procedure has not yet been developed. We can use a lot of methods (also standardised ones) for the calibration of the components or coordinate axes [6], but these partial calibrations give no data about measuring errors and uncertainty in the measurement of a three-coordinate object (e.g. cylinder, plane, ball, etc.). There exist only two methods for assuring traceability of coordinate measurements [1], [2] and [6]. One (comparative method) is suitable only for simple geometry, the other one (virtual CMM) is very complex, requires long calibration time, and the standard used is not traceable.

2 UNCERTAINTY OF MEASUREMENT AND LEVEL OF CONFIDENCE

The formal definition of the term "uncertainty of measurement" in [3] is given as follows:

Uncertainty of measurement is a parameter, associated with the result of a measurement, which characterises the dispersion of the values that could reasonably be attributed to the measurand.

This parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterised by experimental standard deviation (type A evaluation of uncertainty). The other components, which can also be characterised by standard deviations, are evaluated from assumed probability distributions based on experience or other information (type B evaluation of uncertainty).

Estimation of uncertainty is based on the mathematical model of a measurement, which defines the relation between the measured value Y and the input quantities X_1 to X_N :

$$Y = f(X_1, X_2, \dots, X_p, \dots, X_N) \quad (1)$$

Funkcija f mora vsebovati vse veličine, vključno z vsemi popravki 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.

Function f should contain all the quantities, including corrections and correction coefficients, which may contribute an important component of uncertainty to the measurement result. Correct definition of a mathematical model of a measurement (1) is very important for the estimation of the uncertainty of measurement.

S.I.P. Standardne negotovosti posameznih vstopnih veličin podamo kot eksperimentalne standardne odmike:

Če so vse vstopne veličine neodvisne, izrazimo skupno standardno negotovost z enačbo:

$$u(x_i) = s(\bar{X}_i) \quad (3)$$

Če so vstopne veličine med seboj odvisne, moramo upoštevati še povezanost.

Razširjeno negotovost meritve, ki jo pridružimo merilnemu rezultatu, dobimo tako, da standardno negotovost pomnožimo s faktorjem prekrivanja k , ki ga izberemo v odvisnosti od zahtevane stopnje zaupanja. Pri normalni porazdelitvi ustreza faktor 2 stopnji zaupanja 95,45%, faktor 3 pa stopnji zaupanja 99,73%.

3 NEGOTOVOST MERITVE S KMN

Negotovost merjenja s KMN lahko obravnavamo po različnih stopnjah:

- negotovost izmerjenih koordinat merilne točke,
- negotovost izračuna razdalje med dvema točkama,
- negotovost izračuna lege in velikosti geometrijskega elementa (premica, krog, valj itn.).

Negotovosti koordinat in negotovost razdalje med točkama lahko izrazimo z matematičnim modelom in je zato ocena merilne negotovosti dokaj preprosta in natančna. Pri izračunu lege in velikosti geometrijskega elementa je nemogoče definirati linearni matematični model, zato moramo določiti merilno negotovost eksperimentalno.

4 GEOMETRIJSKI ODSTOPKI KMN

Sistematični geometrijski odstopki so sestavljeni iz odstopkov posameznih koordinatnih osi in odstopkov pravokotnosti med osmi [6]. Pri pravokotnosti moramo biti zelo previdni, saj se spreminja vzdolž osi glede na lego pomicne komponente (npr. portal) KMN. Najbolje je določiti pravokotnost v izhodišču koordinatnega sistema in potem glede na kotne odstopke v obravnavanih oseh izračunati spremembe odstopka pravokotnosti glede na izhodiščni položaj. Geometrijske odstopke v osi x prikazuje slika 1. Enaki odstopki se pojavljajo tudi v drugih dveh oseh. Odstopki ene osi vplivajo na merilni pogrešek v vseh oseh.

S.I.N. Standard uncertainties of the input values are defined as experimental standard deviations:

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 \cdot u^2(x_i) \quad (4)$$

If some of the input quantities are correlated, the correlation should be considered.

Expanded uncertainty, which is associated with the measurement result, is obtained by multiplying the standard uncertainty by a coverage factor k , which is chosen regarding the required level of confidence. In normal distribution, the coverage factor 2 corresponds to the level of confidence 95.45% and factor 3 to the level of confidence 99.73%.

3 UNCERTAINTY OF MEASUREMENT WITH CMM

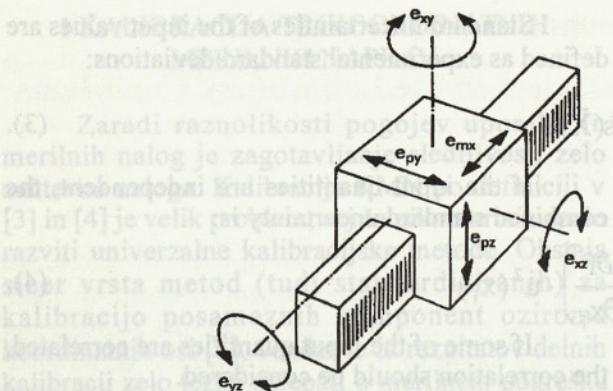
Uncertainty of measurement with CMM can be treated at different levels:

- uncertainty of measured coordinates of a measurement point,
- uncertainty of the calculation of a distance between two points,
- uncertainty of the calculation of the position and the dimension of a geometrical element (straight line, circle, cylinder, ...).

Uncertainties of measured coordinates and the uncertainty of a distance can be estimated by means of mathematical models. The estimation is therefore quite simple and accurate. Estimation of the uncertainty of the calculation of the position and the dimension of a geometrical element is more complicated, because it is impossible to establish a linear mathematical model. In this case the uncertainty should be estimated in an experimental way.

4 GEOMETRIC ERRORS OF CMM

Systematic geometric errors contain errors of the coordinate axes and errors of perpendicularity between the axes [6]. Perpendicularity errors change along the axes. They depend on the position of a moving component of the CMM (e.g. portal). Therefore, we must be very careful when establishing perpendicularity errors. The best approach is to measure perpendicularity errors in the zero point of the coordinate system and then to recalculate them in other points using the results of angular (pitch and yaw) errors along the axes. Geometric errors in x axis are shown in Figure 1. The same errors appear in the other two axes. Errors in one axis influence measuring error in all axes.



Sl. 1. Geometrijski odstopki KMN
Fig. 1. Geometrical errors of CMM

5 POSTOPEK ZA KALIBRACIJO KMN V LABORATORIJSKIH RAZMERAH

Pri kalibraciji v laboratorijskih razmerah moramo zagotoviti sledljivost merjenja na primarni etalon in hkrati čim bolj natančno oceniti negotovost meritve. Obstajata dve metodi, ki ustreza vsem zahtevam. To sta primerjalna metoda in metoda navidezne ali virtualne KMN. Obe metodi sta opisani v [1] in [2]. Za obe metodi je značilno, da moramo kalibrirati KMN za vsak merilni problem posebej. Prva metoda je namenjena le meritvam primitivnih oblik (eno- in dvokoordinatnih), saj kalibriramo napravo pred vsako meritvijo na etalonu, ki mora imeti podobno obliko kakor merjenec. Pri metodi navidezne KMN simuliramo meritev na računalniku in na podlagi znanih geometrijskih odstopkov naprave predvidimo odstopke pri meritvi elementa z idealno obliko in dimenzijsami. Natančnost metode navidezne KMN je v največji meri odvisna od natančnosti meritve geometrijskih odstopkov naprave. Če meritve geometrijskih odstopkov niso sledljive, potem tudi kalibracija KMN ni sledljiva.

Pri raziskovanju metod za kalibracijo KMN posvečamo v laboratoriju za tehnološke meritve največjo pozornost prav sledljivosti, saj je ta pogoj za akreditacijo kalibracijskih in merilnih metod v skladu s standardom EN 45001 in določili EAL (Evropsko združenje za akreditacijo laboratorijs). Razvili smo modificirano merilno metodo z laserskim interferometrom za določanje geometrijskih pogreškov KMN, ki rabi kot temelj za kalibracijsko metodo navidezne KMN. Bistvena prednost te metode pred sedanjo metodo je v tem, da nova metoda upošteva merilno načelo KMN, medtem ko je bila stara metoda izdelana na podlagi načela obdelovalnih strojev. Nova metoda zagotavlja tudi sledljivost meritve.

- e_{mx}** - odstopek merilnega sistema
e_{py} - odstopek premosti v smeri osi y
e_{pz} - odstopek premosti v smeri osi z
e_{xz} - kotni odstopek v ravni xz
e_{xy} - kotni odstopek v ravni xy
e_{yz} - kotni odstopek v ravni yz

5 METHOD FOR CALIBRATION OF CMM IN THE LABORATORY CONDITIONS

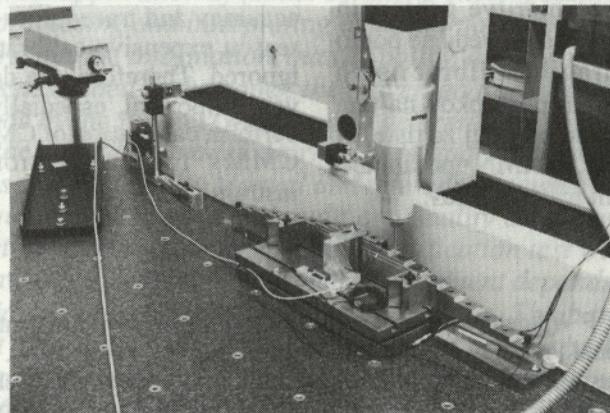
Calibration in laboratory conditions should assure traceability to the primary standard and also give an accurate information about the uncertainty of measurement. At the moment there exist two methods, which fulfil both requirements. One is the comparative method and the other is the method of virtual CMM. Both methods are described in [1] and [2]. The common characteristic of both methods is that a separate calibration is needed for every single measuring problem. The first method can be used only for primitive shapes (one- or two-coordinate), because the CMM is calibrated using a standard similar to the measuring object. The virtual CMM method is based on a computer simulation of a measurement and can also be used also for more complex shapes. Before the simulation it is necessary to establish geometrical errors of the CMM which are later used for predicting the error of measurement of an element with ideal shape and dimensions. The accuracy of this method directly depends on the accuracy of the measurement of geometric errors. If the measurement of geometric errors is not traceable, then the calibration method is also not traceable.

In the research of methods for CMM calibration in the laboratory for production measurement the main attention is paid to the traceability, because it is one of the basic requirements for the accreditation of calibration and measurement procedures according to the standard EN 45001 and EAL (European Association for Accreditation of Laboratories) guides. A modified method for the establishment of geometric errors of CMM using a laser interferometer was recently developed in our laboratory. This method should be used as a part of the virtual CMM method. The main advantage of this method in comparison with the old one is that it concerns the main principle of the coordinate measuring technique, whereas the old one was based on the machine tool principle. The new method also properly assures traceability.

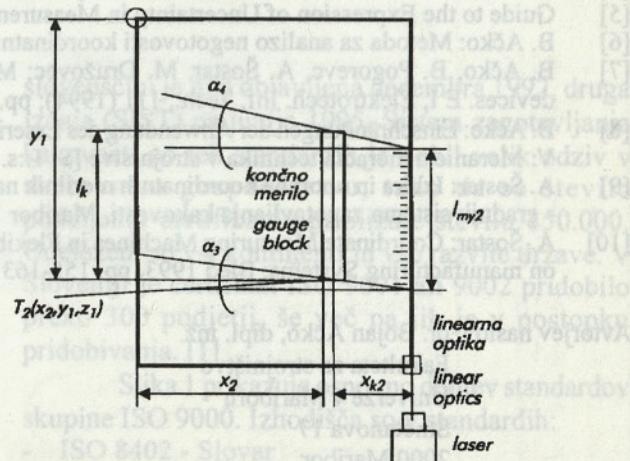
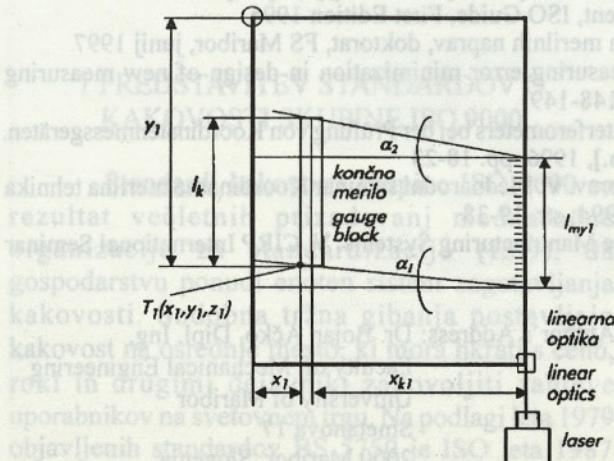
5.1 Postopek merjenja geometrijskih odstopkov KMN z laserskim interferometrom in končnimi merili

Pri tem postopku merimo geometrijske odstopke KMN z laserskim interferometrom, vendar v nasprotju s staro metodo v vsaki merilni točki tipamo površino merjenca. Merjenec pomeni končno merilo. Za različne merilne dolžine uporabljamo različna končna merila (od 100 do 1000 mm). Ker je merjenec kalibrirano končno merilo, imamo pri merjenju tudi primerjavo med merilno vrednostjo laserskega interferometra in dogovorno pravo vrednostjo etalona. Primer meritve v osi y portalne KMN je prikazan na slikah 2 in 3.

Negotovost meritve določamo na dva načina, ki jih predpisuje vodilo ISO [5]. Celotna metoda je obdelana po komponentah in dodatno še po statističnem vrednotenju. Zato vsako meritve izvajamo vsaj 20 krat. Rezultati meritve so pokazali glede na staro metodo znatno večjo stabilnost in tudi natančnost. Problem stare merilne metode je namreč v tem, da je pri meritvi odstopkov tipalo KMN v zraku (ne tipa).



Sl. 2. Meritev odstopkov pozicioniranja KMN v y osi
Fig. 2. Measurement of the positioning errors in y axis



5.1 Method of measurement of geometric errors of CMM using laser interferometer and block gauges

In this method the geometric errors of CMM are measured using laser interferometer, but unlike the old method, surface of measuring object is probed in each measuring position. The measuring object in this case is a block gauge. Different gauge blocks are used for different measured lengths (from 100 to 1000 mm). Since the measuring object is a calibrated standard of measurement, the comparison of the measured value of the laser interferometer with a conventional true value of the standard is possible. An example of the measurement in y axes of a portal CMM is shown in Figures 2 and 3.

Uncertainty of measurement is estimated in two ways, defined in the ISO guide [5]. The whole method is treated by components and additionally by using statistics. Therefore, each measurement is repeated at least 20 times. The results of the experimental measurement have shown much better stability and accuracy in comparison with the old method. The main problem of the old method is that the probe is in the air (is not probing) at the moment of measurement of an geometric error. This does not

Sl. 3. Poziciji za primerjalno merjenje etalonov s KMN in laserskim interferometrom

Fig. 3. Positions for the comparative measurement of block gauges by CMM and the laser interferometer

To ne pomeni dejanskega stanja pri meritvi s KMN. Zato lahko dobimo pri kalibraciji zelo različne rezultate od tistih pri meritvi. Takšna kalibracija pa je seveda povsem neustrezna.

6 SKLEP

Kalibracija je namenjena ugotavljanju odstopkov merilne naprave. Če hočemo, da bodo rezultati kalibracije zanesljivi, morajo biti vse meritve, ki jih kalibracija obsega, sledljive na primarni oz. državni etalon. Pri koordinatni merilni tehniki obstajata trenutno le dve metodi, ki ustrezata vsem kriterijem prave kalibracije. Ti dve metodi (predvsem navidezna KMN) sta zelo dragi, saj je treba napravo kalibrirati pred vsako meritvijo. To seveda tudi poveča zastojne čase naprave. Težko je verjeti, da lahko industrija prenese tako drage postopke, zato bodo verjetno v industriji še nadalje v rabi tako imenovane "metode ugotavljanja zmožnosti naprave" (s končnimi merili, stopničastimi merili, kontrolnimi telesi, nastavnimi obroči itn.), ki niso pravi kalibracijski postopki, vendar pa dajo določene podatke o natančnosti KMN. Običajno so to podatki za linearne meritve v posameznih oseh.

V laboratorijskih razmerah, kjer moramo pogosto uporabljati KMN za meritve zahtevnih merjencev z veliko natančnostjo, se seveda ne bomo mogli izogniti uporabi dragih kalibracijskih postopkov. Zato je razvoj novih postopkov na tem področju izredno pomemben, še posebej za tiste, ki kalibrirajo te naprave in za tiste, ki KMN uporabljajo pri kalibraciji drugih merilnih instrumentov.

reflect the real conditions of the measurement with the CMM. Therefore, calibration results may differ from those of the measurement, and such calibration is, of course, not valid.

6 CONCLUSION

Calibration is used for establishing deviations of measuring instruments. If we want reliable results of calibration, all measurements used in the calibration procedure must be traceable to the primary res. national standard. At present there exist only two methods for the calibration of CMMs at the moment that fulfil all the criteria of a real calibration. However, these two methods (especially virtual CMM) are very expensive, because the machine needs to be calibrated before each measurement. Such calibration also increases the dead time of the machine. It is hard to believe that industry will accept such expensive methods. Therefore, performance tests (methods using gauge blocks, step gauges, artefacts, gauge rings, etc.) will still be used at the industry level for a certain time to come. These tests are not real calibration methods, but they do at least give us some information about the accuracy of a machine. This information is usually data about linear measurements in the coordinate axes and diagonals.

In the laboratories, CMMs are often used for complex measurements requiring a high level of accuracy and traceability at the same time. For this reason expensive calibration procedures cannot be ignored. Therefore, the development in this area is very important, especially for the laboratories that perform calibration of CMMs and for those who use CMMs for calibration of other measuring instruments.

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