

Ugotavljanje vpliva konstrukcije na merilno negotovost koordinatnih merilnih naprav z metodo končnih elementov

Determination of the Influence of the Structure on the Measuring Uncertainty of Coordinate Measuring Devices by the Finite Element Method

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Natančno merjenje je glavni cilj vsakega merjenja v metrologiji in velike zahteve po natančnosti lahko dandanes zagotovijo le koordinatne merilne naprave. Bistvo članka je v tem, da poudari pomen tistih dejavnikov v konstrukcijski izvedbi koordinatne merilne naprave (KMN), ki zmanjšujejo merilno negotovost KMN in s tem vplivajo na kakovostno merjenje; najpomembnejša dejavnika sta: ustreznega geometrijskega oblika konstrukcijskega dela KMN in ustrezeno izbrani material tega dela. Metoda končnih elementov (MKE) je bila uporabljena za iskanje optimalne izvedbe konstrukcije KMN. Iskanje najutrejnješje izvedbe konstrukcije delov KMN z MKE omogoči, da najdemo konstrukcijsko izvedbo KMN z najmanjšo merilno negotovostjo. Prikazana je torej zmožnost MKE pri analizi deformacijskega odziva KMN, seveda za različne materiale glavnih delov portalja KMN, po čemer se bo dalo sklepati o najustrejnješji izvedbi KMN za natančno merjenje. Za raziskovalni vzorec je bila uporabljena KMN OPTON UMC-850, ki je nameščena na Fakulteti za strojništvo v Mariboru.

Ključne besede: naprave merilne koordinatne, negotovost merilna, konstruiranje optimalno, metode končnih elementov

Precise measuring is the principal purpose of all measuring in metrology. Today the high claim of precision can only be assured by coordinate measuring devices. The essence of this paper is to emphasize the signification of all activities regarding the design of coordinate measuring machines (CMM), which reduce the measuring uncertainty of CMM; the most significant activities are: optimal geometric form of the structural part of CMM and optimally selected material of this part. The finite element method (FEM) was used for research into the optimally CMM design. The searching for optimal structural parts of CMM with FEM enables to find the design form of CMM with smaller measuring uncertainty. However, the ability of FEM in analysing deformations response of CMM is presented for different materials of the main parts of the CMM portal, enabling the optimal execution of CMM for the purpose of precise measuring. Research was made on CMM OPTON UMC-850, installed at the Faculty of Mechanical Engineering in Maribor.

Keywords: coordinate measuring devices, measuring uncertainty, optimal design, finite element methods

0 UVOD

Natančno merjenje je glavni cilj vsakega postopka v metrologiji in velike zahteve po natančnosti lahko dandanes zagotovijo le koordinatne merilne naprave. Ta članek poudarja pomen tistih dejavnikov v konstrukcijski izvedbi koordinatne merilne naprave, ki zmanjšujejo merilno negotovost KMN in najpomembnejša dejavnika sta: ustreznega geometrijskega oblika konstrukcijskega dela KMN in ustrezeno izbrani material tega dela.

Odkrili smo prednosti optimiranja z MKE, s katerimi iščemo konstrukcijsko izvedbo KMN z najmanjšo merilno negotovostjo: z izbiro ustreznega materiala in ustrezne geometrijske oblike konstrukcijskih delov KMN po MKE ter s primerno kombinacijo materialov konstrukcijskih delov merilne naprave lahko vplivamo na doseganje velike natančnosti merjenja s KMN; šele optimalno zasnovanata izvedba KMN lahko zagotovi prek zelo natančnega merjenja tudi manjšo merilno negotovost KMN.

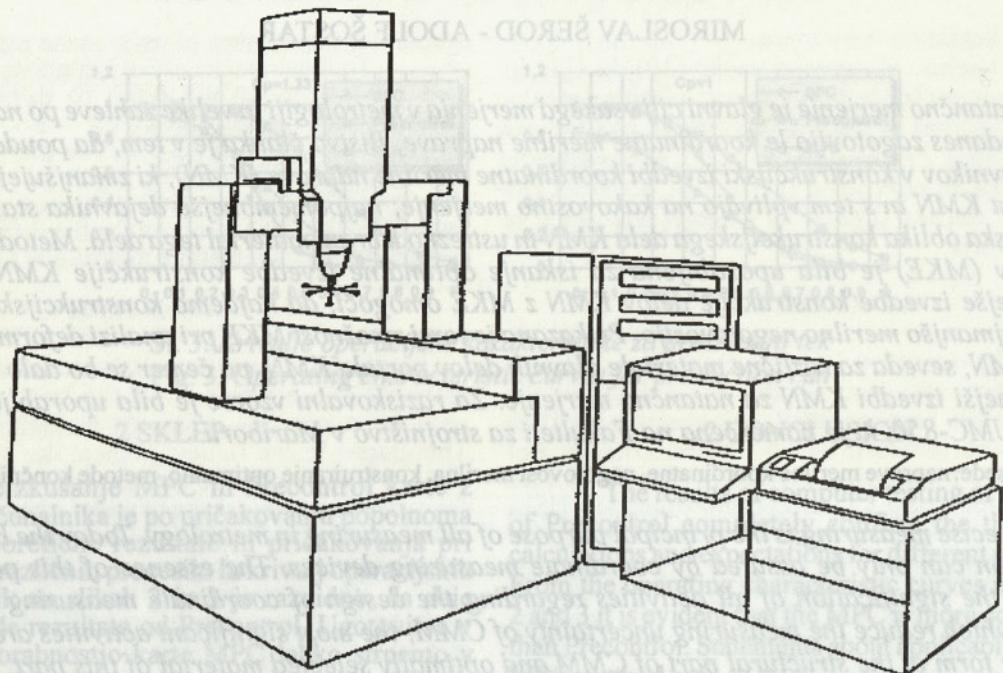
0 INTRODUCTION

Precise measuring is the principal purpose of all measuring in metrology. Today the high claim of precision can only be assured by coordinate measuring machines. This paper emphasizes the signification of all activities involved in the CMM design, which reduce the measuring uncertainty of CMM. The most significant activities are optimal geometric form of the structural part of CMM and the optimal selected material of this part.

We discovered preferences of optimal designing with FEM, with aid of which we search the structure of CMM with the smallest measuring uncertainty: we can influence the high precision of measuring on CMM with FEM by selection of the suitable material, with an optimal geometric form of structural parts and with suitable combination of materials of the structural parts; only the optimally designed structure of CMM assures the smaller measuring uncertainty of CMM.

1 POTEK RAZISKAVE

Raziskava vplivov konstrukcije na merilno negotovost KMN z MKE je bila izvedena na KMN ZEISS OPTON UMC-850, ki je predstavljena na sliki 1.



Sl. 1. Portalna konstrukcija KMN OPTON UMC-850
Fig. 1. The portal project structure of CMM OPTON UMC-850

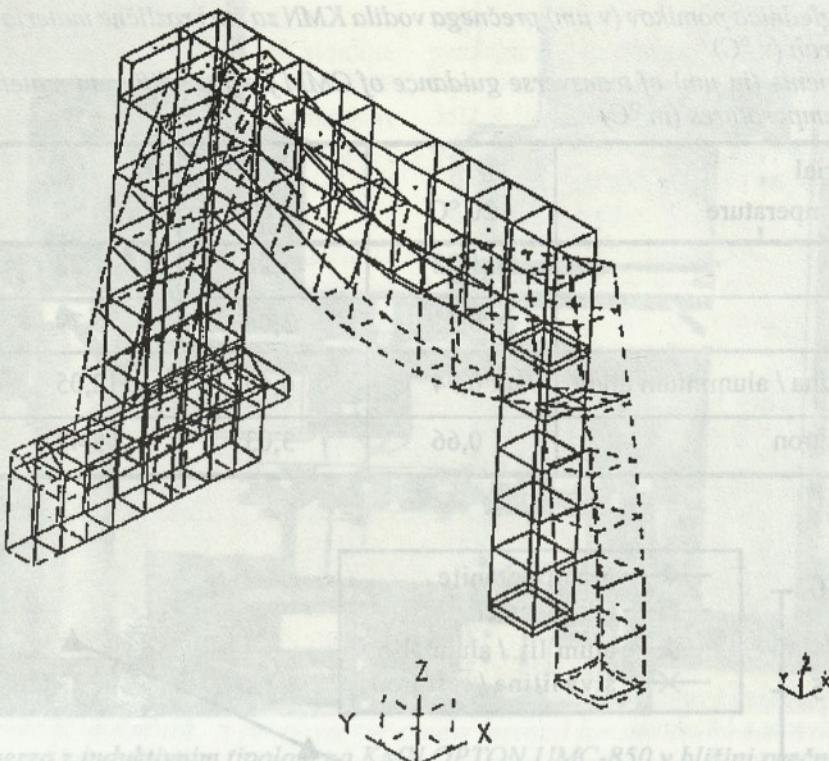
Raziskava je bila usmerjena na iskanje najprimernejše konstrukcije portala KMN, predvsem prečnega vodila portala, ki je za natančno merjenje najbolj odločilen del KMN, saj nosi pinolo z merilnim tipalom, ki je namenjeno neposrednemu merjenju. Raziskava je bila izvedena z uporabo MKE (BERSAFE - za analize pomikov in deformacij in FLHE - za toplotne analize) na računalniku Micro-VAX II in v njej je bilo vključenih približno 300 računskih mehanskih in toplotnih analiz za najbolj obremenjene dele portala KMN OPTON. V preglednici in diagramu je v nadaljevanju prikazan povzetek teh analiz z MKE na najbolj obremenjenem delu portala, to je na prečnem vodilu KMN OPTON. Z računsko analizo lahko določimo deformacijsko (pomiki) in napetostno stanje vsakega konstrukcijskega elementa posebej in dobimo predstavo o stanju obremenjene konstrukcije. Pomik obremenjenih delov pri spremembah temperature je bil glavno merilo analiz. Pomiki so resda majhni, vendar pri merilnih napravah odločilni, saj morajo njihove vrednosti zaradi zahtev po natančnosti biti v razredu tisočinke milimetra ($\pm 1 \mu\text{m}$).

Slika 2 prikazuje mrežni model mehansko in toplotno obremenjenih delov portala KMN; obenem pa predstavlja še mrežo deformacij portala.

Research of the influence of the CMM design on the measuring uncertainty with FEM was made on CMM ZEISS OPTON UMC-850, which is presented on figure 1.

The research was headed towards searching into an optimal structural parts of CMM portal, above all to the transverse guidance of the portal, which is the most decisive part for precise measuring of CMM, because it carries the pinole with measuring probe, meant for direct measuring. The research of an optimal CMM design was executed by means of FEM (BERSAFE - for analysis of displacement and strains and FLHE - for heat analysis) with the aid of the Micro-VAX II computer involving approximately 300 computations of mechanically and heat analysis for the most loaded parts of the CMM OPTON. The table and diagram present the summary of analysis with FEM on the most loaded area of the portal, i.e. on the transverse guidance of CMM OPTON. With the aid of computational analysis, displacements (deformations) and strains on each single element can be determined, showing their performance on state of loaded structure. The basis of analysis are displacements of loading parts during temperature changes. The displacements were truly very small. However, they were decisive for the measuring machines due to the demand that their accuracy class was to be within a thousandth of a millimeter ($\pm 1 \mu\text{m}$).

Figure 2 presents mesh models of the mechanically and thermally loaded parts of the CMM portal; at the same time it also represent the deformation mesh of portal.



Sl. 2. Mrežni model portala KMN OPTON UMC-850
Fig. 2. Mesh models of portal of CMM OPTON UMC-850

Preračun po MKE vključuje primerjavo kombinacije štirih materialov glavnih konstrukcijskih delov KMN (granit, jeklo, aluminijeva litina in siva litina) in različne temperature (med 20 in 26°C). V nadaljevanju se bomo usmerili le na dogajanja v prečnem vodilu portala KMN, ker neposredno vplivajo na merilno negotovost. Vemo, da na merilno negotovost KMN vplivajo zunanji in notranji vplivi. Med zunanje vplive uvrščamo vplive okolja, v katerem obratuje KMN, vpliv človeka - merilca in vplive merilnega predmeta, med notranje vplive pa uvrščamo vse tiste, ki nastanejo zaradi sestave KMN. Med vplivi okolja najbolj prevladuje vpliv temperature.

Analiza rezultatov je pokazala, da se je konstrukcija prečnega vodila KMN, ki je najšibkejši člen v portalni zasnovi KMN v pogledu povzročitve merilne nenatančnosti, deformirala po pričakovanjih. Prečno vodilo (med dvema stebroma KMN) se zaradi ploskovne obremenitve pinole na zgornjem delu upogibno deformira oziroma povesi v smeri delujoče ploskovne obremenitve s pinole. Ta deformacija oziroma povesi vpliva na merjenje. Granitno prečno vodilo ima sicer nekoliko večji pomik od jeklenega, vendar se mu deformacija pri spremembah temperature ne spreminja tako, kakor pri izvedbi iz jekla, torej izvedba vodila iz granita bolje prenaša temperaturne spremembe.

The calculation by FEM assumes combinations of four materials of the main structural part (granite, steel, aluminium alloy and cast iron) and several temperatures (between 20 and 26°C). Further on we shall concentrate only on what is going on in the transverse guidance of the CMM portal, because it directly influences the measuring uncertainty. We know that the internal and external influences exert an influence on the measuring uncertainty of CMM. The external influences are influences of the ambient in which CMM is working, influences of a person, i.e. measurer, and influences of the object to be measured. The internal influences are all those, which have arisen due to the mechanical design of CMM. The influence of the temperature is predominant.

The analysis of the results showed that the structure of the transverse guidance, being the weakest construction part of the portal project structure of CMM, was deformed as had been expected. Due to the surface loads on the upper part, the transverse guidance (between two pillars of CMM) shall bend in the direction of active surface loads from pinole. This deformation and displacement, respectively, influenced the measuring. The displacements were mainly continuously distributed, whereas strains were negligibly small. The transverse guidance made of granite has a little greater displacement than the one made of steel and is better with temperature changes.

Preglednica 1. Preglednica pomikov (v μm) prečnega vodila KMN za štiri različne materiale in pri različnih temperaturah (v $^{\circ}\text{C}$)

Table 1. Displacements (in μm) of transverse guidance of CMM for four different materials and also for different temperatures (in $^{\circ}\text{C}$)

material / material temperatura / temperature	20 $^{\circ}\text{C}$	22 $^{\circ}\text{C}$	24 $^{\circ}\text{C}$	26 $^{\circ}\text{C}$
granit / granite	1,28	1,28	1,28	1,28
jeklo / steel	0,31	3,04	5,79	8,55
aluminijeva zlitina / aluminium alloy	0,94	6,45	12,05	17,6
siva litina / cast iron	0,66	3,03	5,47	7,91

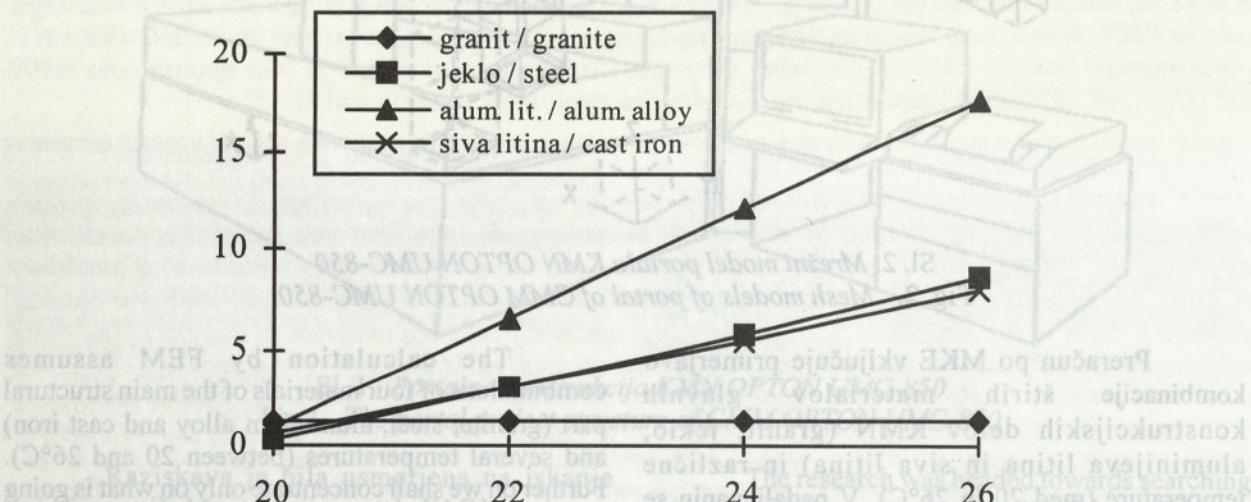


Diagram 1. Diagram pomikov (na ordinati v μm) prečnega vodila KMN za štiri različne materiale in pri različnih temperaturah (na abscisi v $^{\circ}\text{C}$)

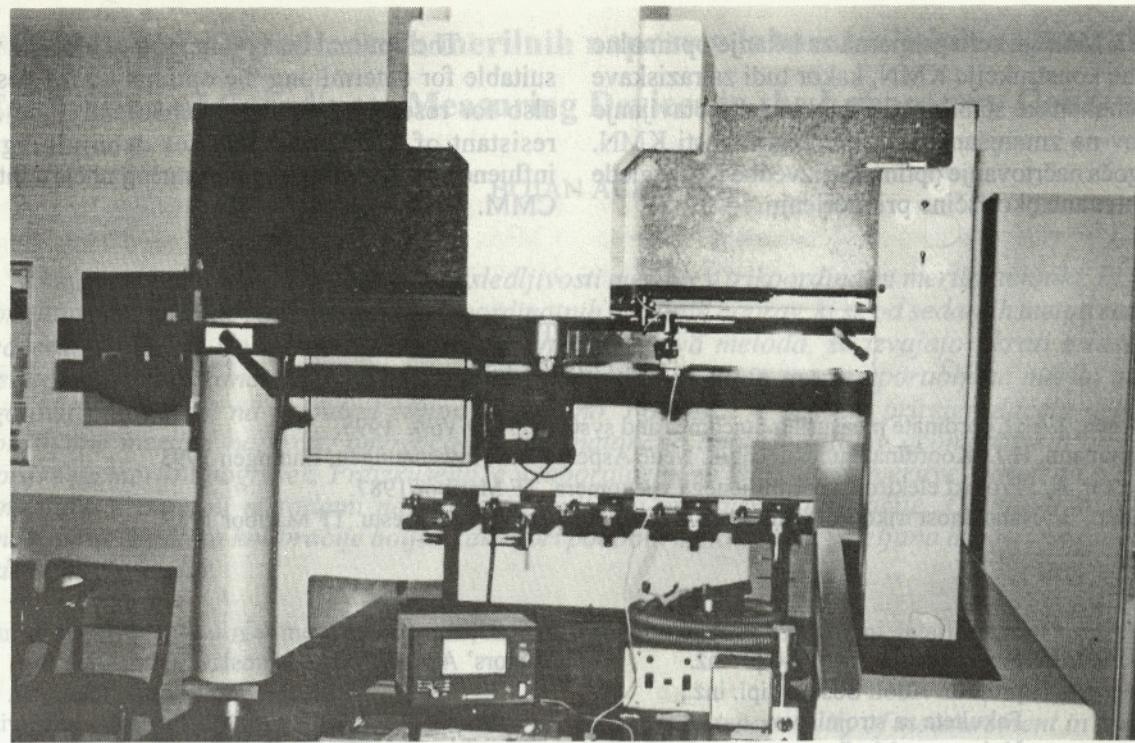
Diagram 1. Displacements (on ordinate in μm) of transverse guidance of CMM for four different materials and also for different temperatures (on abscisse in $^{\circ}\text{C}$)

Primerjalna analiza po MKE med različnimi materiali prečnega vodila (z merami: $1400 \times 150 \times 320$ mm), ki nalega na dva nosilna stebra, je pregledno podana v preglednici 1 in v diagramu 1, ki prikazujeta pomike (v μm) na sredini prečnega vodila pri polni obremenitvi (teža pinole z merilnim sistemom znaša 180 kg in deluje na sredini zgornje strani prečnega vodila prek dveh drsnih ležajev premera 70 mm na medsebojni razdalji 290 mm) in pri različnih temperaturah (od 20 do 26 $^{\circ}\text{C}$).

Za potrditev natančnosti rezultatov analiz po MKE (simulacij stanj) smo izvedli praktične (eksperimentalne) meritve povesov na prečnem vodilu KMN OPTON v laboratoriju za tehnološke meritve na Fakulteti za strojništvo v Mariboru, seveda pri različnih temperaturah. Uporabljeni so bili ustrezni elektronski merilni pripomočki za merjenje pomika. Pomike smo merili prek nevtralne traverze, nameščene v bližini prečnega vodila. Slika 3

The comparative analysis of different materials of transverse guidance (with following dimensions: $1,400 \times 150 \times 320$ mm), which puts on two pillars, was executed with FEM and lucidly presented in the Table 1 and also in Diagram 1, which presents displacements (in μm) at the centre of transverse guidance at full burdening (the weight of pinole together with the measuring system amounts to 180 kg and influences the middle part of the above side of transverse guidance by means of two slide bearings with the diameter of 70 mm on reciprocal distance of 290 mm) and at different temperatures (from 20 to 26 $^{\circ}\text{C}$).

Verification of the FEM analysis accuracy (simulations of state) was executed, also at different temperatures, by means of practical (experimental) measurements on the transverse guidance of CMM OPTON in the Laboratory for Production Measurement of the Faculty of Mechanical Engineering in Maribor. We were measuring displacements on the neutral traverse, parallel placing it near the transverse guidance. The traverse with an



Sl. 3. Traverza z induktivnim tipalom na KMN OPTON UMC-850 v bližini prečnega vodila

Fig. 3. The traverse with an induction probe on CMM OPTON UMC-850 near the transverse guidance

prikazuje namestitev traverze z induktivnim tipalom za merjenje pomikov prečnega vodila na KMN OPTON.

Primerjava numeričnih in praktičnih rezultatov za granitno izvedbo prečnega vodila na KMN OPTON je pokazala, da MKE dobro simulira dogajanje v obremenjenem prečnem vodilu in razlike med vrednostmi pomikov so majhne; po MKE je znašal pomik prečnega vodila $1,283 \mu\text{m}$, na podlagi eksperimentalnih meritev pa $1,1 \mu\text{m}$.

2 SKLEP

Najpomembnejša načela optimalnega konstruiranja so: zagotovitev mehansko in toplotno stabilne konstrukcijske izvedbe KMN, zagotovitev togosti merilnega sistema KMN in upoštevanje načel kakovosti pri konstruiranju. Današnji razvoj v konstruiranju KMN je namreč usmerjen v izdelavo takšne KMN, ki bi lahko uspešno obratovala v skoraj nemogočih delavnških razmerah in ne le v merilnih laboratorijih; razvoj gre torej v izdelavo KMN za delavnice in ne le za merilnice. Pri vsem tem nam koristi MKE, saj omogoča zahtevne elastične in temperaturne analize poljubnih prostorskih konstrukcij.

Primerjava numeričnih in praktičnih rezultatov raziskave je pokazala, da MKE dobro simulira dogajanje v obremenjenih delih KMN OPTON in je prav gotovo cenejša metoda za ugotavljanje vplivov na zmanjšanje merilne negotovosti KMN.

induction probe for measuring displacements in the transverse guidance of CMM OPTON is presented on figure 3.

A comparative analysis of the numerical and practical results for the granite form of transverse guidance showed that the simulation of events in the burdening transverse guidance by FEM was well simulated and that the differences between displacements were small; according to FEM, the displacement of transverse guidance amounted to $1.283 \mu\text{m}$ and according to experimental measuring to $1.1 \mu\text{m}$.

2 CONCLUSION

The most significant principles for optimal designing are: assurance of mechanically and heat resistant of the CMM structure, stiffness of the CMM measuring system, as well as consideration of quality principles when design the CMM. Present trends in structural design of the CMM are namely oriented to make such a CMM, which would also work successfully in the sometimes difficult circumstances in industry, and not only in measuring laboratories; this means that the trend is towards making CMM for industry and not only for laboratories. This paper presents the suitability of the FEM for all of these problems; FEM also enables exact elastic and heat analyses of any 3D structures.

A comparative analysis of the numerical and practical results showed that the simulation of events by FEM was well simulated and also showed that FEM was a cheap method for evaluating the influence on the reduction of the measuring uncertainty of the CMM.

MKE je zelo primerna za iskanje optimalne izvedbe konstrukcije KMN, kakor tudi za raziskave termomehanske stabilnosti KMN in za ugotavljanje vplivov na zmanjšanje merilne negotovosti KMN. Omogoča načrtovanje optimalne izvedbe KMN glede na zahtevane okoliščine pri merjenju.

The optimal design method of FEM is very suitable for determining the optimal CMM design, also for research into the mechanically and heat resistant of CMM and also for determining the influence for reducing the measuring uncertainty of CMM.

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