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Interferometric step gauge for CMM verification

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Abstract

The verification of the measurement capability of coordinate measuring machines (CMM) is usually performed using gauge blocks or step gauges as reference standards. Gauge blocks and step gauges are robust and easy to use, but have some limitations such as finite lengths and uncertainty of thermal expansion. This paper describes the development, testing and uncertainty evaluation of an interferometric step gauge (ISG) for CMM verification. The idea of the ISG is to move a carriage bearing a gauge block along a rail and to measure the position with an interferometer. For a displacement of 1 m the standard uncertainty of the position of the gauge block is 0.2 μm . A short range periodic error of CMM can also be detected.

Keywords: CMM, verification, metrology

(Some figures may appear in colour only in the online journal)

Introduction

In the manufacturing industry, there is a need for quality control of machined parts and for a wide range of products. The coordinate measuring machine (CMM) is a universal measurement machine for measurements of many dimensional specifications such as length, diameter, angle, flatness etc [1]. The accuracy of these measurements is an important and complex issue, as sometimes the dimensional requirements or tolerances of the part to be measured are of the same order as the stated measurement capability of the CMM. Contributors to task-specific uncertainty are e.g. the selected measurement strategy, sampling and fitting, together with the properties of the part to be measured such as surface texture and temperature [2]. From the view of traceability, the most important issue is the metrological properties of the CMM [3, 4]. In metrology, traceability is ensured by calibration; but as a full

calibration includes scale, pitch, yaw and roll errors for each axis, together with orthogonality and probing errors [5, 6], the required work, skill and artefacts result in costs that are too high for most industrial users of CMMs.

However, a procedure called verification of a CMM is possible to perform in a much shorter time than required for full calibration [7]. In verification of a CMM, artefacts of known length, i.e. gauge blocks, are measured in various orientations. The process is described in the standard ISO 10360-2 [8]. One possibility is to perform an interferometric verification by replacing the probe by a retroreflector. The drawback of this method is that errors associated to the probe require additional tests. In addition, as the CMM is not measuring it has to be checked from the manufacturer of the CMM how to acquire valid compensated measurement data of the movements.

Gauge blocks can also be used to perform traceable CMM measurements by the substitution method, whereby the measurement result is checked and corrected by measuring a gauge block of known length [9]. The gauge block should be of the same material and the length should be close to that of the workpiece to achieve the similarity condition required in ISO 15530-3.



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Both gauge blocks and step gauges are robust and fundamental to the testing of CMMs and other length instruments, but there are some drawbacks. Although almost any length can be constructed by wringing gauge blocks, it is time consuming to wring many. Typically, only a single length reference is placed on the same measurement axis when gauge blocks are used. Also, step gauges have finite lengths even though they have several lengths in sequence. Another issue with material standards is the compensation of temperature expansion. Many CMMs used in industry are operated at a temperature significantly different from 20 °C. By measuring the temperature of the material, the standard thermal expansion can be compensated for, but the value of the thermal expansion coefficient is not always so well known. Therefore, temperature adds an error that can lead to a significant amount of uncertainty, especially for lengths over 1000 mm. In addition, CMMs like other instruments utilizing graduated encoder scales as reference suffer from short range periodic errors in the detection of the graduation phase. The periodicity of the nonlinearity is typically some tens of micrometers and is not easily measurable with gauge blocks or step gauges.

For the reasons described above, it was decided to develop the interferometric step gauge (ISG) for CMM verification. The idea of the ISG is to move a carriage bearing a gauge block and reference spheres along a rail and to measure the position with an interferometer. Similar concepts are applied in line scale interferometers and interferometric benches [10], but for verification of CMMs the equipment should be portable and still have submicron accuracy for lengths of about 1000 mm. This paper describes the developed ISG, along with its metrological characteristics and an uncertainty evaluation for a verification task. An example of operation in an industrial environment is also given.

Description of the equipment

The idea is to have a moving target with surfaces for tactile probing with interferometric measurement of the displacement. There also need to be references allowing a differential measurement procedure. The ISG should follow Abbé's principle, and the movement should have good straightness and be motorized for movements with high resolution and automated operation. The weight should be in the range 20–50 kg to make it portable, and the length of the movement over 1000 mm. The use of the ISG should be easy, i.e. no time-consuming adjustments before measurement.

The design process resulted in a frame consisting of a lightweight granite straight edge with a fiber-coupled laser interferometer and a steel carriage driven by a ball screw as shown in figure 1. A laser tracker-type corner cube ball is used as a reflector. The system is designed to follow Abbé's principle: the measurement line of the interferometer is defined by the travel path of the reflector, i.e. it continues through the center points of the gauge block and the two reference spheres on either side of it. To minimize errors due to the moving mass and deformation or position changes due to the drive forces or drift, two reference spheres are fixed at each end of the straight edge. The retroreflector sphere can also be probed, which

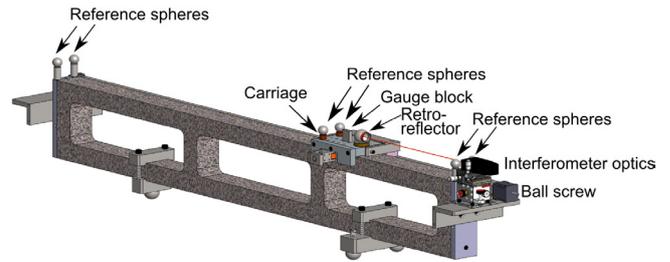


Figure 1. 3D CAD illustration of the developed ISG. The beam from the interferometer to the corner cube ball is shown as a red line.

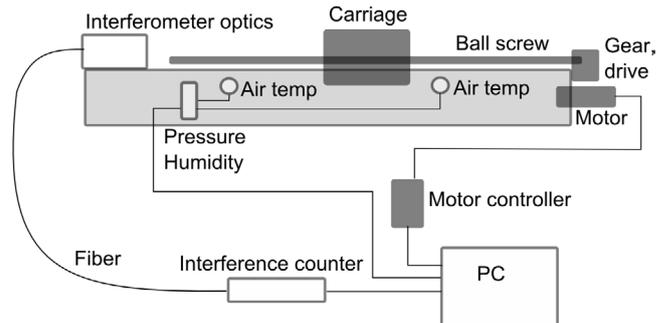


Figure 2. Schematic diagram of the developed ISG.

allows the Abbé error to be decreased if needed. The gauge block is intended to be probed from one surface resulting in a unidirectional measurement but can if needed also be probed from both sides resulting in a bidirectional measurement.

A schematic diagram of the instrument is shown in figure 2. The granite straight edge has a length of 1500 mm and weight 36 kg. The carriage is driven by a DC-servo motor through an enclosed ball screw and the movements are controlled from a PC. Feedback from interferometer is not necessary as the DC-servo motor is able to position with error less than ± 0.5 mm for full range of ISG, but if required it could be utilised. The DC-servo motor is situated far away from the laser interferometer in order to minimize thermal disturbance it might cause. As sub-micron accuracies are intended, it is important that no forces from the motion drive are affecting the metrological loop. The carriage is made of steel and lies under its own weight on the surface of the guideway. The lower surface of the carriage, contacting the granite upper surface of the guideway, functions as a plain bearing for the vertical direction. The carriage is positioned in horizontal direction by a plain bearing contacting the side of the granite guideway. On the other side of the carriage, a spring loaded roller is in contact with the granite guideway to reduce play at the horizontal bearing. The laser interferometer is a Renishaw RLE, which uses homodyne detection allowing the laser beam to be coupled by fiber from an interferometer control unit. The air temperature is measured by two sensors. Atmospheric pressure and humidity are also measured. The refractive index is calculated using the updated Edlen formula [11]. The instrument is controlled by a measurement program written with the Visual Studio.NET development tool and running on a laptop PC. When using the ISG, enough slack in the cabling should be allowed in case the table of the CMM moves.

Error sources and uncertainty budget

The uncertainty evaluation for use of the ISG is presented here and follows the guidelines given in the GUM [12].

The measurement sequence with the ISG is differential: i.e. before probing the position of the gauge block, the position of the spheres close to the interferometer optics are also probed. If there are any movements due to deformation by changing forces or temperatures, this displacement is also seen in the reference sphere position and can thus be reduced. The center position of the two reference spheres is denoted by r_i , where i is the index of step in the measurement sequence. The variable r_i is the coordinate in the coordinate system of the CMM aligned in the direction of the laser beam. The movement of the spheres for measurement step i compared to the beginning of the measurement sequence is now:

$$\Delta r_i = r_i - r_0, \quad i = 1, 2, 3 \dots N. \quad (1)$$

The position of the gauge block measured by the CMM is denoted by l_i . In the beginning of the measurement sequence the interference counter is zeroed and the first position is then l_0 and the displacements

$$\delta l_i = l_i - l_0. \quad (2)$$

The measurement model for the displacements δl of the surface of the gauge block on the moving carriage is:

$$\delta l_i = \frac{D\lambda_0}{2n(t_{\text{air}}, h, p, x_{\text{CO}_2})} + \Delta r_i + \delta l_{\text{Abbe}} + \delta l_{\text{cos}} + \delta t, \quad i = 1, 2, 3 \dots N, \quad (3)$$

where D is the reading of the interference counter corresponding to the displacement in half-wavelengths, λ_0 is the vacuum wavelength, $n(t_{\text{air}}, h, p, x_{\text{CO}_2})$ is the updated Edlén's formula [11] with its input parameters, t_{air} is the air temperature, h is the relative humidity of air, p is the air pressure, x_{CO_2} is the carbon dioxide content, δl_{Abbe} is the correction for the Abbé error, δl_{cos} is the correction for the cosine error, and δt is the correction for thermal expansion.

The laser vacuum wavelength was calibrated by VTT MIKES with a relative standard uncertainty of 5×10^{-9} . The laser is unstabilized, and according to the manufacturer, the vacuum wavelength accuracy is $\pm 10^{-7}$ over 3 years. Based on these data, the standard uncertainty for the wavelength is estimated to be 36.7 fm assuming a rectangular distribution.

The temperature sensors, pressure sensor and humidity sensor were calibrated at VTT MIKES and corrections applied by software. The standard uncertainty of the temperature sensor correction was 0.01 K. The temperature of the dc-servo motor case was observed to rise 1–2 K during normal operation. This slightly heats the beam path air temperature, which is recorded by two sensors. When used under industrial conditions, a value of 0.15 K is estimated for the uncertainty of the air temperature along the beam path. The standard uncertainty for pressure is 15 Pa and for humidity 5%.

The deviation from flatness of the upper surface where the carriage moves was measured to be 6 μm using the CMM Mitutoyo Legex. In an FE analysis it appeared that the flatness is sensitive to the position of the support below the straight edge, due to the effects of gravity. The probing on the gauge block should be at the axis of the laser measurement axis. An

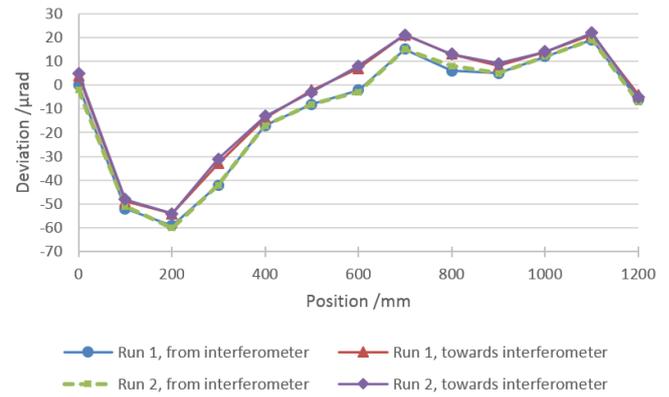


Figure 3. Deviation of pitch angle of carriage of two runs in two both directions.

Abbé error will occur if this is not the case, as there are pitch and yaw angular errors on the carriage. The Abbé error is estimated by assuming that the probing on the gauge block is 0.1 mm off the measurement axis and that the standard uncertainty for angular error is 23 μrad . The guiding error is due to straightness of the straight edge and guiding error of carriage. The magnitude of pitch angle is measured using an inclination measuring instrument (figure 3). By assuming a rectangular distribution for the variation of the magnitude of 80 μrad , the standard uncertainty is 23 μrad . The Abbe offset is estimated assuming a combination of centering error of the retroreflector, straightness error of carriage movement and kinematic error of the CMM. All these three error sources are expected to be less than 30 μm so 100 μm is a conservative estimate.

The stiffness of the carriage was measured using a spring dynamometer. In transverse direction a force of 5 N resulted in a deflection of 0.1 μm , measured by a inductive transducer. In the direction of measurement axis of the ISG a force of 2 N on the gauge block resulted in movement of 0.02 μm of the carriage, measured by the interferometer. A force of 1 N on the retroreflector resulted in deflection of 0.14 μm of the retroreflector. The probing force of a CMM is typically much less than 1 N so deflection due to probing force is small. However, in case the retroreflector is probed by a force larger than 1 N, deflection of retroreflector is not negligible.

The direction of the axis of the probing sequence by the CMM should be parallel to the laser measurement axis, otherwise a cosine error will occur. A cosine error occurs when the distance L to be measured is projected by an angle θ . The cosine error can be estimated by $L\theta^2/2$. It is reasonable to assume a normal distribution for θ , but the distribution for θ^2 is asymmetric and other assumptions easily lead to underestimation of this error source. Guidance on how to deal with the cosine error is found in the Annex of [12]. The cosine error is estimated based on the conservative assumption that the error of the laser beam adjustment is 0.6 mm at a length of 1200 mm. This results in a standard uncertainty for the angle of 0.3 mrad. The standard uncertainty for the squared angle is 0.000 000 12 rad^2 and follows a chi-squared distribution.

The uncertainty budget is shown in table 1. For a displacement of 1 m the standard uncertainty of the position of the gauge block is about 0.2 μm . When an interferometric step

Table 1. Uncertainty budget for the position of the gauge block for probing (L indicates displacement in meters).

	Estimate	Standard uncertainty	Distribution	Sensitivity coefficient	Standard uncertainty	
	x_i	$u(x_i)$		$c_i = \delta l / \delta x_i$	$u_i(l) / \mu\text{m}$	$u_i(L) / \mu\text{m}$
λ_0	0.633 μm	36.7 fm	N	0.001 58 $L \mu\text{m fm}^{-1}$		0.058 L
t_{air}	0 K	0.15 K	N	0.96 $L \mu\text{m K}^{-1}$		0.144 L
p	113 000 Pa	15 Pa	N	0.0027 $L \mu\text{m Pa}^{-1}$		0.0405 L
h	50 %RH	4 %RH	N	0.008 $L \mu\text{m} / \% \text{RH}$		0.032 L
δl_{cos}	0 rad ²	0.000 000 12 rad ²	χ^2	707 107 $L \mu\text{m rad}^{-2}$		0.083 L
δl_{Abbe}	0 rad	0.000 0231 rad	R	100 $\mu\text{m rad}^{-1}$	0.002	
δt	0 K	0.05 K	N	0.696 mm K^{-1}	0.035	

Combined standard uncertainty: $((0.035 \mu\text{m})^2 + (0.184 L)^2)^{1/2}$

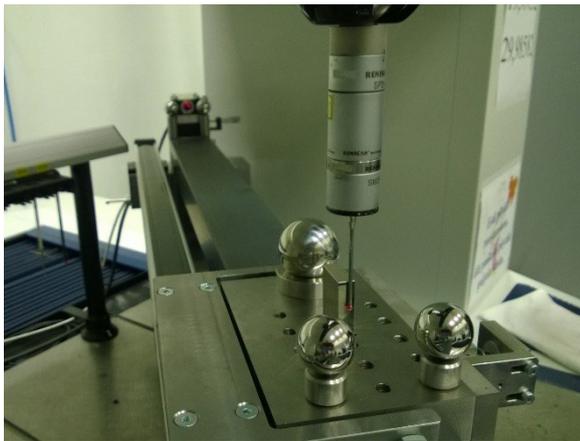


Figure 4. Setup of the ISG on the CMM at MIKES. The diagonal direction of the ISG is because of limitations of table size and measurement volume of the CMM.

gauge is used, the repeatability of the CMM should be added. As these are not features of the ISG they are not included in table 1 but are discussed in the next section. The repeatability and noise of the compensated displacement reading was tested with a static displacement of 600 mm. The standard deviation of the readings were 0.01 μm and are negligible.

Results using the ISG

Laboratory tests

The purpose of the tests was to evaluate the performance and usability of the ISG for CMM checking. The setup is shown in figure 4. The CMM used for the tests was the VTT MIKES Mitutoyo Legex, which is a fixed bridge CMM. The $E_{0, \text{MPE}}$ value (Maximum Permissible Error) of the CMM is $(0.35 + L/1000) \mu\text{m}$, where L is length in mm, and it has been verified with interferometrically calibrated gauge blocks on a regular basis. The environmental conditions in the laboratory are excellent, with a temperature stability of $20 \text{ }^\circ\text{C} \pm 0.2 \text{ }^\circ\text{C}$. The deviation of the value probed by the CMM from the reading of the ISG is shown in figure 5. The measured deviation of 1.85 μm was 0.5 μm larger than the stated $E_{0, \text{MPE}}$ value of 1.35 μm . As an additional check, a gauge block was positioned close to the previous measurement line of the ISG and its central length was measured by CMM. This result is also shown in figure 5.

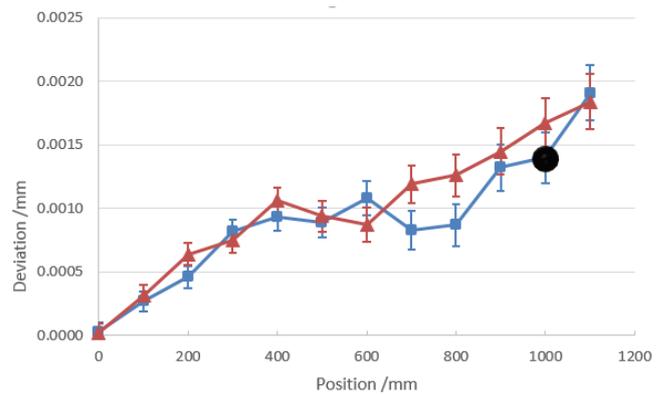


Figure 5. Deviation of the CMM from the ISG in two directions at the MIKES laboratory with standard uncertainty of ISG. Measurement sequence in direction towards the interferometer is indicated by squares and measurement in the other direction by triangles. The large dot at 1000 mm represents the deviation of the CMM compared to a 1000 mm gauge block.

There seems to be acceptable agreement with the ISG result; i.e. according to tests with the ISG and gauge block, the CMM had the same error over the measured distance.

Next, the ability to detect short range periodic error in the direction of one axis was tested. A test run with 20 steps over a length of about 3 μm was performed. The results shown in figure 6 reveal a pattern that is assumed to represent a short range periodic error of the CMM scale with an amplitude of 0.2 μm peak to peak and period of approximately 10 μm .

The repeatability of the CMM was tested by measuring the position of the two faces of the gauge block with the carriage not moving. The average of the standard deviation for the positions of the two faces was 0.2 μm . This means that the repeatability of the CMM is a significant uncertainty component in this kind of test.

Tests in industry

In order to evaluate the usability in an industrial environment, tests were done in a factory producing large gears. The CMM under test was a large gantry type Leitz-PMM-f 1600 with $E_{0, \text{MPE}}$ of $(2.8 + L/400) \mu\text{m}$. This equals 5.3 μm for a length of 1000 mm. The transport and handling of the ISG proved to be very similar to that of a step gauge. Although the size of the transport box and weight of the ISG

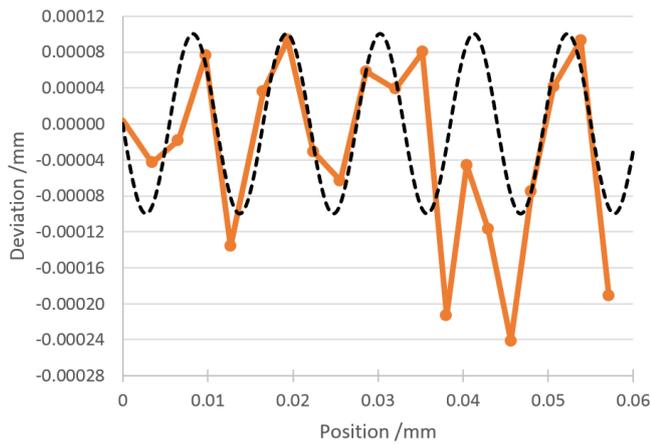


Figure 6. Periodic error test. The dots connected by solid lines are measured data and the dashed line is a sine curve for illustration.

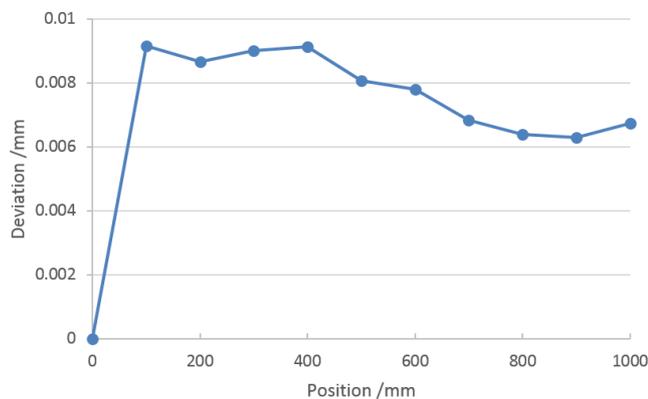


Figure 7. Deviation of CMM compared to ISG for a CMM in industry.

are larger than for a step gauge, both require two people to lift. The ISG was ready for operation around 15 min after lifting it into the measurement volume of the CMM. A step gauge would of course be ready for operation immediately after placing in the CMM, but reliable measurements could only be achieved hours later due to the time it takes for the temperatures to stabilize, and the operator usually needs some time to change and calibrate the probes and test measurement program.

The results of a measurement are shown in figure 7. The first point is an assumed outlier, probably because it was probed manually. The other points were probed with a CNC controlled approach. If the first point is excluded, the remaining points are within the range $\pm 2 \mu\text{m}$, well within the stated measurement capability. During the tests, the carriage moved to each point in the direction of the interferometer, so the reason for the inconsistency of the first point is not due to a backlash in the ISG.

As the objective of the test in an industrial setting was not to verify the CMM but to test the usability of the ISG, the conclusion is that the equipment is practical to use in that setting. The cables of the ISG did not move, as the CMM was of the gantry type, but it is possible that for some types and sizes of CMM the routing of the cables requires some attention.

Conclusion

It is clear that the cost, complexity and need for an operator are all disadvantages of the ISG compared to a step gauge. However, tests in an industrial setting showed reasonable results. In future versions, it would be useful to test how the ISG could be controlled synchronously by signals from the CMM, eliminating the need for an additional operator. This would also allow verification measurements with high point density. The ISG is less sensitive to temperature than a material reference standard. Therefore testing of the geometrical accuracy of the CMM is separated from sample temperature compensation of the CMM.

The developed interferometric step gauge has the functionality of a traditional step gauge but also the ability for arbitrary steps and accuracy comparable to a traditional step gauge. Tests in the laboratory have shown good accuracy and possibilities for verification of CMM accuracy for length measurements. For a displacement of 1 m the standard uncertainty of the position of the gauge block is about $0.2 \mu\text{m}$. Short range periodic error of the CMM can be detected. Tests in an industrial environment show usability as a reference that can be transported.

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