High-accuracy interferometric measurements of flatness and parallelism of a step gauge

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Abstract. The most commonly used method in the calibration of step gauges is the coordinate measuring machine (CMM), equipped with a laser interferometer for the highest accuracy. This paper describes a modification to a length-bar measuring machine for the calibration of step gauges to a high accuracy. A system was also developed for interferometric measurements of the flatness and parallelism of gauge block faces for use in uncertainty calculations.

1. Introduction

Step gauges are commonly used as standards for the calibration of a CMM according to International Standard 10360 [1]. On the other hand, once calibrated, a CMM affords the most common method for the calibration of step gauges, using a laser interferometer to measure the displacement of the probe as described in [2]. The major disadvantage of this method is that a CMM cannot be utilized for any other calibrations while a laser interferometer is set up to calibrate step gauges. Nor is the temperature on a CMM ideal, as it is not equipped with the best temperature-measuring system available. For these reasons, it was decided to modify a current length-bar measuring machine for the calibration of step gauges, as the temperature system is far superior to that of a normal CMM.

The major disadvantage of such a system is that it cannot be aligned accurately to the centre of the step face. A phase-shifting flatness interferometer was used with a specially designed periscope to measure the flatness and parallelism of each of the step gauge faces, resulting in an improved uncertainty budget calculation.

2. Step gauge calibration on a modified length-bar measuring machine

When deciding to investigate the calibration of step gauges, the systems used by other national metrology institutes (NMIs) were studied. Most of these laboratories use CMMs incorporating a laser interferometer for higher accuracy. However, at the CSIR National Metrology Laboratory (NML) it was decided to modify the current length-bar measuring machine as the CMM is required most of the time for the calibration and measurement of master parts and CMM standards for industry. In addition, the environment of the CMM was felt to be inadequate for accurate step-gauge calibration. The temperature system on the length-bar measuring machine has an uncertainty of ±0.005 °C as opposed to the resolution of the temperature system of the CMM of only 0.01 °C. The modified length-bar measuring machine will also be used for the measurement of lower-accuracy length bars which cannot be calibrated on a length-bar interferometer.

First, an accurate probe had to be designed. A probe that had been developed for the calibration of internal diameters was evaluated for the measurement of a step gauge. This probe uses Br-Cu parallel springs and gauge-block comparator probes to measure the displacement of the main probe. A new mirror layout had to be designed using a plane mirror interferometer as described in [3], which allows the probe to move over the steps. This is illustrated in Figures 1 and 2, where the measuring probe is fixed to the mirrors and its displacement is measured to ensure a constant pressure. The probe with the new mirror layout and laser system was evaluated on a universal measuring machine, by internal and external measurements of gauge blocks which were wrung together to form a mini step gauge. The standard deviation was calculated to be 6 nm, with an overall uncertainty for both internal and external measurements of 20 nm. Following this evaluation, the system was installed on the length-bar measuring machine.

Problems were encountered with the alignment of the laser and the optics to the trolley and slide. After a few alignment methods were tried, it was decided to use a quadrant detector. The quadrant detector replaced each

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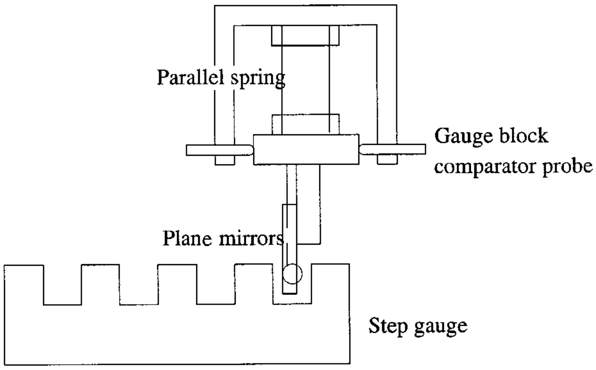

Figure 1. Probe consisting of plane mirrors, Br-Cu parallel springs and gauge block comparator probes.

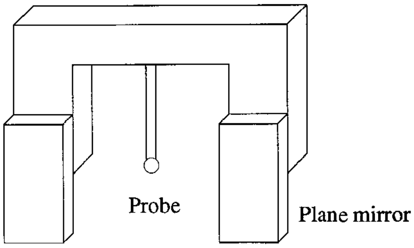

Figure 2. Plane mirrors fixed to the probe.

individual plane mirror, to align first the laser to the slide and then to the second arm of the interferometer. The alignment achieved was better than 0.2 mm over the total travel of 1.5 m, which resulted in an uncertainty of 0.05 μm/1 m when measuring a step gauge.

The length spacing is determined using the following:

$$l = L_i - L\,(\alpha_a\,\Delta t_a) + \delta_m + E + \delta_p + \delta_{am} + \delta_{aa} + \delta_f + \delta_r, \qquad (1)$$

where the symbols represent

l	length spacing of the step gauge at the reference temperature of 20 °C;
L_i	length spacing indication of the measuring instrument;
L	nominal spacing of the step;
α_a	linear coefficient of thermal expansion of the step gauge;
Δt_a	(t_a – 20 °C) departure of the step gauge temperature t_a from the reference temperature of 20 °C during the measurement;
δ_m	correction for the determination of the linear accuracy of the laser (i.e. index of refraction and wavelength corrections for laser scales and positional accuracy);
E	correction for the combination of artefact and probe contact deformation to an undeformed condition of the artefact;
δ_p	correction for the determination of the probe ball diameter;
δ_{am}	correction for laser alignment errors;
δ_{aa}	correction for alignment errors of the step gauge;
δ_f	correction for flatness of the faces;
δ_r	correction for parallelism of the faces relative to face one.

Using (1), the major uncertainty contributions are as follows. The length spacing indication, L_i, using the laser interferometer is ±0.02 μm/m. The temperature system to measure Δt_a of the length bar is ±0.005 °C, resulting in 0.06 μm/m in the measured length. The alignment of the laser, δ_{am}, was as previously stated 0.2 mm over 1.5 m, which results in 0.05 μm/m. The step gauge is aligned to better than 0.1 mm over 620 mm, resulting in 0.013 μm/m. The probe ball diameter, δ_p, was calculated to have an uncertainty of 0.02 μm using a number of standard gauge blocks. The velocity of light correction from the separate individual uncertainty calculations of temperature, humidity and pressure measurements was calculated to be better than 0.2 ppm/°C, resulting in 0.2 μm/m. The repeatability on a 500 mm length bar was calculated to be 0.05 μm.

The combined standard uncertainty was calculated according to [4] as

$$u_c = (0.09 + 0.35\,L)\ \mu\mathrm{m}, \qquad (2)$$

where L is expressed in metres.

After initial testing, the complete system was verified to check the calculated uncertainties when using gauge blocks and length bars. The gauge blocks were wrung together to form a mini step gauge. Internal and external measurements of the gauge blocks gave an uncertainty of 0.05 μm, showing that there is virtually no backlash in the system. Length bars of 500 mm and 1000 mm were then measured to detect any linear error in the system, arising for example from temperature, velocity of light correction or alignment. Again, the results were very satisfactory. The length bars, which were calibrated at another NMI, agreed to within 0.1 μm for the 500 mm bar and 0.25 μm for the 1000 mm bar.

3. Interferometric measurements of flatness and parallelism of each face relative to face one

Although the above system is very accurate, as shown by the measurements of length bars and gauge blocks, it has the disadvantage that it cannot position the probe in the centre of the step face as accurately as a CMM.

It was estimated to achieve only ±0.2 mm. Although the probe can be moved up and down and left and right to measure the parallelism of each face, it was felt that another system should be developed for these measurements.

A system was therefore designed based on the flatness interferometer so that the NML could study its possibilities. As the main problem was moving between the steps, a special periscope had to be designed to facilitate this. Figures 3 and 4 show the periscope with the steps facing in the same direction as face one, and in the opposite direction, respectively. The periscope was small enough to be able to move between the steps of the step gauge, only for steps having a 40 mm spacing, where the mirrors are stationary and the step gauge is moved. The design also allows each mirror to be aligned separately, simplifying the alignment of the complete system. The alignment of the periscope was verified on a gauge block, which had been previously measured for parallelism, and when compared had a deviation of 0.81″ for parallelism and a flatness value of 17 nm, as shown in Figures 5 and 7.

An uncertainty of 0.2 mm off-centre for the probe and a parallelism of 0.81″ will result in an error of 0.001 μm.

Each face of a Koba step gauge was measured for flatness and parallelism relative to face one. The results showed that the average flatness value is 73 nm and the average parallelism value is 30″. Figures 6 and 8 show the printout and interference fringes of face two for flatness and parallelism, relative to face one.

The largest deviation of flatness over the total surface of all the faces measured is 114 nm. However, it should be noted that the flatness over the central 0.2 mm of all the faces was most acceptable, with a peak-to-valley value of better than 20 nm. The parallelism of the faces was less satisfactory and indicated that the steps were not adequately aligned. Surprisingly, the parallelism of the first step was extensive (17″), the reason being that this was the only step made from a solid piece and was not to be aligned with any other.

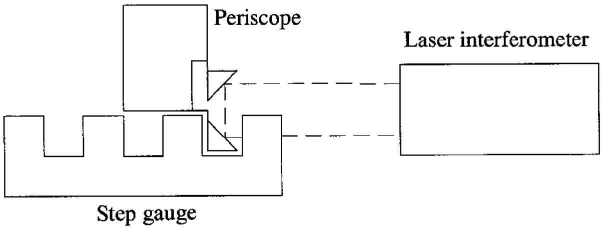

Figure 3. Periscope measuring steps facing in the same direction as face one.

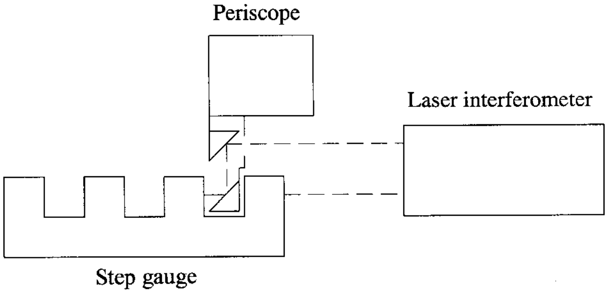

Figure 4. Periscope measuring steps facing in the opposite direction to face one.

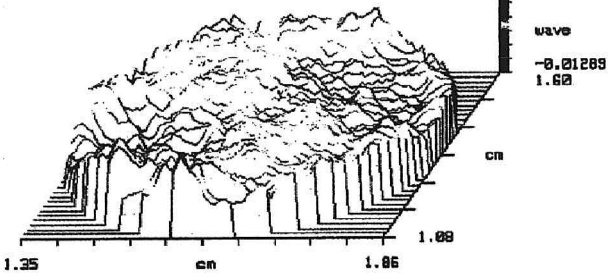

Figure 5. Flatness and angle measurements of gauge block through periscope.

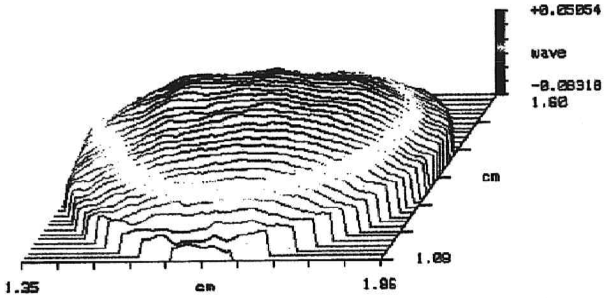

Figure 6. Flatness and angle measurements of face two, step 1, relative to face one.

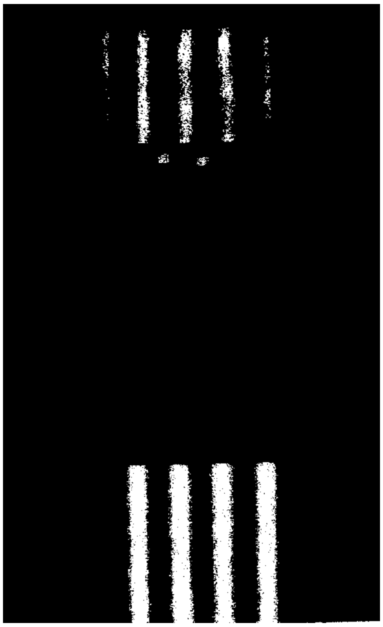

Figure 7. Interference fringes of built-up step gauge/gauge blocks through periscope.

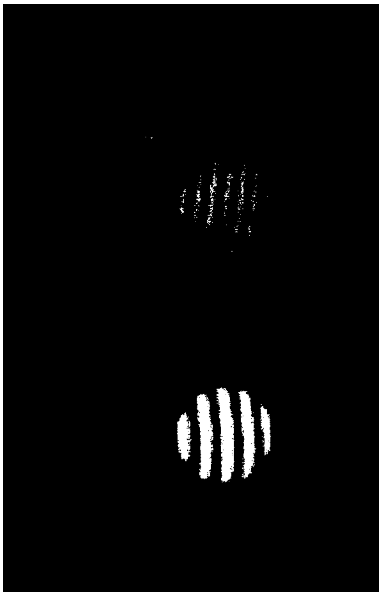

Figure 8. Interference fringes of step gauge faces one and two, step 1.

The worst parallelism was 75″, which will result in an error of 0.07 µm in a 0.2 mm off-centre measurement. The flatness and parallelism will change (2) to

$$u_c = (0.115 + 0.35\,L)\ \mu\text{m}, \tag{3}$$

with L in metres.

This refers to the entire step gauge, where the maximum values for flatness and parallelism were used. A separate uncertainty for each length measurement can be calculated from the flatness and parallelism measurements of each face δ_f and δ_r in (1), using the equipment described above.

4. Conclusions

The step-gauge measurements on the length-bar measuring machine showed very satisfactory results when using length bars and gauge blocks. Although it cannot be positioned in the centre of the face as accurately as a CMM, its overall accuracy is superior to the CMM/laser interferometer combination.

The system for measuring the flatness and parallelism of the steps was very satisfactory and will be used in uncertainty calculations, especially for a machine of this nature which does not measure through the centre line as described when a CMM/laser interferometer is used for the calibration.

The periscope system allows the length spacing of the steps to be measured. This can be done with a ring interferometer as described in [5, 6] and will be investigated in future work.

References

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