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LARGE MEASUREMENT RANGE MECHANICAL COMPARATOR FOR CALIBRATION OF LONG GAUGE BLOCKS

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Abstract – A new design of mechanical gauge block comparator for calibration of long gauge blocks is described. The comparator is constructed by modification of a commercially available universal length measuring machine. It is able to compare the different nominal size gauge blocks with its 300mm measurement range. This has the advantage that a reference metric size gauge block can be used to calibrate the inch size square or rectangular section gauge blocks or vice-versa. Line scale of the length-measuring machine, which is calibrated by a laser interferometer and gauge blocks, is used for the measurement of displacement. Calibration procedure adapted from EAL-G21 guideline is described with the aid of the results. The uncertainty of the measurements is evaluated and the parameters, which has influence on the uncertainty, is described in detail. The successful application of the comparator for calibration of metric or inch gauge blocks in different cross sections up to 500mm or 20 inch nominal size is presented with the results. The uncertainty of the comparator with k=2 is $U = [\,(150^2)+(0.5L)^2\,]^{1/2}$ nm, where L is the gauge block length in mm. For instance, U is calculated as 292 nm (k=2) for 500mm long gauge block.

Keywords : Gauge blocks, mechanical comparators

1. INTRODUCTION

Gauge blocks are most accurate standards in dimensional metrology and widely used for establishment of traceability chain from National Metrology Institutes (NMIs) to workshop floors. The traceability chain is achieved by calibration of the gauge blocks according to defined standards. International standard ISO 3650 [1] cover the range of accuracy requirements along the traceability chain and calibration method is selected according to accuracy requirements of the standard and the user. Calibration by interferometry, known as primary method, allows the length of the gauge block to be directly compared with wavelength standards. Such calibration methods are performed for gauge blocks of highest quality, which are then in general used solely as standards for calibrating other gauge blocks by mechanical comparison.

The separation line between the short and long gauge block is described in ISO 3650 as 100mm length. The gauges over 100mm is specified as long gauge blocks and should be calibrated in horizontal position using their airy points whereas short gauge blocks (below 100mm) are calibrated in vertical position.

In mechanical comparison methods, the similar nominal size gauge blocks are compared to each other by suitable probing elements. Since the compared gauge blocks are in the same nominal sizes, the inductive probes which have a short measurement range with high accuracy is used in the mechanical comparison technique.

Apart from ISO 3650, the gauge blocks are still manufactured and graded according to U.S. Federal Specifications GGG-G-15C [2]. Federal standards cover rectangular and square section gauge blocks as well as metric and inch dimensions while ISO 3650 only covers the rectangular and metric gauge blocks. Metric gauges according to ISO 3650 are most commonly used length standards in the world. Therefore, most NMIs and calibration laboratories possess gauge blocks according to ISO 3650 specifications. However, they are sometimes requested to calibrate inch gauge blocks in square or rectangular sections by their customers. In this time, there are two possible solutions: either they should obtain inch size gauge blocks to use as a reference or they should obtain a comparator, which will allow them to perform calibration using metric gauge blocks as reference. As the dimension difference between the inch and metric size gauge blocks is in the millimetres range, use of inductive probes is not possible for such applications. There is a need for another length measurement equipment, which has a long measurement range with high accuracy. This could be a line scale or a laser interferometer used for distance measurement with suitable probing.

Commercially available long gauge block comparator [3] cannot be used for this purpose, as its measurement range is not suitable. Commercial Universal length measuring machines [4-6] can be utilised for these purposes, however some modifications are essential for them to be used for calibration of gauge blocks with the required uncertainties.

A commercial universal length-measuring machine [5,6] has been modified in UME for calibration of inch size gauge blocks using metric size gauge blocks as a reference. A proper temperature control mechanism and temperature measurement system are added to the system. Besides, remote control mechanism for moving of the gauge blocks has been constructed with specially designed table holding the gauges on their airy points. This paper describes the modification process and represents the results showing performance of the comparator during long gauge block measurements up to 20 inch.

2. DESCRIPTION OF THE COMMERCIAL LENGTH MEASURING MACHINE

Mahr 828 CiM universal length measuring machine [5,6] has been modified to be used for long gauge block calibration. The machine has the following advantages.

The measuring machine bed is made of high-strength black granite (Fig. 1). All slides supported by the machine bed are equipped with air bearings, which provides improved moving mechanism for the moving anvil during the measurement. The moving anvil responsible for contacting the gauge blocks is integrated in a measuring slide. The measuring slide is equipped with a high-resolution incremental path measuring system (0.01μm) with a large measuring path of 300mm. The scale of the measuring system is located exactly on the moving anvil axis. Motion of the moving anvil can be remotely controlled. Five measuring forces from 0…11N can be pre-selected in any desired increments. Electronic measuring force monitoring ensures the accuracy and reproducibility of each measuring force.

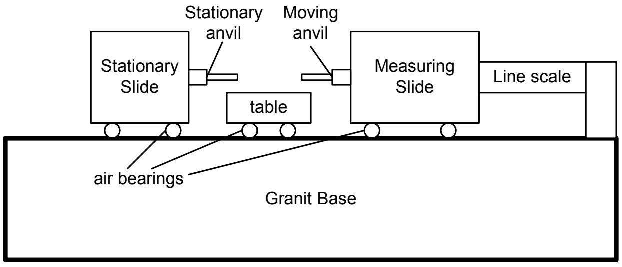


Fig. 1. 828 CiM universal length measuring machine

In spite of the advantages described above, the 828 CiM machine has some disadvantages particularly for long gauge block calibration. The measuring table is controlled manually for determination of the turning points during the measurements. In addition, there is no temperature control mechanism around the machine. Closer approach of the operator to the long gauge blocks during manual adjustment in the measurement process affects the temperature stability significantly. This increases the uncertainty of calibration considerably.

3. MODIFICATIONS

The disadvantages are overcome by modification of the machine. They are given as following:

3.1. Measurement table and motor-driven mechanism

A specially designed homemade measurement table holding the gauges on their airy points is integrated to the machine. This measurement table enables easy and accurate alignment of the gauge blocks. With this arrangement, alignment difficulties for determination the turning points, is significantly eliminated (Fig. 2.).

Manual alignment is replaced by home made motor-driven mechanism, which provides remote alignment of the gauges. In this way, closer approach of the operator to the gauges and to the measurement environment is prevented during manual adjustment (Fig. 3.). Additionally, precise control of the alignment mechanism is provided by fine adjustment performed with the help of the integrated motor-gear system.

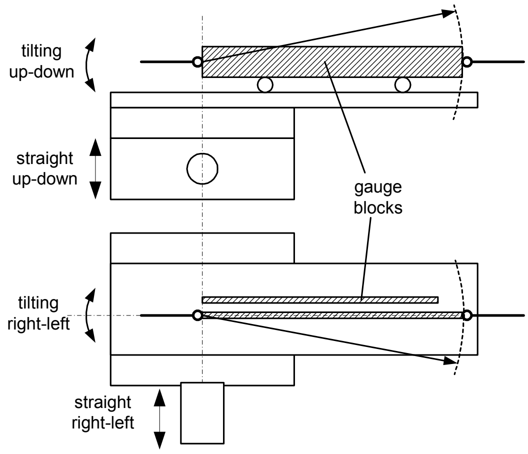


Fig. 2. Convenient gauge block alignment

3.2. Temperature measurement and control system

A temperature measurement system is integrated to the machine since the length of the gauge block is corrected to the reference temperature of 20°C. It consists of 4 pieces platinum resistance thermometers (Pt100) and a digital multimeter. The Pt100 sensors are calibrated at 18°C, 19°C, 20°C, 21°C and 22°C against a reference platinum resistance thermometer (Pt25). Calibration of reference thermometer was previously made to ITS 90 triple point of water and melting point of gallium. A homemade dry bath is used for calibration of the Pt100 sensors. The resistance values taken from the multimeter at certain temperature points are used to determine the regression equations for each individual Pt100 sensor. These equations are assigned to the regarding sensors and used for conversion of resistance values into temperature values in the software. During gauge block temperature measurement, the resistance values of the sensors measured by the multimeter are delivered to the computer via IEEE card.

A temperature-controlled chamber is manufactured and fitted around the comparator. It is used to maintain the temperature within 20 ±0.1°C in order to reduce the uncertainty contribution from thermal expansion coefficient of the gauge blocks. Running water at about 20°C is circulated in the copper pipes mounted inside the chamber using a refrigerated and heating circulator. Fig. 4 shows the thermal stabilisation of the reference and test gauge blocks. The sensors Pt101 (on the left side of the gauge) and Pt103 (on the right side of the gauge) are used for temperature measurement of reference gauges while Pt102 and Pt104 are used for test gauge blocks. 10mK thermal equilibrium is obtained during the comparison measurement of the gauge blocks (Fig. 5).

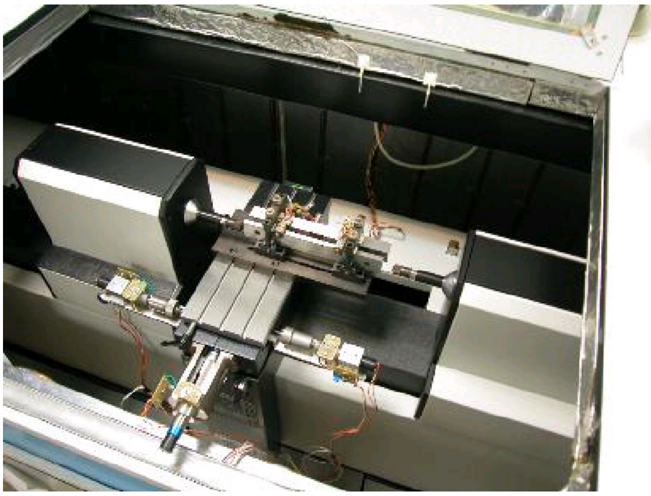


Fig. 3. Mechanical comparator

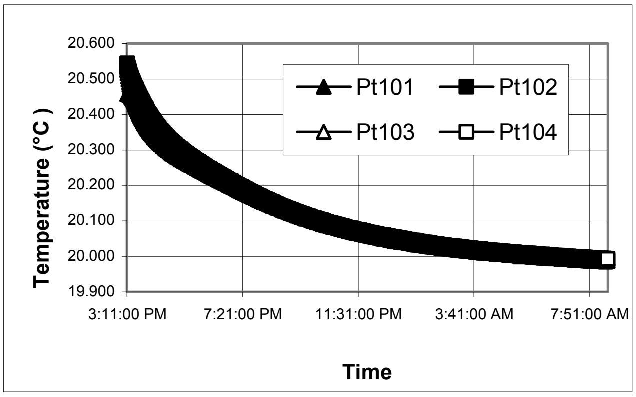


Fig. 4. Thermal stabilisation of the gauges

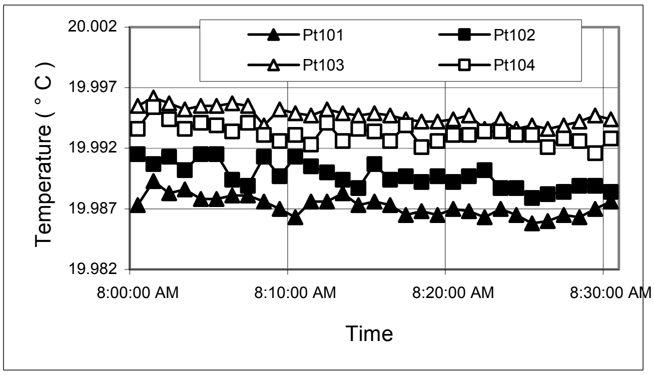


Fig. 5. Thermal equilibrium of the gauges during measurement

4. GAUGE BLOCK MEASUREMENT

The length of the reference gauge block previously calibrated (usually by interferometry) is transferred to the gauge block under test by mechanical probing. Five series of comparison measurement are performed for each gauge block. To do this, following procedure is carried out.

The temperature measurement of the gauge blocks is first carried out automatically with the aid of the software. The reference gauge block is then probed and the alignment process shown in Fig. 2 is carried out to find the correct measurement point for determination of the central length. After the length-measuring machine is set to zero, the same mechanical probing is performed for the test gauge block with the same alignment process. The value on the display of the length-measuring machine is typed into the computer used for gauge block measurement. Later, another measurement is obtained from the test gauge block by mechanical probing. The values taken from the length measuring machine display are combination of probing and the line scale values. The measurement is completed by re-probing the reference gauge block and obtaining another set of temperature measurements from the gauges. The software running in windows environment calculates the required temperature corrections due to the gauges being at different temperature. This is usually very small like 1 to 5 nm even sometimes less than 1nm. The correction values are added to measurement values (Test-Reference) taken from the display of the length-measuring machine.

Four more series of comparison measurements are repeated and mean value of the five measurement results are calculated. The mean value is added to the actual value of the reference gauge block in order to determine the test gauge block length.

Similar nominal size reference gauge blocks are used for calibration of metric gauge blocks. For inch gauge blocks, metric reference gauge block, nominal size of which is near to the test inch gauge block is used. These are usually 100mm/4inch, 125mm/5inch, 150mm/6inch, 175mm/7inch, 200mm/8inch, 250mm/10inch, 300mm/12inch, 400mm /16inch, 500mm/20inch.

In this way, maximum difference between reference and test gauge block is determined as 8mm. However, the mechanical comparator has the ability to perform measurements up to 50mm size difference in the reference and test gauge blocks. Fig. 6 shows the gauge block measurement.

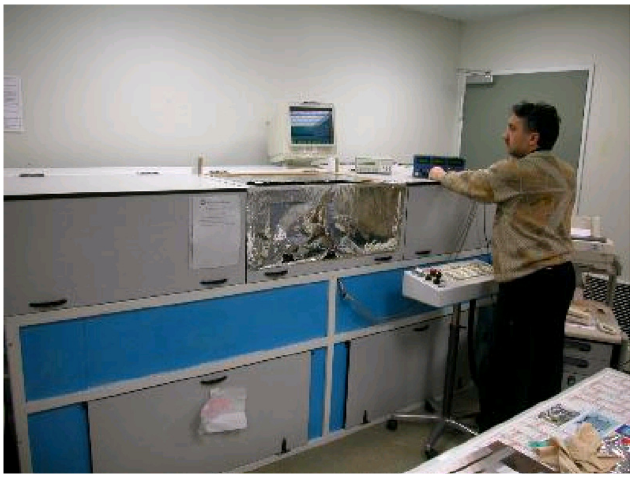
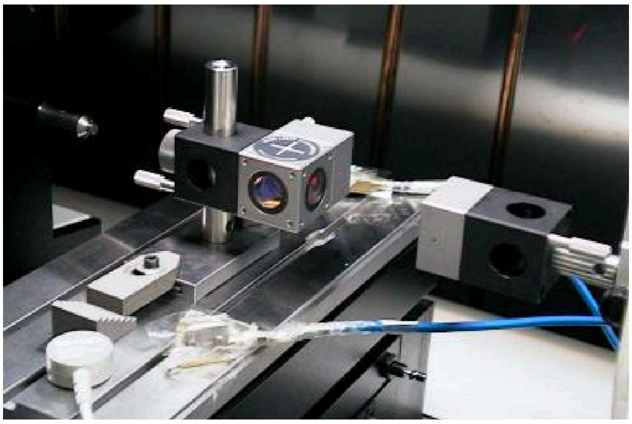


Fig. 6. Gauge block measurement

5. CALIBRATION OF THE INSTRUMENT

Calibration of the mechanical comparator has been performed in different steps. First the geometrical errors of the measuring slide have been checked using a laser interferometer with its angular optics and electronic level meter. Pitch and yaw error of the slide along its measurement range (300mm) have been determined using angular optics and roll error has been determined by the level meter. The errors have been found less than 3 arc seconds over 300mm range and less than 0.5 arc seconds over 50mm measurement range in any part of the length measuring machine scale. The straightness error of the slide (peak to peak) has been found as 0.5μm over its 300mm measurement range. As the scale of the measuring system is located exactly on the moving anvil axis, it fits very well with the Abbe principle and reduces the Abbe errors, which may be produced by the geometrical errors described above. In case of possible Abbe offset due to deflections, for example 1mm will cause 2.5nm Abbe error for 0.5 arc seconds over the 50mm range.

Accuracy of the length measuring machine scale has been investigated using the laser interferometer with its linear optics and it is found that maximum error over the measurement range of 50mm in any part of the line scale is less than 100nm. Fig. 7 illustrates the calibration process using the laser interferometer. It should be noted that calibration was performed in the environment of 20 ±0.1°C and the temperature variation has been noted as less than 10mK during the calibration process.



a)

b)

Fig. 7. Calibration of the line scale by laser interferometer a) location of linear optics, b) location of laser head

A procedure adapted from EAL-G21 [7] has been used for checking the probing performance of the instrument as well its calibration considering all combinations such as moving anvil and measuring slide error. The calibration has been carried out with the aid of gauge blocks. Gauge blocks with different nominal lengths have been used to cover the entire calibration range (up to 500mm). Although maximum difference between reference metric blocks and test inch blocks is 8mm (500mm/20inch), the performance of the instrument up to 50mm difference has been investigated. The gauge block pairs used for this purpose and calibration results are given in TABLE I. The gauge block certified values have been taken by interferometric measurements.

TABLE I. Calibration results of mechanical comparator

Nominal length		Certified value	Measured mean value	Difference	Measured standard deviation
A mm	*B* mm	*C* (*B-A*)/μm	*M* (*B-A*)/μm	(*C-M*) μm	(*B-A*)/μm
200	200	0,193	0,197	-0,004	0,008
250	250	0,010	0,041	-0,031	0,006
300	300	0,120	0,090	0,030	0,004
500	500	0,810	0,870	-0,060	0,014
175	200	25000,037	25000,055	-0,018	0,009
200	250	50000,360	50000,420	-0,060	0,011

Applied measuring force by the moving anvil has been checked using a load tester. It is about 0.4N.

6. UNCERTAINTY CALCULATIONS

The measurement uncertainty of the mechanical comparator has been calculated according to GUM [8]. The calibration results and the parameters, which have influence on the measurement, have been taken into consideration. These parameters are explained below.

6.1. Reference Standard

Reference Standard: The associated uncertainty of measurement with the length of the reference gauge block is given in the calibration certificate of gauge blocks as $U = (35^2)+(0.4L)^2]^{1/2}$ nm L:mm with k=2.

Drift of the reference standard: The temporal drift of the length of the gauge block is estimated to be zero with the limits of ±30nm. The previous certificate of the reference gauge blocks has been used for this purpose. It is taken as rectangular distribution.

6.2. Mechanical comparator measurement

Calibration of the comparator: The maximum permissible deviation according to the calibration given above is taken as ±120nm.

Resolution: The resolution of the comparator is 10nm. It is taken in to uncertainty budget as a rectangular distribution.

Variation in length: For gauge blocks of grade 0 the variation in length should be ±180nm (ISO 3650). Assuming that this variation occurs on the measuring faces along the short edge of length 9mm and that central length is measured inside a circle of radius 0.5mm, the correction due to central misalignment of the contacting point is estimated to be within ±10nm.

6.3. Temperature measurement of the gauge blocks

Reference gauge block temperature: Temperature of the reference gauge is measured with an uncertainty of ±0.015°C. It is assumed to be a rectangular distribution. As the reference gauge block temperature is measured twice (at the beginning and at end of the measurement), this value is divided by √2. The value in terms of length due to this uncertainty can be calculated by (0.015 / √2 *11.5E-6 *L*).

Test gauge block temperature: Temperature of the test gauge is measured with an uncertainty of 0.015°C. It is assumed to be a rectangular distribution. As the test gauge block temperature is measured twice (at the beginning and at end of the measurement), this value is also divided by √2. The value in terms of length due to this uncertainty can be calculated by (0.015 / √2 *11.5E-6 *L*).

Thermal expansion coefficient of the reference gauge block: Nominal value for thermal expansion coefficient of steel is about 11.5E-6 (1/K). The value may vary from gauge to gauge and can be estimated with an uncertainty of 1E-6 (1/K). This is assumed to be rectangular distribution. The maximum allowable deviation of gauge temperature from 20°C is ±0.1°C. The value in terms of length due to this uncertainty can be calculated by (0.1*1.0E-6 *L*).

Thermal expansion coefficient of test gauge block: As the test gauge is also steel, the same treatment as described above can also be applied. The value in terms of length due to this uncertainty can be calculated by (0.1*1.0E-6 *L*).

The difference between thermal expansion coefficient of the gauge block and line scale: The line scale is made of glass. Thermal expansion coefficient of the glass varies between 10ppm to 6ppm. The worse case is chosen (6ppm). The difference between steel thermal expansion coefficients is about 5.5ppm. This is assumed to be rectangular distribution. The maximum allowable deviation of the gauge temperature from 20°C is ±0.1°C. The value in terms of length due to this uncertainty can be calculated by (0.1*5.5E-6**dL*). *dL* is the length difference between nominal size of reference and of test gauge block. Considering 20 inch/500mm is the worse case, 8mm is taken for the uncertainty contribution, (*dL* = 8mm, 0.1*5.5E-6 *8mm = 4.5nm).

Temperature difference between the gauge blocks and the line scale: Temperature difference between the gauges and the line scale is not corrected. However it is taken in to uncertainty budget. This is assumed to be rectangular distribution. The maximum temperature difference between gauge blocks and the line scale is about ±0.01°C. The value in terms of length due to this uncertainty can be calculated by 0.01*6E-6 *dL*. This leads to 0.01*6E-6 .8mm = 0.5nm

6.4. Repeatability of the measurement

The pooled estimate of the standard deviation is about 20 nm. Five measurements are performed for each gauge during the calibration. This is taken in to uncertainty budget as 20 / √5 = 9nm.

6.5. Combined and Expanded Uncertainty

The combined standard uncertainty, being the root sum square of the all uncertainty contributions, is calculated. The appropriate coverage factor can be taken as *k*=2 and the expanded uncertainty is determined by multiplying the combined uncertainty value by 2. The expanded uncertainty, which is expressed for confidence level of 95%, is given by:

$U = [\,(150^2)+(0.5L)^2\,]^{1/2}$ nm, where L is the gauge block length in mm.

7. PERFORMANCE OF THE INSTRUMENT

Overall performance test is carried out using the gauge blocks calibrated by interferometry. These certificated gauge blocks have been measured by the mechanical comparator and the results shows that the comparator performs very well within the calculated uncertainty limits. Maximum deviation was obtained as 60nm.

The metric gauges in square section have been measured using the reference gauges of same nominal sizes rectangular blocks. The results are illustrated in TABLE II. and Fig. 8.

TABLE III. and Fig. 9 shows the performance of the instruments for inch size gauge blocks. The inch size square section gauge blocks have been measured using nearer nominal sizes rectangular metric gauge blocks.

TABLE II. The results of the metric square gauge blocks

Nominal length (mm)	Certified Value (nm)	Uncertainty of the Cert. Value (nm)	Measured value (nm)	Uncertainty of the measured value (nm)
150	-27	69	-45	168
200	90	87	97	180
250	265	106	301	195
300	190	125	169	212
500	800	207	860	292

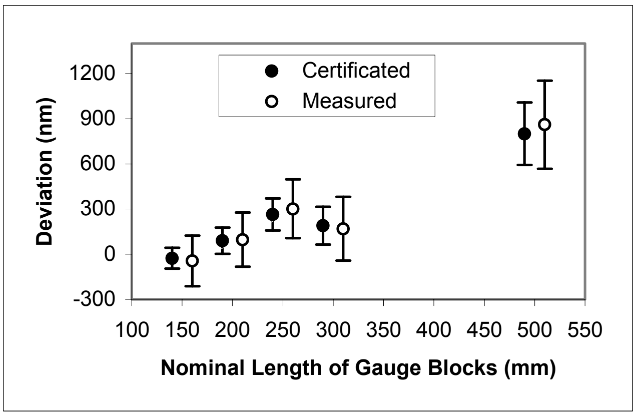


Fig.8 . The performance of the comparator for metric blocks

TABLE III. The results of the inch size square gauge blocks

Nominal length (inch)	Certified Value (µinch)	Uncertainty of the Cert. Value (µinch)	Measured value (µinch)	Uncertainty of the measured value (µinch)
5	5,4	2,9	4,3	6,3
8	12,4	3,1	14,4	6,8
12	9,8	3,4	9,37	7,7

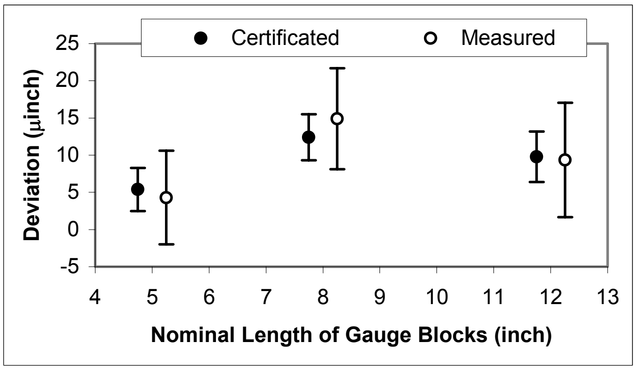


Fig. 9. The performance of the comparator for inch blocks

8. CONCLUSIONS

The mechanical comparator presented enables the calibration of inch size square or rectangular gauge blocks using metric size gauge blocks as reference or vice-versa. The performance tests showed that the comparator works well with the uncertainty of $U = [\ (150^2)+(0.5L)^2\ ]^{1/2}$ nm, (where L is the gauge block length in mm) for metric gauge blocks and $U = [\ (6^2)+(0.5L)^2\ ]^{1/2}$ µinch for inch size gauge blocks (where L is the gauge block length in mm).

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