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A non-contact calibration system for step gauges using automatic collimation techniques

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Abstract

To calibrate transfer standards for length calibration, a non-contact calibration system for step gauges and gauge blocks has been developed, in which a laser interferometer was equipped to obtain the length displacement and dual-stage driving-position techniques were used to carry step gauges to approach the measuring location. A non-contact collimation technique combined with an optoelectronic microscope was proposed for achieving identification. The optoelectronic microscope eliminates both the contact deformation resulting from the mechanical force and motion deviations. The combination of dual-stage driving-position techniques and the non-contact collimation technique can ensure that the collimation repeatability is less than 20 nm. The experimental tests and comparison results indicated that the non-contact strategy and dual-stage position techniques can provide a reliable method for building a length calibration system for gauges, industrial line scales, and end bars.

Keywords: step gauge, dimensional metrology, coordinate measuring machine, laser interferometer, optoelectronic microscopy, length bar calibration

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

1. Introduction

In geometrical metrology, actual physical parts of a known length which can have contact with mechanical sensors play a critical role as reference standards. These standards have been becoming increasingly important for assessing the accuracy of calibration instruments. Both gauge blocks and step gauges perform the functions of the most reliable materialized standards in length measurement and uncertainty assessment [1]. Coordinate measuring machines (CMMs) represent one of most versatile dimensional measuring instruments, offering rapid, accurate, and automatic measurements for the production floor [2, 3]. Step gauges are physical standards with multiple indicated values, which are constructed by a series of working surfaces of gauge blocks. The standard scale values are defined as the distances between parallel working surfaces. In acceptance tests and verification according to ISO 10360-2, gauge blocks and step gauges are usually reference standards used for the verification of CMMs [4]. Both step gauges and gauge blocks provide several distances on a single measurement axis, resulting in smaller uncertainty for the calibrating stability. In the verification of CMMs and other length instruments, the artifacts of step gauges and gauge blocks are measured in various orientations, which have been described according to the ISO rules [4, 5]. Furthermore, step gauges are often used for the error measuring methods of machine tools, in order to reduce distance deviations due to repeated alignment, the complexity, and the measuring environment [6].

Technologies for developing novel step gauges have been proposed. For example, a monolithic ceramic step gauge with a low thermal expansion coefficient was developed as a reference standard to obtain a smaller uncertainty [7], because the thermal expansion coefficient of the step gauge dominates the contribution to the expanded uncertainty of the calibration instruments. In order to overcome the inherent limitation of the finite lengths and thermal expansion of step gauges, an interferometric step gauge was developed, in which a moveable target gauge block moves along a rail over a carriage bearing and the surface positions of the gauge block are probed with a laser interferometer. The standard uncertainty in the measurement of gauge blocks is about 0.2 µm for a 1.0 m length [8].

To ensure their traceability in the metrology system, both step gauges and gauge blocks must employ calibration instruments, in which the measurement capability is higher than that of step gauges and blocks. The dimensional requirements or tolerances of various calibration instruments represent an important issue. Several National Metrology Institutes (NMIs) and accredited calibration laboratories offer calibration services for step gauges, ranging from an uncertainty of less than 0.1 µm to the best expanded uncertainties of slightly over 300 nm for a 1 m measurement length [9].

For general applications, with the advances of CMMs in the last two decades implemented by NMI and CMM manufacturers, a calibrated CMM can feature a calibration function for step gauges [10–12]. The uncertainty of conventional CMMs has reached a level of 0.3 + L/1000 µm. In CMM solutions, a mechanical sensor is employed to perform the collimation and measurement function. The uncertainty of a CMM solution is limited by the probing head [12, 13].

To decrease the uncertainty of the CMM calibration instruments for step gauges, the most commonly used method is that the contact probing approach in CMM calibration instruments is equipped with a laser interferometer [14, 15]. In this approach, the contact prober attached to a measuring head of the CMM ensures the position of the working surface of the gauge block, and an interferometer following Abbe's principle measures the location of the probe by an automatic measurement system [15]. To decrease the uncertainty of the interferometry, a phase stepping interferometer has been used in CMM solutions for gauge block calibration [16]. For the versatility of a calibration instrument, a Twyman–Green interferometer was adopted in the National Physical Laboratory (NPL) to measure the length of gauge blocks, length bars, and Hoke gauges. A phase stepping method was used to process interference patterns to obtain a 3D topographic model of gauge blocks and platen surfaces, in order to reduce the flatness and parallelism between the gauge blocks in a step gauge [9, 13].

Typically, both a linear guide system and a plane mirror interferometer have been used in these CMM- interferometer systems [17]. The four-path laser interferometer used in the National Metrology Institute of Japan (NMIJ) has achieved an expanded uncertainty of 0.5 µm for 1000 mm [10].

The combination of a laser interferometer with a CMM instrument has become the general methodology for the calibration of step gauges. Several international key comparisons have shown that the CMM calibration solution for step gages can reach an uncertainty of tens of nanometers [18–21]. Although the improved CMMs satisfy the general requirements for calibrating step gauges, they are operated with slow movement profiles to minimize the residual vibration, which results in a low efficiency and a bottleneck in production lines [17, 26]. The remaining concern is the contact probe in the CMM solution. The alignment procedure carried out by the contact prober can become tedious. Using a contact-type prober, the contact force between the probe and the surface of the step gauge leads to measurement errors due to force deformation, together with the probe motion in an up and down direction, which is orthogonal to the measurement line [22–25]. The uncertainty estimation resulting from the contact collimation method dominates the standard uncertainty of these instruments [10, 26].

To address these issues, we replaced the CMM probe with a non-contact optoelectronic microscope to perform the collimation function. This method can reduce the errors associated with the contact probe. In addition, a dual-stage driving method was applied to satisfy both the length range and simultaneous the displacement resolution. In our work, the displacement resolution was improved due to the use of a piezoelectric (PZT) actuator. The metrological characteristics and an uncertainty evaluation of our developed system will now be described for the verification of step gauges.

2. Non-contact calibration system for step gauges

The non-contact strategy of our developed step-gauge calibration system was performed by the combination of a laser interferometer and an optoelectronic microscope technique. As shown in figure 1, the calibration instrument was built in a home-made bridge CMM. A laser interferometer, an optoelectronic microscope, and a dual-stage driving configuration were integrated into the granite platform of the bridge CMM. An interferometer with a laser wavelength of 632.8 nm was installed on the pedestal platform. The displacement of a moving step gauge or gauge blocks is measured with laser interferometry. The displacement range of the movement is over 640 mm. As shown in figure 1, two reflective mirrors were installed at the end of the laser beams in the reference and measurement arms. The reflector in the reference arm is installed on an extended cantilever. The cantilever and the spectroscope are fastened on the CMM worktable by forcing screws. Thus, the reflector in the reference arm and the spectroscope keep constant displacement with each other. Both

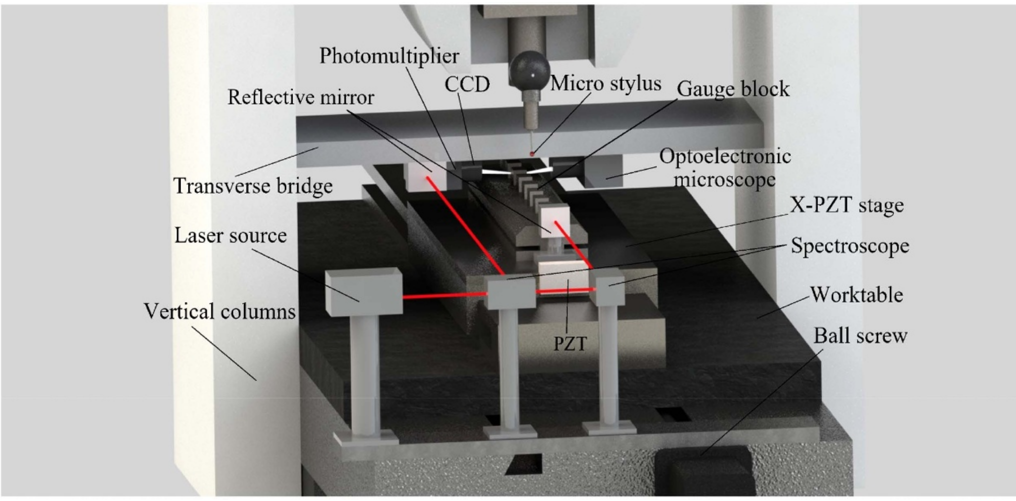

Figure 1. An illustration of the developed non-contact calibration system for step gauges. The optoelectronic microscope and CCD camera perform the function of non-contact collimation. Additionally, a laser interferometer was equipped to measure the length displacement between the centers of the front or back faces of individual gauge blocks with respect to the central point of the first gauge with its nominal direction. The beams from the interferometer to the reflective mirrors in both reference and measured light paths are marked as red lines.

the reflector in the measurement arm and the step gauge are mounted on the X-PZT stage. The reflector in the measurement arm normally locates at the front of the first gauge block of the step gauge. The reflecting mirror is normal to the central axis of the measurement line. The XL80 laser interferometer by Renishaw with a laser wavelength stability of less than 10^{-8} is used to measure the distance.

A steel transverse bridge was installed between the two vertical columns of the CMM. An optoelectronic microscope was suspended on the down side of the transverse bridge. The optoelectronic microscope consists of a CCD camera and a photomultiplier to perform identification of the measuring surface.

The movement operation of the dual-stage driving should have a good straightness and be motorized with a high resolution. To minimize errors due to the moving mass and deformation due to the drive forces, a dual-stage driving configuration was designed for obtaining the fine location of gauge blocks. The driving system consists of the CMM worktable, an X-PZT stage driven by a PZT actuator, and control circuits. The granite worktable on the carriage bearing is driven by a ball screw along the guide rail. The stacked PZT actuators are assembled on a flexure elastic element with enough stiffness for the structural deformation displacement. The X-PZT stage links the guide rail through a frame structure. The frame structure was fastened on the front side of the movable CMM granite worktable, on which the step gauge is also mounted. In the fine motion of step gauges, there is not interference among the X-PZT stage and the guide rail. The later experiments shown that the dual-stage driving configuration ensure the mechanical stability for obtaining the fine position of step blocks.

The measurements are carried out along the measurement line, which passes through the central points at respective working surfaces of gauge blocks. The working surface of the mirror locating in front of the measurement arm can also be probed by optoelectronic microscopy. This configuration allows adjustment of the concentricity between the measurement line and the laser beam, and rectifies the parallelism between the gauge blocks and the retroreflector mirror. During the measurement process, the step gauge and its pedestal are driven by the moving worktable of CMM and the PZT to the exact measurement position. The optoelectronic microscope collimates and identifies the working surface of gauge blocks, and the laser interferometer measures the interval displacement between the gauge blocks.

Figure 2(a) presents the horizontal structure of a step gauge. A few gauge blocks are distributed on a steel pedestal, with equal intervals between each of them. The working planes of gauge blocks refer to the ideal planes, which are all parallel to each other and equally spaced one after another by a constant distance in the longitudinal direction. The central point of the gauge working surface is an intersection point of the working planes and the measurement line. As shown in figure 2(b), the measurement line passes through the central points in the working faces of the gauge block and directs the normal vector of the working surface along the longitudinal direction. Moreover, the measurement line is concentric with the extended line of the laser beam. During the length measurement, the central points of the working gauge block are practically intersection points of (1) a plane representing the gauge surface at its individual longitudinal position, (2) the extended line of the measurement beam of the interferometer, and (3) the focus point of the light beam of the optoelectronic microscope. The measurement line passes through the center points of the gauge block and the measurement retroreflector mirror. The central points of the working gauge block are collimated by the optoelectronic microscope from one side surface, resulting in a unidirectional measurement, while, if needed, also from both sides, resulting in a bidirectional measurement.

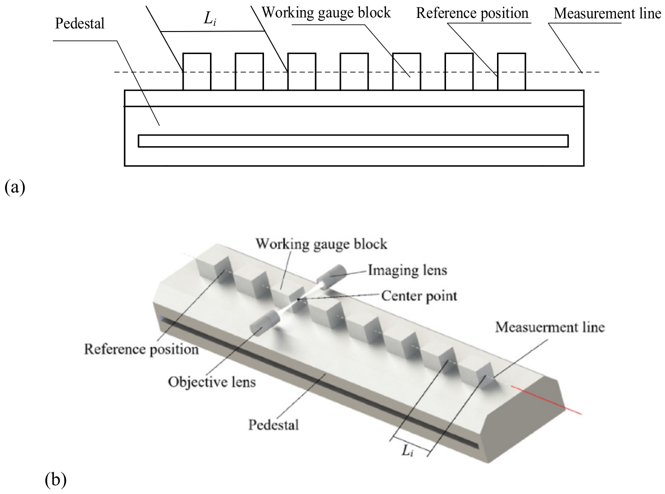

Figure 2. Schematic structure of a step gauge in (a) the transverse section and (b) a 3D schematic diagram of its working conditions. The measurement line, concentric with the extended line of the laser beam, passes through the central points in the working faces of the gauge block.

3. Automatic collimation techniques

For the contact calibration instruments in a CMM equipped with a laser interferometer, the stylus of CMMs contacts with the central points of two working surfaces of the gauge block for each displacement measurement. During this length measurement, the actual tracking curves of the moving stylus are in a three-dimensional space, which results in the deviation of tracking curves from the length definition of step gauges. The moving stylus results in other error sources, such as force correction of face probing, deformations due to the contact force, stylus diameter calibration, parallelism deviations from the measurement line, and contact deviations due to the position measurement. All of these measurement errors contribute to the measurement uncertainty of the measurement system. The non-contact automatic collimation, in which an optoelectronic microscope replaces the contact stylus, can eliminate these measurement errors.

The central points of working planes for each gauge block are identified in real time by an optoelectronic microscope. As shown in figure 3, the light emitted from a coupling fiber light source passes through a condenser lens and illuminates the target reticle. The pattern of the target reticle is focused through an objective lens at the working surface of the gauge block. The cross-line pattern of the target reticle is superposed with the reflected image of the working surface of the step block after it passes through the measurement line. The reflected images are magnified by the images lens and separated through a beam split. Half of the image light is imaged onto the CCD camera. The exact position of the working surface can be identified, monitored, and adjusted through the images in the CCD camera. The left half of image light is modulated through an oscillator slit and illuminates the photomultiplier tube. The reflected images of both the target reticle and the working surface of the step block are observed simultaneously through the CCD camera and photomultiplier.

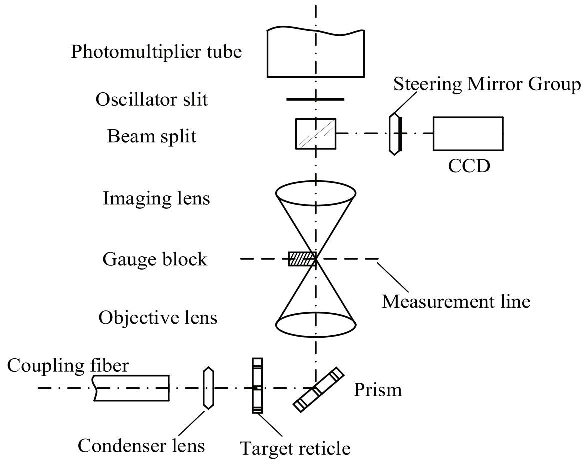

Figure 3. An optoelectronic microscope performs the identification of central points in a working gauge block.

The modulated signals passing through the oscillator slit are used for automatic collimation.

Figure 4 shows the non-contact automatic collimation techniques employed for the identification performed by optoelectronic microscopy. The optical axis of the optoelectronic microscope is perpendicular to both the image plane and the measurement line. A gauge block is driven by the driving system moving along the measurement line or the extended laser beam. As shown in figure 4(b), when the working surface of a gauge block is moved to the focus point of the light axis of the optoelectronic microscope, the central point of the gauge block coincides with the measurement line. In this condition, the reflected focused image of the target reticle is located in the central position of the image plane of the photomultiplier. The collimation signal coming from the photomultiplier triggers the laser interferometer to obtain the locations of the gauge block. Then, the gauge block is moved

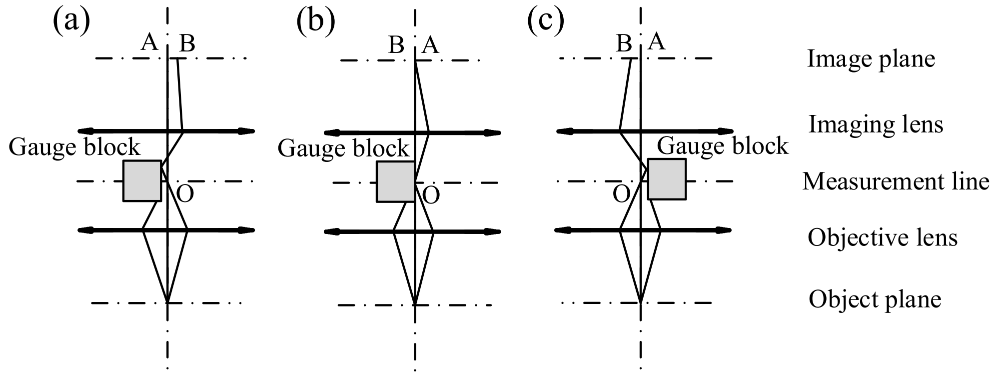

Figure 4. Non-contact collimation techniques for the identification of central points of step gauges.

to the next collimation location, where the laser interferometer obtains the distance between two neighboring blocks. As shown in figures 4(a) and (c), when the working surface of a gauge block approaches or departs from the focus point of the optical axis of the optoelectronic microscope, the reflected attern will depart from the central position of the image plane in the photomultiplier tube. In these conditions, the working surface should be continuously driven to the focus point by the X-PZT stage, until the working surface and the focus point of the optical axis are superimposed on each other. The reflected images in the CCD camera help us to install and adjust step gauges, as well as to preliminarily identify the position of working surface with respect to the measurement line. The non-contact collimation method accurately aligns the working surface of step gauges with the optical axis along the measurement line.

The system follows Abbe's principle, in which the measurement line is defined as a line which passes through the center points of gauge blocks on both sides. Additionally, the measurement line coincides with the extended line of the laser beam in the measurement path. Of course, collimation identification in the optoelectronic microscope cannot decrease the errors due to the lack of flatness and parallelism in the working faces of gauge blocks. The illustration in figure 4 shows that the gauge block can purposefully be measured in a unidirectional direction from only the left/right side surface, but, if necessary, it can also be measured in a bidirectional from both sides.

To obtain automatic collimation, a phase discrimination method was used to perform the non-contact collimation techniques. Both the working surface of the step gauge and the target reticle were imaged using the photomultiplier tube. An oscillator slit was used to modulate the obtained images into phase values. In one scanning period of the oscillating slit, the reflected images will pass through the slit twice. The light intensity of the images will undergo two attenuation processes from the maximum to the minimum value. When the reflected image of the target reticle collimates with the working surface of a gauge block, the oscillating frequency of the light intensity will be double the value of the scanning frequency, which refers to the exact collimation position. When the frequency of the collected image signal is exactly equal to twice that of the oscillating frequency, the output signal of the phase discrimination approaches a zero value; otherwise, the output signal is positive or negative, depending on the direction of the phase signal. In this way, the translation direction of the measurement surface can also be identified.

4. Dual-stage driving-position techniques

The movement of the calibration instrument should have a good straightness and be motorized with a high-resolution operation. The dual-stage driving system was designed for the requirements of both the accuracy and moving speed. In dual-stage driving techniques, two steps of horizontal linear manipulation are realized by both a linear translation stage with primary coarse movement and an X-PZT micro-stage. The linear translation supported on the air bearing was driven by a ball screw along the guide rail of CMM. The micro-stage is a flexure structure equipped with an integrated PZT actuator, which is installed on the granite stage of the CMM. In the initial driving procedure, the measurement distance of the gauge block was defined in advance by the control software. For a coarse position, the measured step gauge was driven close to the optical axis of the optoelectronic microscopy. Then, both the optoelectronic microscope and the X-PZT stage obtained a fine position. The X-PZT actuator drives the stage in approximately 100 nm steps. This fine movement is monitored by the optoelectronic microscope. When the central point of the gauge block approaches the exact collimation location, the condition of the zero output from phase discrimination will start the measurement of laser interference.

As shown in figure 5, there are jump deviations between the profiles of the actual driving voltage and the ideal motion line. To minimize the jump step of the guide rail, the step change of the driving voltage for driving the PZT actuator was optimized. The moving resolution of the PZT stage was reduced sharply and a positioning error of less than 5 nm was obtained. After voltage optimization, the driving system enables collimation with a position accuracy of a few nanometers. The dual-stage driving and position techniques enable the measurement system to operate with high acceleration–deceleration profiles

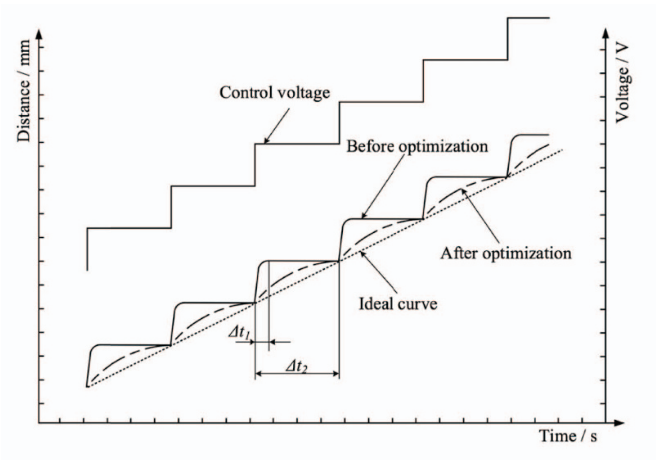

Figure 5. Step change of the driving voltage for a piezoelectric (PZT) motor was optimized to minimize the step jump of the guide rail. The deviations between the driving voltage and the motion profile are reduced by the optimized driving voltage.

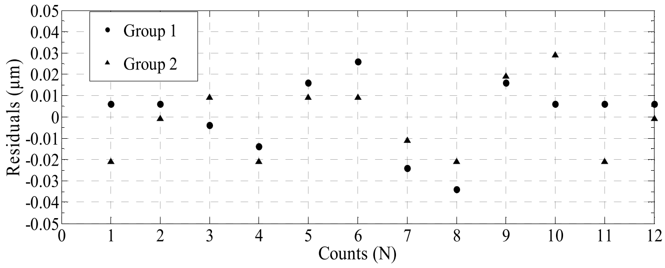

Figure 6. Two groups of readings were recorded to verify the repeatability of the automatic collimation performed by both the optoelectronic microscope and the dual-stage driving.

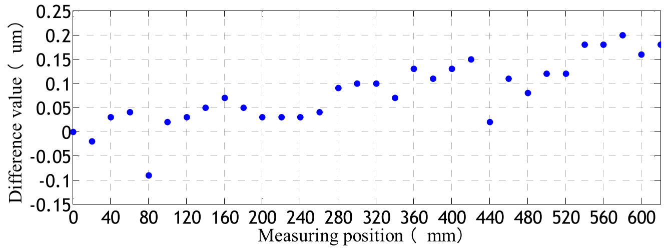

Figure 7. Difference in the comparison data obtained in the Changcheng Institute of Metrology and Measurement (CIMM) and the National Institute of Standards and Technology (NIST).

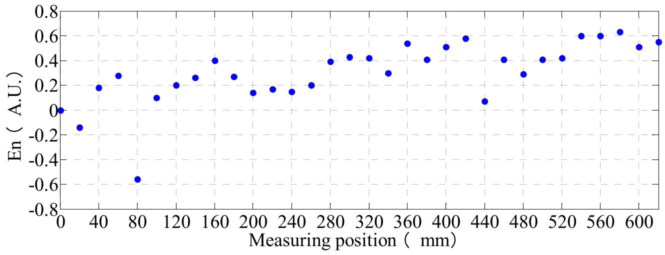

Figure 8. En values obtained from the comparison results recorded in CIMM and NIST.

and reduce the residual vibration, which leads to a high efficiency in batch measurement.

5. Comparison results and discussion

A standard step gauge was used to experimentally verify the repeatability and uncertainty of our developed non-contact collimation techniques and the calibration system for step gauges. The measurement artifact is manufactured by the KOBA company. It has a steel frame, ceramic gauges, and a 640 mm nominal length with a step length of 20 mm. The thermal expansion coefficient of the tungsten carbide gauges is $\alpha = 11.5 \times 10^{-6}\ \mathrm{K}^{-1}$. The repeatability of the automatic collimation function of the developed optoelectronic microscope was verified experimentally. Dual-stage driving moved the step gauge until the optoelectronic microscope triggered the interference for the measurement of the collimation position. Then, the standard step gauge was moved for the next collection. The measurement processes for each block of the step gauge were repeated 12 times. At the same time, the environmental conditions, such as the temperature, humidity, and atmospheric pressure, were recorded. The refractive index was calculated using the updated Edlen formula [24]. Two groups of the readings are shown in figure 6. The repeatability of automatic collimation was analyzed by the standard deviation formula, resulting in a repeatability of less than 0.02 μm. The optoelectronic microscope eliminated both the contact deformation and the motion deviations, which ensured a small value for the collimation repeatability.

The comparison measurements of our step-gauge calibration system were conducted with the standard reference data measured in the National Institute of Standards and Technology (NIST) in American. The standard step gauge was measured independently. The differences between the collected data obtained in the Changcheng Institute of Metrology and Measurement (CIMM) and NIST in American are shown in figure 7. A CMM equipped with a laser interferometer was used to measure the block distances of the standard step gauge, in which error separation techniques were used to decrease the uncertainty due to the contact probe and other deviations [25]. In figure 8, the estimated values of $|E_n|$ in each point are less than a unit, implying that the comparison results are compatible.

$$En = \frac{L_{\mathrm{CIMM}} - L_{\mathrm{NIST}}}{\sqrt{U_{\mathrm{CIMM}}^2 + U_{\mathrm{NIST}}^2}} \tag{1}$$

Here, L_{CIMM} and L_{NIST} are the measurement data collected independently by our developed calibration instrument in CIMM and by the calibration instrument in NIST, respectively. Moreover, U_{CIMM} and U_{NIST} represent the respective measurement uncertainty values. The uncertainty evaluation of the calibration measurement followed the guidelines given in the GUM (guide to the expression of uncertainty in measurement) [27].

Error sources and the uncertainty budget were estimated. The uncertainty components of the laser interferometry are attributed to the wavelength stability and the measurement errors from the temperature, humidity, and pressure measurement. In our laboratory conditions, the error of the temperature sensor is 0.005 °C ($k = 2$), the relative error of the humidity sensor is 4%, and the absolute error of the pressure sensor is 10 Pa. For the nominal distance of 640 mm in a step gauge, the uncertainty contribution from the laser interferometry to the final standard uncertainty is estimated to be $u_1 = 5.94 \times 10^{-8}$ l calculated by the Edlen's formula.

The experimental data indicate that the standard deviation of the collimation repeatability is $u_2 = 0.02$ µm. The parallelism and flatness of the step blocks manufactured by the KOBA company is $u_3 = 0.03$ µm $+ 3 \times 10^{-8}$ l. The uncertainty contribution due to the thermal expansion coefficient of the step gauge resulting from the temperature measurement error is $u_4 = 0.288 \times 10^{-7}$ l. The component contribution resulting from the parallelism error of 0.3 mm/1000 mm between the laser beam and the guide rail is $u_5 = 5.196 \times 10^{-8}$ l. The guiding errors from the straightness of the guide rail and carriage are considered to be zero because that there are no Abbe offset errors assuming zero alignment between the laser beam and the measurement line. The above individual components of standard uncertainty are uncorrelated. The expanded uncertainty of the calibration instrument is estimated to be $U = 0.07$ µm $+ 0.25 \times 10^{-6}$ l at the 95% confidence level ($k = 2$). The dominant contribution of expanded uncertainty comes from the thermal expansion coefficient of the step gauge.

In contrast to the contact-type calibration system, the non-contact instrument has advantages: An optoelectronic microscope performs the automatic identification, in which both the measurement standard and the collimation benchmark remain stable, without moving. The Abbe errors are reduced to a negligible minimum value, where the measurement line of the step gauge is consistent with the extended line of the laser interferometer. The optoelectronic microscope focuses at the intersection points. Additionally, in contrast to the dynamic collimation techniques of the inductance stylus, the driving-position techniques of the X-PZT stage perform a quasi-static collimation procedure, which further reduces the repeatability values.

6. Conclusion

Step gauges and gauge blocks provide physical standards for maintaining traceability in dimensional metrology. They are used to calibrate a wide range of instruments and other length standards. A non-contact calibration system for step gauges was developed herein. A laser interferometer and a dual-stage driving system were integrated into a specified CMM. An optoelectronic microscope was designed to perform the function of non-contact automatic collimation. The non-contact collimation method reduces the disturbance coming from the probe deflection and other deformation resulting from the mechanical force.

In the design of the instrument, the relevant error sources of interferometers in particular were taken into account and eliminated or minimized. The developed system can provide a confident instrument for length metrology of 640 mm, with an expanded uncertainty of $U = 0.07$ µm $+ 0.25 \times 10^{-6}$ l at the 95% confidence level ($k = 2$). The comparison results indicated that the developed technique can provide a reliable collimation method for building other standard calibration systems, such as gauges, industrial line scales, and end bars. In the future, the greater flexibility achieved will ensure that the machine can calibrate various standards, such as long-range linear transducers, industrial line scales, and end bars.

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