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Abstract. A stroboscopic scanning white light interferometer (SSWLI) can characterize both static features and motion in micro(nano)electromechanical system devices. SSWLI measurement results should be linked to the meter definition to be comparable and unambiguous. This traceability is achieved by careful error characterization and calibration of the interferometer. The main challenge in vertical scale calibration is to have a reference device with reproducible out-of-plane movement. A piezo-scanned flexure guided stage with capacitive sensor feedback was attached to a mirror and an Invar steel holder with a reference plane—forming a transfer standard that was calibrated by laser interferometry with 2.3 nm uncertainty. The moving mirror vertical position was then measured with the SSWLI, relative to the reference plane, between successive mirror position steppings. A light-emitting diode pulsed at 100 Hz with 0.5% duty cycle synchronized to the CCD camera and a halogen light source were used. Inside the scanned 14 μm range, the measured SSWLI scale amplification coefficient error was 0.12% with 4.5 nm repeatability of the steps. For SWLI measurements using a halogen lamp, the corresponding results were 0.05% and 6.7 nm. The presented methodology should permit accurate traceable calibration of the vertical scale of any SWLI. [DOI: 10.1117/1.OE.52.12.124104]

Keywords: stroboscopic; scanning white light interferometry; MEMS; nanoelectromechanical systems; calibration.

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1 Introduction

Micro(nano)electromechanical systems [M(N)EMS] is a key technology that both enables and demands innovative metrology. This technology is predicted to strongly impact the daily life of humans.[1] MEMS-based accelerometers and pressure sensors are used in the aeronautical and automotive industries. The functionality and reliability of those devices is based on repeatable deformation and displacement of the M/NEMS parts under mechanical, thermal, magnetic, or electrostatic excitation.

Scanning white light interferometry (SWLI) is an established methodology for static topography characterization of M/NEMS devices. To obtain high-resolution SWLI images, the bandwidth of the light source should be broad and the coherence length should be short.[2] The SWLI is not restricted to measuring static samples—oscillating objects can be characterized with a stroboscopic SWLI (SSWLI) featuring a modulated light source. For these dynamic measurements, the light source should permit rapid switching. Incandescent lamps (with choppers), white-light light-emitting diodes (LEDs), and supercontinuum (SC) sources fulfill most of these requirements.[3,4]

In SSWLI, the SWLI instrument is augmented with stroboscopic illumination and appropriate synchronization to allow dynamic characterization of oscillating samples. Samples oscillating at 2.41 MHz have been measured using SC lasers,[5] whereas a hybrid light source (nonphosphor white and cyan LED) has allowed stroboscopic measurements of a capacitive micromachined ultrasonic transducer oscillating at 2.71 MHz.[6]

To have reliable measurements with surface topography measuring instruments like SWLI, the measurement method needs to be validated, different kinds of errors characterized, and their scales should be calibrated with transfer standards (TS) traceable to the definition of the SI meter.[7] These include noise characterization, lateral and vertical scale calibration, deviation from flatness calibration, and orthogonality error characterization.[8,9] Traceable calibration, measurement modeling, and uncertainty analysis are needed to analyze the uncertainty in a measurement.

(S)SWLI is a three-dimensional measuring instrument with lateral (X, Y) and vertical (Z) measurement capability. The basic measurement result is a height (z) value relative to a selected reference plane, or several values in case of multiple reflecting interfaces, for each (x, y) pixel. The height reference level can be either a set height on the vertical scanner scale or a specific area in or near the sample within the view of the instrument. The latter provides better robustness against thermal drift during repeated measurements by largely excluding the instrument structure from the metrology loop.

Lateral calibration of an (S)SWLI can be done as with traditional optical microscopes, e.g., using calibrated stage micrometers or grating samples as TS.[8] Static z-scale calibration can be done, e.g., using step height standards or gauge blocks with traceable lengths wrung to reference plates to serve as TS of length scale.[8,10,11] Proper calibration should

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include several heights in order to identify nonlinearities of scale. Flatness deviation can be calibrated using traceably calibrated flatness standards.

To validate and calibrate the SSWLI, one needs, in addition to calibration with static samples, to study its properties during dynamic measurements. For that purpose, a TS capable of producing height profiles moving at different frequencies and amplitudes is necessary. In addition, proper samples for transient motion need to be identified.

To address the above needs, an accurate vertical scale calibration technique that is applicable to both static and dynamic measurements was developed. The approach called for designing and building a TS to bring traceability from a laser interferometer at the Centre for Metrology and Accreditation (MIKES), Finland, to the (S)SWLI setup at the Electronics Research Laboratory at the University of Helsinki, Finland. The approach was to be based on quasidynamic measurements where the moving mirror position of the TS is stepped between consecutive (S)SWLI scan measurements. The TS performance was to be determined both with a stroboscopically operated LED synchronized with a camera and with a traditional nonstroboscopic halogen lamp to determine the similarity of those measurement modes. The method was designed such that it can be extended to allow calibration of dynamic stroboscopic measurements of oscillating samples.

2 Calibrated Transfer Standard for SSWLI

Laser interferometry with a calibrated laser frequency is the standard way to realize traceable displacement measurements.[12] To bring traceability to the SSWLI instrument's vertical scale, a traceably calibrated TS was designed and manufactured, see Fig. 1. The TS fulfills a set of requirements to be useful for M/NEMS characterization with SSWLI.

First, the TS is measurable both with a reference instrument connected to the national standard by an unbroken chain of calibrations and with the SSWLI device under calibration. The TS operates in a desired frequency (dynamic) range and exhibits a few nanometers of vertical displacement reproducibility. Dimensional characteristics—size of the sample and support structure—are suitable for the measuring devices. Surface finishing characteristics of the moving mirror—surface roughness and reflectivity—allow measurements with both systems (reference interferometer and SSWLI). Second, the TS was produced from selected materials to ensure precise thermal management of the system, including physical dimensions and coefficient of thermal expansion of the components in the reference material.

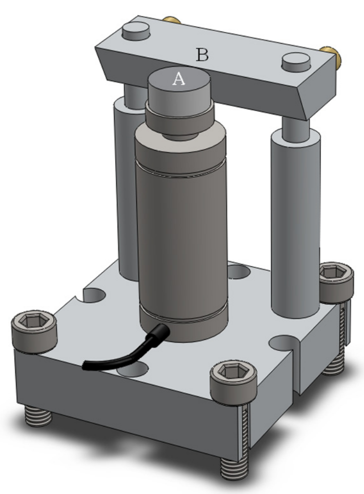

Fig. 1 Transfer standard (TS). The moving mirror (A) is mounted on a piezo stage. The reference flat (B), its posts, and the baseplate are made of Invar alloy. The height of the TS is 10 cm.

The TS contains a flexure guided piezo stage (Queensgate Instruments, type NPS-Z-15B, Devon, United Kingdom) with internal capacitive sensors and a mounted mirror, along with an electronic controller (NPS 3330), providing a TS for quasidynamic and low-frequency dynamic calibration (<1 kHz). The TS is mounted on a custom-built Invar holder with a static reference plane. The Super Invar piezo stage and Invar holder with the Invar reference flat next to the moving mirror contribute to TS stability in terms of thermal expansion. Calculating from the thermal expansion coefficients and dimensions, the height of the moving mirror on the piezo stage changes by 33 nm/°C compared to the height of the reference flat when operated near 20°C.

The batwing imaging phenomenon present in SWLI measurements of edges[13] should not distort the calibration since the mirror and the reference plane are laterally offset by more than 100 μm. Moreover, the flat areas used for the calibration can be selected some distance away from the edges of the mirror and reference plane to ensure the absence of batwing influence.

The phase change caused by light reflection[14,15] from both the moving mirror and the static reference is constant and does, therefore, not affect the measured mirror displacement relative to the reference flat. In the current setup, the reference surface has higher roughness than the moving mirror. Surface roughness may contribute to (S)SWLI measurement error if the surfaces slightly drift in the lateral directions during a calibration measurement series. The averaging and linear drift reduction procedures as described in Sec. 3.3 suppress this error.

2.1 *Laser Interferometer Measurement*

A symmetric differential heterodyne laser interferometer (SDHLI) system[16] was used to calibrate the TS in a vertical setup, see Fig. 2. In this setup, the interferometer tracks the displacement of the moving mirror in units derived from the wavelength of the Zygo 7702 laser head. The measurements were performed in the MIKES nanometrology laboratory with a temperature stability of 20.0 ± 0.1°C.[17] The relative humidity stays at $47 \pm 2\%$.

The position information was read from the interferometer using Zygo ZMI electronics, which give position readings as integers (>100,000 samples/s), in this case in units of $\lambda/1024$, because the electronics phase resolution is $2\pi/512$ and the measurement beam reflects once from the moving mirror. The vacuum wavelength λ_0 (ca. 633 nm) of the laser has been traceably calibrated at MIKES.[18] The interferometric position l is related to the vacuum wavelength, interference counter k, and refractive index n of the laboratory air by

$$l = \frac{k\lambda_0}{2 \cdot 512 \cdot n} - c - \delta_{\mathrm{periodic}}(k). \tag{1}$$

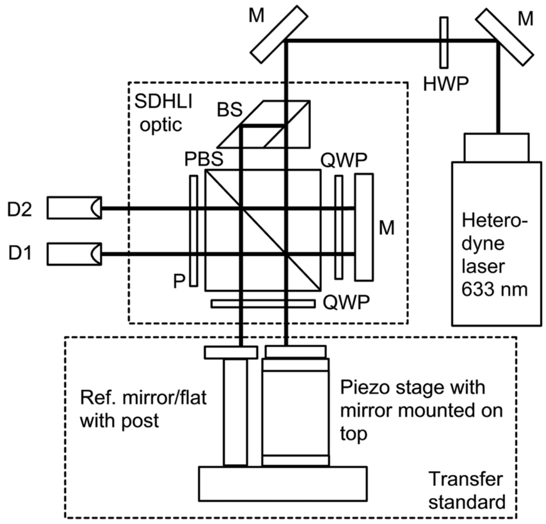

Fig. 2 TS calibration setup. D1 and D2 are the measurement and reference photodetectors, P is a polarizer, PBS is a polarizing beamsplitter, M is a mirror, QWP is a quarter-wave plate, HWP is a half wave plate, and BS is a beamsplitter.

Here δ_{periodic} is the periodic nonlinearity in the interferometer, and c is the (arbitrary but fixed) origin offset of the laser interferometer. The periodic nonlinear error ($\lambda/2$ period) of the interferometer was suppressed to subnanometer range with an error separation technique.[16]

SDHLI measures differentially the change in optical path length of the measurement and reference arms. The SDHLI measurement beam illuminated to within 1 mm, the same spot on the mirror near the edge that was used in the (S)SWLI measurements to reduce the Abbe error. The beam diameter is 2 to 3 mm. For the SDHLI reference beam, a small static mirror, with an adjustable mount connected to the TS baseplate, was mounted near the reference flat next to the moving mirror. The laser interferometer measurements were done in the same staircase stepping pattern as with the SSWLI, with a stepping pace of 2 to 3 s/step.

2.2 *Autocollimator Measurement*

Parasitic tilt of the TS moving mirror, which might cause Abbe error, was determined with an autocollimator (Moeller-Wedel Elcomat 3000, Wedel, Germany). The piezo stage carrying the mirror was measured in the same vertical orientation as in the SDHLI and (S)SWLI measurements. The autocollimator results show that the mirror's tilt angle changed by 1.2 μrad or less along the full scan range of the stage.

2.3 *Uncertainty of the TS*

The uncertainty of the calibrated TS is estimated according to guide to the expression of uncertainty in measurements.[19] The following model was used for the step displacement (Δl) calibration measurements:

$$\Delta l = l_2 - l_1 - \alpha r + \frac{\beta^2}{2} L - \delta_{\text{rep}}, \tag{2}$$

where l_1 and l_2 are interferometric readings at two positions, before and after stepping the TS. L is nominal displacement. The next two terms are small-angle approximations for the Abbe and cosine errors; α is the change in mirror tilt angle (later assumed to linearly depend on displacement), r is the Abbe distance—in this case, uncertainty due to reproducibility of the measurement point on the mirror surface—and β is the cosine error angle due to, e.g., a mirror plane not being orthogonal to the laser beam direction. δ_{rep} is the estimated error due to day-to-day repeatability, noise, and drift during the measurement, and a small (<0.5 nm) position scanning hysteresis effect in the TS. The Abbe error and repeatability error appear with a. negative sign in the model indicating subtraction of the unknown zero-mean error. The sign of the small-angle cosine error correction is positive because the cosine error is a scale effect that makes distances look smaller.

In both SDHLI and SSWLI measurements, the angle of the TS is adjusted so that the mirror surface is orthogonal to the measuring beam. In the SSWLI, the adjustment is done by minimizing the number of fringes in the view of the CCD camera by visual observation, whereas in the SDHLI, adjustment is done by aligning the reflections of the laser beams. Both instruments see only the same projection of the stage translation to the axis orthogonal to the mirror surface. The remaining uncertainty in the cosine error term is mostly due to uncertainty of the SDHLI alignment. The uncertainty of β is based on an estimation of the adjustment accuracy, and by assuming a normal distribution of β, an exponential distribution approximates the distribution of β^2. A small systematic scale correction (multiplying by 1.00005) based on the estimated mean cosine error was applied to the measured values.

The uncertainty budget for the calibrated amplitude in the TS calibration measurement is presented in Table 1. The terms related to SDHLI residual periodic nonlinearity and repeatability of the measurement are based on sets of repeated measurements of the TS with the SDHLI. The uncertainty contributions due to the parameters shown in the table are assumed to be statistically independent and are thus quadratically combined. The validity of the independence assumption is based on the existence of a few dominating components in the budget that originate from different sources. The length-dependent part of the uncertainty becomes significant at distances >10 μm. For 10 μm distances and shorter, the standard uncertainty is <2.0 nm, whereas for 15 μm, the uncertainty is 2.3 nm.

3 SSWLI Calibration with Transfer Standard

3.1 *Scanning White Light Interferometry*

SWLI relies on localizing interference fringes appearing during a scan of the optical path length to derive a surface or interface topographic map of the sample. Images are taken at height intervals of, e.g., 1/8 (depending on algorithm) of the effective mean wavelength of the light source. The position where the sample-to-beamsplitter and a reference mirror-to-beamsplitter distances are equal is calculated for all pixels individually. In SSWLI, the sample motion is frozen using pulsed light synchronized with the sample motion, otherwise the data acquisition and data processing are identical to that used in SWLI. A variable phase delay between the light pulses and the sample oscillation permits imaging samples in different phases of their oscillation.

3.2 *(S)SWLI Setup*

The (S)SWLI setup, Fig. 3, comprises a Nikon microscope structure, a Nikon 10× Mirau objective coupled to a

Table 1 Uncertainty budget for calibrated transfer standard (TS) displacement.

Parameter	Symbol	Distribution	Standard uncertainty	Sens. coeff.	Uncertainty contribution
Laser vacuum wavelength	λ_0	Normal	<0.0001 nm	$L/633$ nm	$<1\times 10^{-6}L$
Refractive index	n	Normal	<0.00001	L	$<1\times 10^{-5}L$
Per. nonlinearity (residual)	δ_{periodic}	Rectangular	0.5 nm	1	0.5 nm
Noise, drift, repeatability	δ_{rep}	Normal	1.5 nm	1	1.5 nm
Abbe angle	α	Normal	1 μrad $L/10$ μm	1 mm	$1\times 10^{-4}L$
Cosine error	β^2	Exponential	0.0001 rad^2	$L/2$	$5\times 10^{-5}L$
			Combined standard uncertainty		$[(1.6\text{ nm})^2+(1.1\times 10^{-4}L)^2]^{1/2}$

Note: L is the nominal displacement.

0.5× tube lens, and a Pulnix (TM-670GE) camera. The vertical scan is provided by a factory calibrated piezoelectric scanning stage (PI p-725.1CD) with built-in capacitive feedback and 100 μm travel.[20] Available light sources include a halogen light bulb (Philips, type 77241, Amsterdam, The Netherlands) and LED sources. The data are acquired and the profiles calculated based on the recorded interference using custom-built software. The heights are calculated based on Larkin's algorithm.[21] The objective was vertically scanned in 68.75 nm steps corresponding to ¼ interference fringe period with halogen and LED lighting.

In SSWLI mode, the sample movement is frozen by pulsed illumination.[22] Short and bright light pulses allow measuring oscillating surfaces with minimum blurring induced by sample motion. However, shortening the light pulses may decrease the vertical resolution of the SSWLI measurement due to a change in the illumination spectrum when using, e.g., LED sources.[23]

The stroboscopic light source was a white LED (Cree XM-L U3-1B—cool white). The LED was driven by a custom-built pulser that creates electric pulses (minimum 6.2 ns full duration at half maximum) with peak currents >5 A.[6] The timing between illumination and camera operation was controlled by a dual-channel signal generator (Tektronix, AFG 3252, Beaverton, Oregon).

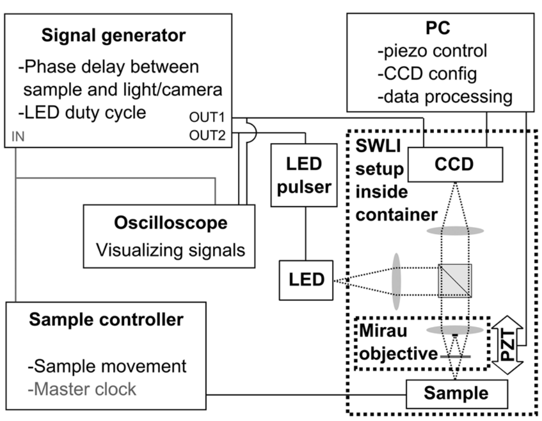

Fig. 3 Stroboscopic scanning white light interferometer setup. The gray connection from the sample controller is not used in the quasi-dynamic measurement.

The frequency and duty cycle were 100 Hz and 0.5%, parameters that can also be used in low-frequency dynamic SSWLI measurements. The setup resided in a thermal isolation box, excluding the light source and most of the electronics. The entire setup sits on a high-quality vibration isolated optical table. The TS measurements were also done with a continuous halogen lamp instead of the pulsed LED. In the quasidynamic measurements, the TS position command was changed between the individual scans. To carry out dynamic measurements on the oscillating TS, the sample the controller has must be synchronized with the stroboscopic measurement.

3.3 *SSWLI Calibration*

The SSWLI calibration measurements with the TS gave information about the vertical scale and accuracy of the SSWLI instrument and enabled traceability of the SSWLI measurements to the SI meter. In the (S)SWLI measurements, the TS was aligned using interference fringes seen in the CCD camera image, so that the mirror surface is orthogonal to the optics. The reference flat and the moving mirror are close to each other so that both fit into the camera view. The vertical positions of the moving mirror and the reference flat on the (S)SWLI piezoscanner scale were calculated as the average across rectangular areas of the height maps. The sizes of these areas were 60 pixels × 116 pixels and 60 pixels × 50 pixels (89 μm × 74 μm and 89 μm× 172 μm), respectively. The areas were laterally separated by 450 μm. The scan range in the (S)SWLI calibration measurements was from 32 to 56 μm of the total 100 μm vertical scanner range. One scan took <1 min.

The temperature inside the instrument enclosure varied slowly, by ~0.2°C around 22°C, during the measurements, whereas the relative humidity varied a few percentage points around 45% RH. The effect of the difference in ambient conditions between SDHLI and (S)SWLI measurements on the behavior of the TS is estimated based on the change in dielectric constant[24] of air in the TS capacitive sensor. The effect is $<2\times 10^{-5}$ and thus negligible.

The TS was scanned up and down with 1 μm changes in position command through the same 15 positions that were calibrated with SDHLI. This was repeated three times. For both the halogen and LED light sources, this procedure of thrice up and down was repeated after a few hours. A least-squares line was subtracted from each symmetric set of going three times up and down to reduce effects due to thermal and other drifts. The LED and halogen measurements were performed on different days. Each of the 24 resulting sets of 15 values was centered by subtracting the mean value.

The bidirectional stepping combined with linear drift removal and repeated measurements suppress noise and drift effects in the averaged result. In the scatter of the individual results, nonlinear drift causes variation between the two scan directions. The possible variation due to lateral drifting of the measurement area relative to TS has been estimated by analyzing the height map images. The roughness pattern on the reference flat drifted laterally at maximum 1 pixel (1.5 μm) between the beginning and end of a series of three bidirectional repeats. Offsetting the averaging window for reference flat by 1 pixel in either direction in the height maps leads to ~2.5 nm shift in mean height per one unidirectional stepping scan. This effect is further suppressed to the subnanometer level by the removal of linear drift.

4 Results

The results are shown in Figs. 4 (LED) and 5 (halogen) and in Table 2.

The scatter, or variation, of the measurements with the halogen bulb was slightly greater than with the LED (mean standard deviation 6.7 nm for halogen and 4.5 nm for LED). The behavior seems to be linear and fitting an amplification coefficient correction (scale correction coefficient) using the LED results yielded a different value (1.0012) than with the halogen results (1.0005). The difference was <1/1000. The high repeatability, especially of the stroboscopic LED measurements, indicates that the SSWLI is capable of good height resolution.

Although the small difference in fitted linear scale correction seems real, i.e., it is not caused only by random noise, more measurements in different conditions are needed to justify different calibrations for stroboscopic LED and halogen lighting. The halogen light also possibly causes more heating inside the instrument enclosure than the LED lighting.

With the scan range used in the measurements along with the other measurement parameters, the (S)SWLI instrument presents a small proportional scale error. Measuring the whole 100 μm (S)SWLI scan range would probably reveal a nonlinear scale error. While denser spacing of measurement points can be used to measure the instrument behavior in finer detail, characterizing longer scan ranges can be done either by covering the SWLI scan range with multiple TS scans with different offsets or by using a TS stage with a longer displacement range. Longer range calibration also

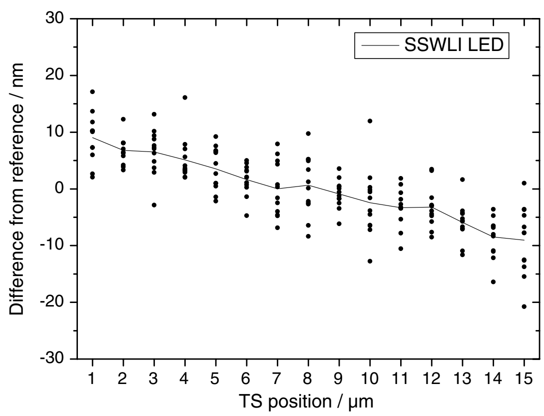

Fig. 4 Stroboscopic light-emitting diode results—scatter of individual results and their mean (solid line), as differences from the reference values measured with symmetric differential heterodyne laser interferometer.

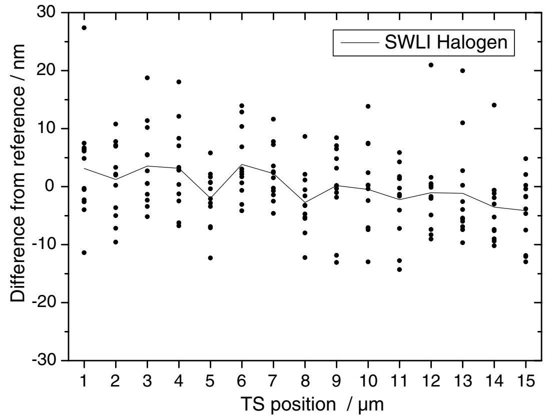

Fig. 5 Halogen light results—scatter of individual results and their mean (solid line), as differences from the reference values measured with symmetric differential heterodyne laser interferometer.

Table 2 Measured values for each nominal step position. The standard uncertainty of the reference is 2.3 nm or less for all distances.

Nominal TS position/μm	Stroboscopic scanning white light interferometer, light-emitting diode/nm	Scanning white light interferometer halogen lamp/nm	Symmetric differential heterodyne laser interferometer reference/nm
1	−7115.4	−7121.3	−7124.4
2	−6096.4	−6102.0	−6103.2
3	−5076.8	−5079.7	−5083.3
4	−4059.6	−4061.5	−4064.7
5	−3042.7	−3048.2	−3046.2
6	−2027.2	−2025.0	−2028.9
7	−1012.5	−1010.2	−1012.5
8	4.7	1.3	4.0
9	1019.0	1020.0	1019.9
10	2033.1	2035.1	2035.6
11	3047.5	3048.6	3050.8
12	4062.6	4064.8	4065.8
13	5074.9	5079.6	5080.8
14	6087.4	6092.3	6095.9
15	7101.4	7106.3	7110.5

allows selecting optimal scanning ranges from the full (S) SWLI scan range in terms of, e.g., linearity.

5 Conclusion

A method for quasidynamic traceable and accurate calibration of SSWLI and SWLI devices was demonstrated. The method relies on a TS. The calibrated TS comprises a vertically scanning flexure guided piezo stage with capacitive feedback and an electronic controller, attached to a mirror and a frame with a reference surface. The TS was calibrated by laser interferometry. The TS mirror displacement can be accurately driven into desired value, making it unnecessary to build or acquire staircase-like reference materials with which one must measure the different fixed heights at different lateral positions.

The estimated standard uncertainty of the TS in the (S) SWLI calibration was 2.3 nm. The scale error in the SSWLI measurement of the TS was linear with 0.12% error in the amplification coefficient within the scanned 14 μm range. The repeatability of the stepped height pattern was 4.5 nm (one standard deviation) with the measurement parameters used. With a traditional halogen lamp illumination, the results were less repeatable (6.7 nm) and the fitted error of amplification coefficient was 0.05%.

The piezo stage TS and controller can be commanded to produce continuous oscillatory motion, thus providing a path toward traceable dynamic measurements with SSWLI.

Acknowledgments

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