Calibration of the z-axis for large-scale scanning white-light interferometers

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Abstract. The calibration of white-light interferometers is an important requirement to make the results of these fast and accurate measurement tools comparable to the well-established tactile techniques. In this paper we present an approach for the calibration of the z-axis of a large-scale scanning white-light interferometer (SWLI) covering the full scanning range by utilizing a newly developed step-height calibration standard. The standard was specially adapted to the requirements of the large-scale WLI with an x-y-field of view of 38 x 28 mm² and a z-scan range of 70 mm. We have developed a new procedure to calibrate the z-scale by using the measured WLI data of the step heights of the standard to obtain an inverse characteristic to compensate non-linearities of the length reference, which is in our case simply the lead screw of the step-motor-driven linear stage. We describe the development of our standard, present measurement results before and after the calibration and discuss the uncertainties of the procedure.

1. Introduction

Scanning white-light interferometry [1][2] is gaining more and more importance in research and development as well as in manufacturing quality control. So far mainly classic microscopic white-light interferometers have been used to measure small object features [3]. However, the improvements in precision mechanical manufacturing have caused an increasing demand for large-scale high precision measurements [4][5] with uncertainties in the micrometer range. In comparison to microscopic setups, large-scale scanning white light interferometers use a Michelson setup of the interferometer, in which the object under test is imaged onto the camera through the beamsplitter by a telecentric optics. The reference path is fixed and the whole interferometer is moved in respect to the specimen by a translation stage. Interference appears always in the focus of the telecentric objective due to the optical operation principle and, thus, these kind of white-light interferometers can have a scanning range of several mm or even tens of mm. Therefore, motor driven linear stages have to be employed for the z-scan instead of high-precision piezos. In opposite to piezoelectric stages, motorized stages can exhibit a considerable measurement error from non-linearities in the motion. Consequently, for high-precision measurements the z-scale has to be calibrated. Although some publications [6][7] address this topic, until now no standard describes the procedure in detail.

Currently there is no detailed procedure which describes the measurement error of a large-scale WLI by means of an error budget. In addition the non-linearities of the linear stages used in the examined WLI is random and can vary from device to device. At a first step we measured the non-linearities...
using a commercial high precision displacement laser interferometer. We tried to compensate the non-linearities of the linear stage by employing a lookup-table generated with the measurement data. However we could not see a significant improvement of the measurement error of our WLI. We concluded that the laser interferometer measurement is not directly relatable to the WLI measurement. In addition errors like cosine and Abbe error can falsify the result. So we had to find a different solution and followed a common method for the calibration of a measurement device by the comparison to traceable calibrated standards. In the case of dimensional measuring devices this could be for example high precision gauge blocks, or step height standards. For example coordinate measuring machines (CMMs) are commonly calibrated using a set of gauge blocks or a ball plate standard.

For the calibration of the z-axis of a WLI with a 70 mm scan range some special requirements have to be considered. Various step height standards are commercially available [8][9][10], but most of them only cover a height range from a few µm up to about 1 mm. Keeping in mind that the measurement range of large-scale WLIs exceeds 1 mm a potential step height standard for calibrating such WLIs must consist of multiple steps and cover the full z-range. Currently a depth setting standard with step heights up to a few mm is available from the Physikalisch Technische Bundesanstalt PTB [11]. This standard is not suited for calibrating the full z-scale of a large-scale WLI because it only has 6 different steps with a maximum height of 5 mm. Another approach is putting together a number of gauge blocks on a reference flat. But as the blocks are usually 9 mm wide only 4 blocks could be measured at once with the field of view (FoV) of the WLI.

Our approach addresses the calibration of the full z-scale by the use of a specially developed set of step height standards. With the help of these standards we were able for the first time to obtain a basic calibration of the z-axis of the large-scale WLI over the full z-range of 70 mm.

2. Development of the new Step Height Standards

2.1. Geometry

Our first idea to calibrate the z-axis by putting together gauge blocks of different heights on a reference flat was not practical. Commercially available blocks have a certain width and only 4 blocks could have been positioned in the 38 x 28 mm² FoV of the WLI. A calibration of the full z-axis of the WLI stitching together multiple measurements of gauge blocks would be too complex and time-consuming. In addition, a temperature variation over the necessary long measurement period could be a possible error source.

Another approach we had in mind was the manufacturing of customized gauge blocks with a width of only 1-2 mm to allow a higher number of steps within the field of view. Such blocks cannot be manufactured using hard metal as it would be necessary for the desired precision.

To solve these problems we have developed new step height standards to cover the full z-scale of the WLI with multiple steps in form of a stepped shaft, where every step is represented by an annular surface. Figure 1 shows a model of one of the step height standards. This geometry can routinely be manufactured with high precision in a cylindrical grinding process.

To define the exact geometry we had to consider the (1) special requirements of the measurement with our WLI, (2) limitations of the manufacturing process, and (3) the calibration procedure. First we had to define a reasonable number of steps which could be placed in the FoV. To ensure sharp edges in the manufacturing process and to account for the calibration procedure the steps could not be narrower than 1 mm. This still corresponds to about 7 to 8 pixel in width in the WLI measurement, which is appropriate for evaluation. Consequently, up to 19 steps of such a standard could be located in a field of view of 38 x 28 mm², measured simultaneously, and evaluated in an appropriate way. The steps were distributed equally over the whole z-range of the WLI (70 mm), which results in a distance of 3.75 mm. As with this coarse standard the z-scale can only be analyzed at some sample points, a potential non-linearity of the z-axis would not be fully captured. To solve this problem we developed a similar standard with a spacing of the steps of 0.295 mm (Figure 2). By merging the measurements of
the fine and coarse standard the z-scale can be calibrated with the appropriate distance of the sample points. One of the annular surfaces of the steps was assigned to act as a reference plane (highlighted in Figure 1 and Figure 2). This assigned surface defines the basic coordinate system for the calibration of the standards and the WLI measurement. The origin of the the z-axis of the coordinate system is also defined by this reference plane. The assigned step was chosen because it corresponds to the position of the reference switch of the linear stage of the WLI. To assign the coordinate system for the calibration in x and y direction a flat was designed on one side of the standards (see Figure 1) acting as a coordinate reference. This flat also defines the lateral orientation of the standard for the WLI measurement.

2.2. Manufacturing of the standards
We have searched for a suitable material that can be precision machined, which is durable and hard enough to withstand a calibration with stylus instruments. A low thermal expansion coefficient also was an important property. Considering the geometry of the standard, glass or other hard materials with a low thermal expansion coefficient have been discarded as material because of massive problems in the processing and the cost factor. So we have selected a special high-grade steel which is commonly used for precision gauges. The material (90MnCrV8) can be hardened and has a relative low thermal expansion coefficient of $\alpha = 12.2 \cdot 10^{-6} \text{1/K}$.

The standards finally were manufactured in a special cylindrical grinding process by [12]. To ensure a good surface quality with a low roughness, to account for the optical measurement method, the steps were additionally lapped. With this treatment we achieved a surface roughness of $R_z \sim 0.6 \mu m$. With this roughness the surface is nearly optical flat and, thus, the error due to speckle effects [13] is minimized. The flatness of the steps is below 2 $\mu m$, which is important for the data evaluation.

2.3. Calibration of the standards
Usually high precision stylus instruments are utilized to achieve a traceable calibration of standards for the micro and nano range, with the desired uncertainty. Stylus instruments could not be used for the calibration of our standards because these instruments usually have a vertical dynamic range of only a few millimeters, which is not sufficient for the high aspect ratio of our coarse standard. Consequently, a calibration with the desired uncertainty was only possible with a high precision CMM and appropriate care in the calibration process. The standards have been calibrated using a Carl Zeiss Prismo coordinate measuring machine. To achieve high comparability, the calibration procedure was adapted to the measuring and evaluation process for the calibration of the WLI. The evaluation area for every step was limited to eliminate errors due to the non-perfectly sharp edges of the steps. Every step was acquired as an annular surface with a width of 0.2 mm by measuring a number of radial profile lines. A plane was fitted to the single measurement points corresponding to each step. The distances $D$ between the fitted planes and the reference plane (origin) on the standard were then calculated referred to the center of the standard to define the calibrated step heights (see Figure 3). The x-y plane and the origin of the basic coordinate system for the evaluation were assigned by measuring
the reference plane on the standard. The flat on one side of the standard (see Figure 4) defines the x-z plane of the basic coordinate system when measuring with the CMM. The coordinate system during the calibration was defined to match the coordinate system of the WLI. The coordinate system is right handed where the tilt angles are defined as shown in Figure 4.

**Figure 3.** Calculation of the distances of the fitted planes to the reference plane.

**Figure 4.** Definition of the coordinate system for the calibration of the standard and the WLI: \( A(YZ) \) - Angle in the YZ plane; \( A(WZ) \) - Angle in the XZ plane.

The following object features have been calibrated: The distance of the fitted plane for every annulus surface in respect to the reference plane on the standard (see Figure 3) and the angles in the XZ and YZ planes. Furthermore the flatness of the annulus surfaces of every step and the parallelism between the annulus surfaces and the reference plane according to ISO 1101 were calibrated.

To calculate the uncertainty a special procedure called virtual CMM which is described in [14] was applied. Taking into account the 1 mm width of the annulus surfaces at the steps and to keep the uncertainty as low as possible a stylus with 1 mm diameter was used for the measurement. To further reduce the uncertainty the substitution method [15] was used.

With the described calibration procedure we finally achieved an expanded uncertainty \( U \) for the step height/distance of \( U = 0.4 \mu m + 0.6 \cdot 10^{-6} \cdot D \), where \( D \) is the nominal distance in m to the reference plane on the standard. The maximum expanded uncertainty for the distance/step height for the calibration of our standard results in about 450 nm.

### 3. Calibration of the Large-Scale WLI

The first step of our calibration procedure for the z-axis is the measurement of the coarse standard. For this, the standard is positioned in the center of the FoV. The height of the standard is adjusted so that the interferences appear on the reference plane at the zero position of the z linear stage (Figure 5). Tip and tilt are adjusted to align the center parallel to the measurement devices. The measured topography data (Figure 6) is evaluated with a software algorithm. Therefore, (1) the center of the topography of the standard is determined by means of image processing, (2) masks concentric to this center are set (Figure 6) to define the analysis area for every annulus surface of the steps with a width of 0.2 mm, and (3) the regression plane is calculated for the topography in every analysis area. To make the measurement comparable to the tactile calibration of the standard a low pass filter for the topography data is applied. Based on the evaluated angles of the regression planes and the calibrated angles of the annular surfaces the overall tilt of the standard is determined and corrected.

Subsequently, the distances \( D \) of the annulus surfaces to the reference plane of the standard are calculated in the same way (Figure 3) as described in the section 2.3. The calibrated step heights are corrected by the measured temperature of the standard to derive a coarse deviation curve of the z-scale at certain sample points.

The size of the field of view and the necessary width of the annular surfaces of the standards limit the number of possible step heights of a single standard to approximately 20. Thus, it is necessary to
employ an additional finer standard with a smaller step size. The Nyquist-Shannon Sampling Theorem [16] has to be considered to measure all relevant spatial frequency components of the z-scale non-linearities. Thus, a fine standard is measured in the same way, in a height position where its reference plane matches with one of the steps of the coarse standard (Figure 5) to cover the distance between the steps of the coarse measurement. Next the data is evaluated as described above to derive a finely sampled deviation curve for a small section of the z-axis.

In a post processing step the data of the two measurements is merged to achieve information of the z-scale with a finer spacing for the sample points. Therefore, the interpolated data of the fine standard is shifted by an offset so that the deviation curves for both measurements overlap in a certain region. The result is then used to generate a correction table (actual value/target value) for the z-axis which can be saved in the software of the device to calibrate the WLI. The values between the sample points are interpolated linearly.

![Figure 5. Schematic arrangement for the calibration procedure of the large-scale WLI with the help of the novel step height standards: $d_{zC}$ - height difference for coarse standard; $d_{zF}$ - height difference of fine standard; $d_{zT}$ - Total height difference for sample point.](image1)

![Figure 6. 2D color coded measured height result for the coarse standard (also shown are the analysis areas).](image2)

4. Discussion of the Error Sources

Currently, there still are some potential error sources in our calibration procedure that until now have not been analyzed in detail.

From previous studies we know that the linear stage of the examined WLI can have a considerable periodic position error which correlates with the lead screw pitch. As in our case the length reference is represented by the lead screw this error will contribute to the error of the WLI measurement. We have developed the fine standard that was used for these studies for various calibration purposes. Consequently, the spacing of the steps is not small enough to fully capture the periodic errors of the linear stage in respect to the Nyquist-Shannon-Sampling Theorem. As in the correction table for the z-axis calibration the values between the sampling points are interpolated linearly, with the standards we used it is not possible to calibrate all position errors of the linear stage.

There are also some error sources in the evaluation procedure for the measured WLI data. During the calibration of the standards with the CMM all annulus surfaces of the steps could be acquired completely. Due to the limited field of view, some of the steps can only be measured partially with the WLI (Figure 6). Thus, fitting a regression plane to an annulus which does not fit completely into the FoV is susceptible to flatness deviations and can cause an error in the measured distance $D$.

The merging of the measurement data from the coarse and fine standard could also cause an error when generating the correction table for the calibration of the z-axis. The individually measured distances with the coarse standard $d_{zC}$ (Figure 5) exhibit an uncertainty. The measurements with the
fine standard $d_T$ also have an uncertainty. Consequently, when merging both measurements the uncertainty for $d_T$ is approximately the sum of the two contributions. As the standards were made from a high-grade steel the thermal expansion coefficient is not negligible for step sizes of a couple of tens of mm. The temperature of the standards is acquired during the measurement to account for a temperature difference between the standards and the surrounding. An accurate measurement of the standard’s temperature is not a simple task. A measurement error of the temperature of the standards during the data acquisition can falsify the correction of the calibrated distances of the steps in the evaluation procedure. Therefore, an uncertainty in the temperature measurement results in a step height error, which also contributes to the overall error of the calibration procedure. Another question is the long-term stability of the calibration. Due to wear and aging of the linear stage the linearity behaviour could change over time. At the current point we cannot make a statement about the long-term stability of the calibration procedure. The investigation of these uncertainty contributions will be addressed in our future studies.

5. Example Calibration

Figure 7 shows an example result for the calibration of a large-scale WLI. From the comparison of the curves it can clearly be seen that the measurement deviation of the WLI on average can be reduced by a factor of 3 when employing the newly developed step height standards and our calibration procedure.

![Comparison of the deviation curves for an example calibration of a large-scale WLI.](image)

6. Conclusion and Outlook

We have described the development of two new step height standards which enable a detailed calibration of the full z-scale of a large-scale Scanning White-Light interferometer with a vertical scanning range of 70 mm. We have designed two standards in form of a stepped shaft (Figure 1, Figure 2), where every step is defined by an annular surface. The coarse standard has 19 steps with a spacing of 3.75 mm. The fine standard consists of 18 steps with a spacing of 0.295 mm. Every standard has a reference plane to trace the calibrated sample distances to the zero position of the motorized linear stage of the WLI.
In addition, we have discussed the special requirements for the standards in respect to measurements with a large-scale WLI with a field of view of 38 x 28 mm$^2$. The requirements for a traceable calibration of the standards have also been pointed out. With a special calibration procedure we have achieved a maximum expanded uncertainty for the calibrated step heights of about 450 nm.

The new standards make possible for the first time a new approach for the calibration of the full z-axis of large-scale WLIs. We developed a procedure to calibrate the full z-axis of a large-scale WLI with the help of our novel standards. The calibration procedure can account for all possible non-linearity errors in the z-scale by merging the measurements of a coarse and a fine standard. Reference planes are utilized to realize the combination of the samples from multiple measurements. The result of an example calibration for a large-scale WLI (Figure 7) proofs that the measurement error can be reduced on average by a factor of 3 with our procedure.

Future work will address a detailed analysis of the error sources and will employ a fine standard with a step spacing small enough to sample all spatial frequency components of the linear stage non-linearity according to the Nyquist-Shannon Theorem.

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