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Study of some systematic effects in Mitutoyo short gauge block interferometer

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ABSTRACT
In this work, the systematic effects related to optics and fringe fraction extraction of the Mitutoyo gauge block interferometer (GBI) short gauge interferometer were evaluated. Some parameters, such as the front wave curvature, imager defects and uncertainty associated with fringe fraction extraction from phase stepped interferometric image stacks were analyzed. A new proprietary software for phase extraction was developed and used. The software utilizes the direct fit of the sinusoidal wave to all measured phase points. A better evaluation of effects from GBI data processing was possible due to this locally developed software. The high quality of the optics of the GBI is demonstrated through the analysis of the height maps of the Mitutoyo reference flat plate. The metrological analysis shows possible directions of improvement of the interferometer.

Section: RESEARCH PAPER

Keywords: Optical interferometry; gauge block; systematic effects; phase stepping; imaging

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1. INTRODUCTION

Mitutoyo's short gauge block interferometer (GBI) has been used at Inmetro (the Brazilian National Institute of Metrology) for many years as its main calibration and measurement capability (CMC) unit for short gauge block measurements. With this instrument, Inmetro participated in the international CCL Key Comparison held in 2011 [1]. The GBI is considered a well optimized automated instrument that suits both precise measurements and routine calibrations. In terms of operating principle, it is similar to the famous NPL short gauge interferometer [2]. In order to improve this interferometer, it is planned to upgrade it with a modern computer and several new internal hardware modules. This upgrade will be done in 2 stages, starting with our own processing software development with later hardware modification. In order to preserve continuity in the quality of our measurements, it was decided to study systematic effects of the GBI; in this way, it could be guaranteed that the upgraded version will be, at least, not worse and preferably better in performance.

It is generally known that the study of the systematic effects of absolute instruments is not an easy task. Nevertheless, this is an important step for further improvements of this kind of instruments. The GBI was investigated for systematic effects associated with wave front curvature, imager defects and accuracy of the fractional fringe determination by phase stepping technique utilized. As compared to GBI software, a more accurate method of fringe fraction extraction was used in this study as part of the developed software. An important evaluation of wave front curvature error was performed comparing height maps of Mitutoyo optical flat as measured with both GBI and Zygo interferometers. The systematic effect caused by saturation and noise of the imager was evaluated.

2. GBI HARDWARE AND MAIN PROCEDURES

The GBI, in terms of optics and operational principle, is a Michelson type of the interferometer equipped with a digital camera for output imaging and a phase stepping unit. The main principles of phase stepping interferometry are well known [3]. The instrument can perform both point measurements and the whole map calculation from data taken during measurement. The fractional fringe ambiguity is resolved by using two He-Ne frequency-stabilized lasers of red (633 nm) and green (543 nm) colours using the coincidence method. Laser light is fed to the optical input by fibre optics, with an intermediate automated shutter operated by the software.

During the measurement cycle, the image stack of 16 image frames is acquired. Each image contains a complete interferogram at a given phase step. The phase shifting unit provides equally spaced in-phase positions for each interferogram. Phase shifting in GBI is achieved by moving an optical wedge of high quality inside the optical path of the reference arm [4]. Correct positions of the wedge are controlled by a back looped linear stage.
The camera has a 10-bit resolution of 660 × 494 pixels with automatic exposure/gain. The data is collected by PC via a digital camera interface. The data is saved as two image stacks of a three-dimensional array each, corresponding to the two lasers used. Temperature, pressure and all other necessary ambient parameters are measured almost simultaneously with interferometric images and saved into separate files. Some parameters, like the thermal expansion coefficient, are entered manually as necessary. Some details of the hardware can be found in Mitutoyo publication [4] and in the manual of GBI image stack processing software.

In order to verify GBI processing software, a dedicated software for processing Mitutoyo data files was developed (interferogram processor). The software for simulation of theoretical image stacks with known variable parameters was also developed. The simulated data sets can be processed by both our and Mitutoyo interferogram processors. Those simulated theoretical stacks were used to study systematic errors of both processors in phase determination, i.e. in fringe fraction extraction.

Mitutoyo original software named GBPAK-PSI is used in the original GBI instrument for data acquisition, processing and result acquiring. The data is further processed by Mitutoyo interferogram processor using a 4-point algorithm, presumably similar to that described in [3]. The archived data could be reprocessed later to verify results if necessary.

The interferogram processor developed at Inmetro uses the same data stacks as the GBPAK-PSI. The phases are extracted from the shape of the sinusoid-like output wave form, which is point intensity vs. phase. The phase from the sine wave form is found by fitting algorithm similar to that described in [5], [6]. The algorithm uses the least squares criteria. All 16 points are taken into account for phase extraction. A simple theoretical sine wave is used as a fit model with 4 parameters, i.e. amplitude, offset, frequency and phase. Since the original data presents significant pixel noise, some neighbouring area around the point of interest is used to average out part of the pixel noise. Therefore, three points on interferogram image are selected either automatically or manually. One is the gauge block centre and two symmetrical points on each side of the block located on reference plate. For all three points, the light intensity from all frames is found. Thus, as measured output, we have three wave forms of 16 points each. Next, the phase of each wave form is determined by sine function fitting algorithm. The hardest part of the data processing is performing a quick and accurate fit of the sine wave to the phase points of the measured data set. The procedure is described in [5]. Furthermore, the block diagram of the iteration procedure used to perform the actual adjustment is presented in the same reference [5]. Figure 1 shows the general block diagram of the developed software with the main functionalities implemented. The software is organized in a simple manner with three main steps: reading, processing and saving results. To assist the user with maximum useful information and functionality some graphical user interface (GUI) was developed with menu, interactive markers and plotting to represent and control all the processing flow.

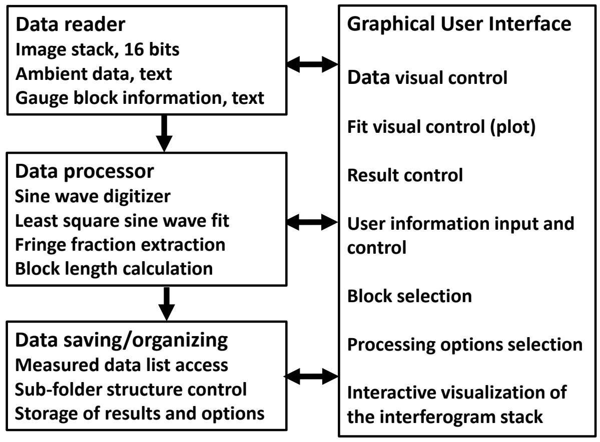

Figure 1. Block diagram of the data processing software with main features already implemented and tested.

One example of the processing is shown in Figure 2. The measured light intensity points as dots (and dashed line) and the result of the fit (solid line) are shown in this figure. It can be noticed that the measured points represent some saturation at the top of the intensity curve. The flat top of the curve, which is supposed to follow the sine wave shape, clearly indicates a saturated imager at the maximum intensity. The middle of the saturated area is marked by a vertical arrow in Figure 2. This is probably an effect of auto exposure of the imager. This is a potentially disturbing fact, because it can result in undeisred additional uncertainty in phase determination depending on the procedure used for phase extraction. Despite some disturbance of the measured points, the direct fitting algorithm resulted in reasonably correct phase determination, as can be seen by comparison of dashed and solid lines in Figure 2.

In order to evaluate possible errors resulting from saturation, we have modified the saturation point in our software by increasing its value to compensate for saturation. After that, the fit result obtained with corrected and non-corrected data were compared. Results demonstrate quite reasonable agreement within 0.002 of the fringe. We also have tried to modify

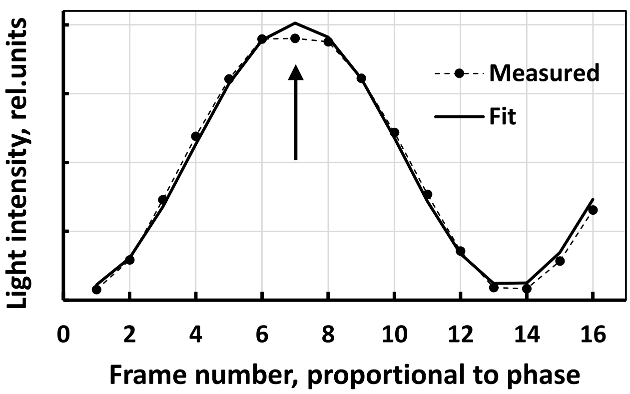

Figure 2. The waveform as measured at each of 16 frames of the interferogram stack (dots). Dashed line is an eye guide. Each frame corresponds to certain phase; each dot is light intensity of the interferogram at gauge block centre. The corresponding sinusoidal function fit is also presented as the thicker solid line. The fit was calculated by our interferogram stack processor. The 7th frame exhibits lower intensity than that expected due to saturation of the camera as indicated by arrow in the figure.

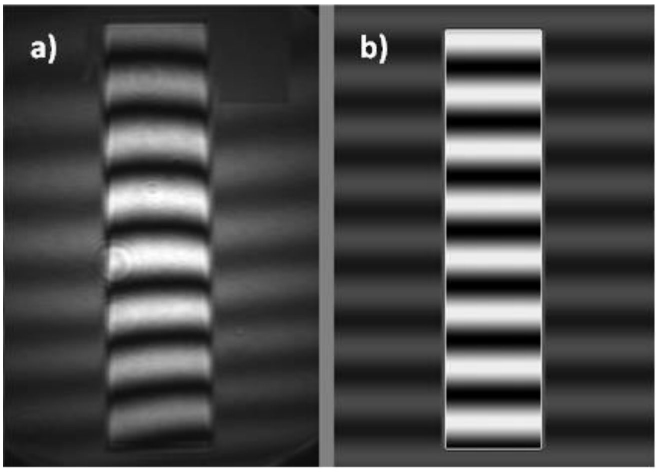

Figure 3. Informative portion of one frame as measured by Mitutoyo GBI (a) and theoretically simulated by our software (b). Simulated interferogram stacks of known fringe faction were used to study systematic effects due to possible defects of imaging system when processed by both our and GBI software packages.

Mitutoyo data to correct saturated frame. Calculating fringe fraction of corrected and non-corrected data by GBI software package also resulted in good agreement for most of the cases within 0.005 of the fringe.

The Inmetro interferogram processor was used to calculate the data previously measured and processed by GBI software for comparison of both methods. A reasonable agreement between both processors was found. The maximum difference of about 0.005 of the fringe was observed.

The next step was to discover possible systematic effects by both processors with theoretically simulated interferogram stacks. Multiple different cases were studied varying phase difference (fringe fraction) saturation level and noise. In Figure 3, we show portions of one frame measured by GBI (a) and theoretically simulated one (b) of approximately same fringe fraction at central point of the gauge block to illustrate our approach to study this systematic effect.

Unfortunately, at this time, there are not enough data available to carry out a good statistical analysis. For this reason, we simply present the typical and the worst-case observations. Main observations are as follows:

a. Both processors are very stable to pixel noise with insignificant fringe fraction variations due to random noise.
b. Mitutoyo processor presents lower stability in phase determination under specific conditions when the peak of the sine wave is on the side of the wave form. With maximum fringe fraction difference up to 0.008 in the fringe fraction observed in extremal cases (that are not probable in practice), as compared to 0.003 of the fringe fraction in similar cases by our processor.
c. In most cases, uncertainty of fringe fraction determination is about 0.005 for GBI and 0.001 for our processor, where both values are in the fringe fraction.
d. Both processors are quite stable to the saturation of the imager.

3. FRONT WAVE CURVATURE OF THE GBI

The systematic effect of the GBI associated with front wave curvature on front wave curvature was studied and evaluated. This effect is predominantly taken into account by the initial calibration procedure integrated into Mitutoyo hardware and software. In this procedure, a special high flatness calibration flat is provided by Mitutoyo that is used to obtain the correction map of the GBI. The appropriate correction is automatically applied to the calculation of the final length of the gauge block. We measured Mitutoyo calibration flat with Zygo metrology system model Verifire™ Laser Interferometer. Measurements were performed at Photonics Division of the Institute of Advanced Studies (IEAv) of the Aerospace Science and Technology Department (DCTA), São José dos Campos, SP.

In Figure 4, the orthogonal cut of the height map measured by Zygo interferometer is presented. It is easy to see that the central part of the flat (approximately 13-14 mm wide), which is used to find the central length of the gauge block is only several nanometres away from the ideal flat surface. Similar results were obtained through the GBI correction height-map analysis.

In addition, the comparison of multiple measurements with and without application of flatness map correction was made. This comparison revealed only a small difference of a few nanometres in all the cases. Thus, we can conclude that our GBI possesses a quite flat front wave that significantly improves the quality and reliability of the measurements. It was estimated that after applying the flatness correction, the residual uncertainty is within about 3 nm. This means that all principal optics of the GBI (namely, reference mirror, beam-splitter and wedge used for phase shifting) are high-quality optical elements. As a result, we will continue using the same main optical elements of the interferometer, including the optical wedge for phase-shifting purposes.

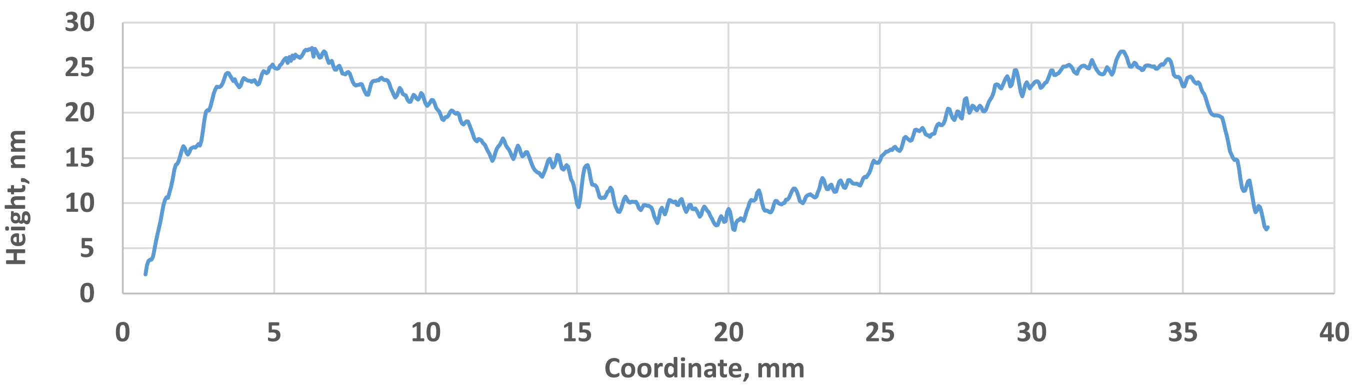

Figure 4. Typical profile of the Mitutoyo glass reference plate as measured by Zygo Verifire Laser Interferometer. The intersection is taken from the full map that is interferometer output. Only the central part is shown.

4. CONCLUSIONS

The study of systematic effects on absolute measurement capabilities is considered a good metrological practice. This type of investigation is carried out periodically at the various National Institutes of Metrology. Mitutoyo GBI is Inmetro's main CMC unit for short gage block measurements. Some systematic effects of this instrument were studied, with the main results as follows. A more accurate and stable algorithm of phase extraction was developed. The uncertainty due to front wave curvature was estimated to be within 6 nm ($k = 2$), where k is a coverage factor. The worst-case uncertainty due to imaging defects and phase extraction was estimated to be about 5 nm ($k = 2$) for GBI software and about 2 nm ($k = 2$) for our software.

This study was important to ensure that measurements are always performed accurately, and associated corrections are carefully applied. It also ensured that the uncertainties estimated by the equipment manufacturer at the time of delivery remained valid. The important know-how gained during this study will be used for future improvements of this interferometer.

REFERENCES

[1] M. Viliesid, P. Dubé, C. Colín, Calibration of gauge blocks by optical interferometry comparison - final Report, Metrologia 59(1A) (2022), art. No 400.
DOI: 10.1088/0026-1394/59/1A/04005

[2] A. J. Lewis, Absolute length measurement using multiple-wavelength phase-stepping interferometry, Doctoral thesis, Imperial College, 1994, London.

[3] P. Hariharan, Optical Interferometry, Rep. Prog. Phys, 54 (1991), pp. 339-390.
DOI: 10.1088/0034-4885/54/3/001

[4] T. Narumi, S. Shutoh, T. Nakamura, J. Iida, M. Sawabe, Development of new automatic gauge block interferometer up to 250 mm, Conference on Recent Developments in Optical Gauge Block Metrology, San Diego, USA, 1998, SPIE 3477, 76.
DOI: 10.1117/12.323094

[5] I. Malinovski, R. S. França, M. S. Bessa, C. R. Silva, I. B. Couceiro, Coherent double-color interference microscope for traceable optical surface metrology, Surf. Topogr.: Metrol. Prop. 4 (2016), art no. 024006.
DOI: 10.1088/2051-672X/4/2/024006

[6] I. Malinovsky, I. B. Couceiro, R. S. Franca, M. S. Lima, C. L. S. Azeredo, C. M. S. Almeida, J. P. von der Weid, Imaging interference microscope for nanometrology, Acta IMEKO 3(3) (2014), pp. 28-32.
DOI: 10.21014/acta_imeko.v3i3.98