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Evaluation of the systematic effects in Mitutoyo short gauge interferometer related to optics and imaging.

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Abstract. Some systematic effects (uncertainties type B) of the Mitutoyo GBI short gauge interferometer were evaluated. Namely the front wave curvature, imager defects and uncertainty associated with fringe fraction extraction from phase stepped interferometric image stack. A new proprietary software for phase extraction was developed and used in this study. The software utilizes the direct fit of the sinusoidal wave to all measured phase points. Better evaluation of effects from GBI data processing was possible due to this locally developed software. High quality of the optics of the GBI is demonstrated by analysis of the height maps of the Mitutoyo reference flat plate. The metrological study performed shows possible directions of improvement of the interferometer.

1. Introduction

The short gauge block interferometer (GBI) from Mitutoyo is used at Inmetro (National Metrology Institute of Brazil) for many years as its main calibration and measurement capability unit (CMC) for short gauge blocks measurements and with this instrument Inmetro participated in international CCL Key Comparison 2011 as well [1]. The GBI is considered as a very well optimized automated instrument that suits both precise measurements and routine calibrations. It is also similar to famous NPL short gauge interferometer [2]. To get better this equipment it was planned to upgrade it with modern computer and several new internal hardware modules.

This upgrade will be done in 2 stages starting with our own processing software development with further hardware modification later on. In order to preserve continuity in quality of our measurements it was decided to study systematic effects of the GBI so that we guaranty that upgraded version will be at least not worse and preferably better in performance.

It is generally known that study of the systematic effects of absolute instruments is not that easy task. But this is 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.

2. GBI hardware and main procedures

The GBI in terms of optics and operational principle is a Michelson type of the interferometer equipped with digital camera for output imaging and phase stepping unit. Main principles of the 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 use of two He-Ne frequency stabilized lasers of red (633 nm) and green (543 nm) colors. Laser light is feed to the optical input by fiber optics with intermediate automated shutter operated by the software. During measurement cycle image stack of 16 image frames are acquired, each containing full interferogram at certain phase step. Phase shifting unit provides well controlled equally spaced in phase positions for each interferogram. The whole process is repeated for each color. Thus, as the optical output of GBI we have two image stacks one for each laser.

Phase shifting in GBI is achieved by moving optical wedge of high quality inside of optical path of reference arm. The camera is 10 bits 660x494 pixels with automatic exposure/gain. The data is collected by old PC that is outdated in its operational system and performance.

Mitutoyo original software is programmed to take 16 separate interferogramas equally spaced by phase shifting procedure. The data is saved as image stack cube 3 dimensional array. The data stack is taken with both lasers. Temperature, pressure and all other necessary ambient parameters are measured almost simultaneously with interferometric images and saved into separate files. Some parameters like thermal expansion coefficient are entered manually as necessary.

3. Image stack processing software

In order to verify GBI processing software of the GBI we have developed our own software for processing Mitutoyo data files (interferogram processor). We also develop the software for simulation theoretical image stacks of known variable parameters that 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.

Mitutoyo original software named GBPAK-PSI is acquiring 16 phase stepped images via digital interface. Phase shifter is fully controlled by software [4]. The data is measured and saved as image stack cube 3 dimensional array. The main output of measurement is two data stacks corresponding to two lasers. The data is further processed by Mitutoyo interferogram processor by some procedure that is not available. The data could be reprocessed later to verify results if necessary.

Our interferogram processor uses same data stacks as the GBPAK-PSI. We extract the phases from the shape of the sinusoid like output that is point intensity vs. phase. We fit sine wave measured using least square fitting algorithm similar to that described in [5]. All 16 points are taken in account for phase extraction. Simple theoretical sine wave is used as fit model with 4 parameters, i.e. amplitude, offset, frequency and phase. Since original data also presented significant pixel noise some area around the point of interest used to average out large part of the noise. Therefore we select automatically or manually 3 points on interferogram image one is gauge block center and 2 symmetrical points on each sides of the block located on reference plate. Next step is to average intensity of each point using all frames and determine phase of each by sine wave by 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 presents the general block diagram of the developed software with the main functionalities implemented. The software is organized in a simple manner with 3 main steps: reading, processing and saving results. To assist the user with maximum useful information and functionality the user interface (GUI) was developed with menu, interactive markers and graphical representation of all the processing flow.

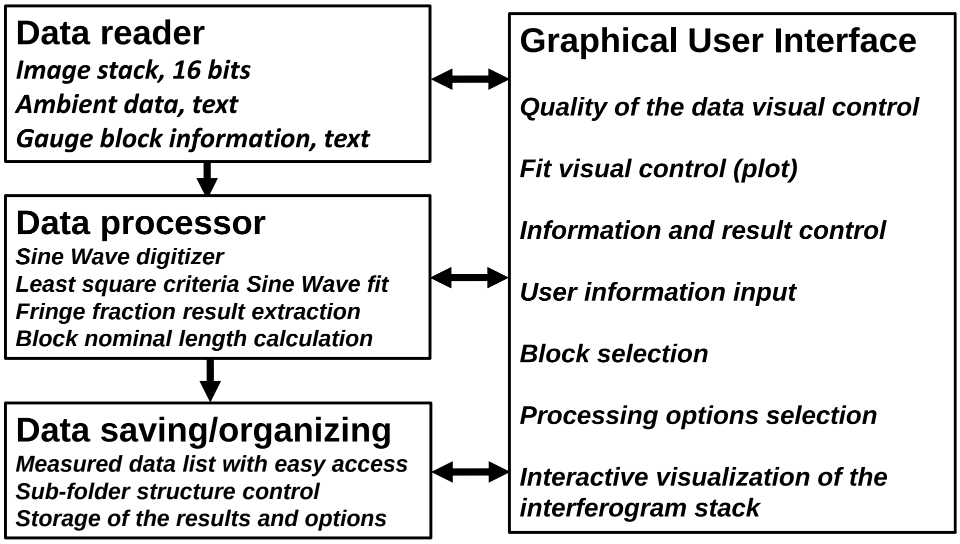

Figure 1. Block diagram of the data processing software with main features already implemented and tested.

In figure 2 it is demonstrated both measured by GBI 16 intensity points as dots (dashed line) and result of the fit as solid line. It is easy to see that measured points represent some saturation at the top of the intensity curve. Flat top of the curve that is supposed to follow sine wave shape clearly indicates saturated imager at the maximum intensity. The middle of the saturated area is marked by vertical arrow in figure 2. This is probably effect of auto exposure of the imager. This is potentially disturbing fact because it can result in unwanted additional uncertainty in phase determination depending on procedure of phase extraction used. Despite some disturbance of the measured points, the fitting algorithm resulted in reasonably correct phase determination as can be seen by comparison of dashed and solid lines in figure 2.

We have tested our interferogram processor with data previously measured by GBI and find out quite reasonable agreement between both processors within 0.005 in fringe fraction.

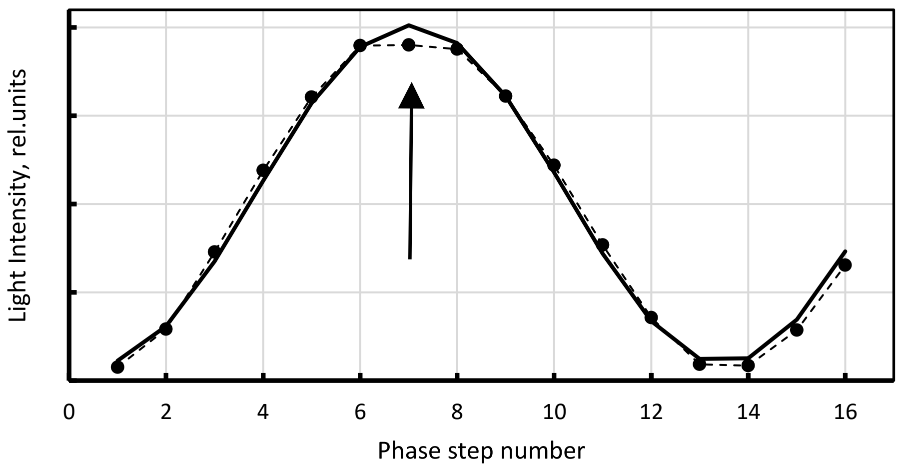

Figure 2. The phase of measured by GBI averaged by pixel binning point on the gauge block (dots and dashed line) and corresponding sinusoidal

function fit (thicker solid line). The fit is calculated by our interferogram stack processor. Saturation of the imager is indicated by the arrow.

Next step was to figure out 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. Main observations are as follows:

1. Both processors are very stable to pixel noise with insignificant fringe fraction uncertainty.
2. Mitutoyo processor represents less stability in phase determination in specific conditions when peak of the sine wave is on the side of the curve. With maximum fringe fraction difference up to 0.009 in fringe fraction observed in extremal cases (that are not probable in practice). As compared to 0.003 in similar cases by our processor.
3. In most of the cases uncertainty of fringe fraction determination is about 0.005 for GBI and 0.001 for our processor.
4. Both processors are quite stable to the saturation of the imager.

4. Front wave curvature of the GBI

The systematic effect of the GBI associated with front wave curvature was studied and evaluated. This effect mostly is taken on account by original calibration procedure built into Mitutoyo hardware and software. In this procedure special high flatness calibration flat is provided by Mitutoyo that is used to obtain the correction map of the GBI. Proper correction is automatically applied to final gauge block length calculation. We have measured Mitutoyo calibration flat with Zygo metrology system model Verifire™ Laser Interferometer. The 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. We also managed to extract the GBI calibration map from Mitutoyo data file. In figure 3 the horizontal cut of the data measured by Zygo interferometer is presented.

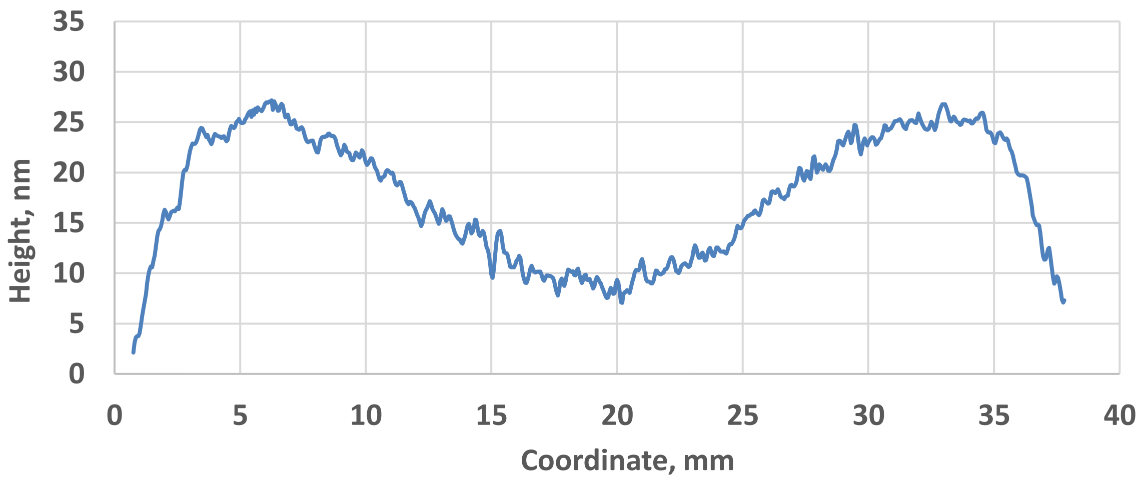

Figure 3. Typical profile of the Mitutoyo glass reference plate as measured by Zygo Verifire Laser Interferometer. The intersection is taken from the full map that is interferometer output, only central part is shown.

It is easy to see that central part of the flat approximately 12-13 mm wide that is used to find central length of the gauge block is only several nanometers out of ideally flat surface. Similar results were found out from analysis of the correction map. Thus, we can conclude that our GBI possess quite flat front wave that significantly improve the quality and reliability of the measurements. We have estimated that after applying front wave flatness correction the residual uncertainty is within 3 nanometers. Because of this we will continue using the optical wedge for phase shifting purposes.

5. Discussion and conclusions

The study of systematic effects on absolute measurement capabilities is considered a good metrological practice. This type of investigation is carried out periodically in the various National Institutes of Metrology. The Mitutoyo GBI is Inmetro's main CMC unit for short gage block measurements and this study was important to ensure that measurements were carried out accurately and associated corrections were carefully applied. It was also ensured that the uncertainties estimated by the equipment manufacturer at the time of delivery remain valid. Even more important was demonstrating that Diopt has the capacity to develop suitable software for a complex instrument like this interferometer and update it with a new hardware in a fully controlled manner, in addition to validating its results.

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