White-light interferometer with internal length standard

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1. INTRODUCTION

White-light interferometric (WLI) techniques[1,2] are often used in microscopy to measure the surface topography of objects such as height gauges, binary optics, machined parts, IC-packaging modules and micro-electro-mechanical systems (MEMS). These white-light interferometers, or optical profilers, have the advantage of delivering whole-field, non-contact, high-accuracy 3D topographic measurements of a number of different kinds of micro-objects. The principle of operation of these interferometers is based on the detection of the peak or phase of fringes that are narrowly localized around the surface at the best focus position. Narrow localization of fringes is obtained through the use of a low coherence light source, such as a halogen lamp that emits white light. The intensity signal is registered at each pixel of the CCD detector as the objective of the microscope is scanned along the optical axis through focus. Various algorithms are used to determine the best focus position at which the narrowly localized fringes achieve maximum contrast; these algorithms can also determine the phase of the fringes so as to enhance the resolution down to a sub-nanometer level. However, high sensitivity measurement does not automatically guarantee high accuracy; rather, high sensitivity depends on proper calibration of the scanner speed and the mean wavelength of the detected fringes. In this paper we describe these two major parameters that need careful calibration in a white-light interferometer. An addition of a laser-based interferometer into an optical profiler creates a primary length standard for calibration.

2. CALIBRATION OF WHITE-LIGHT INTERFEROMETER

A white-light interferometer achieves its high accuracy through the proper calibration of the system. It is important to understand all the parameters of the system that can alter calibration. Also, one must use a proper procedure and standard for system calibration in order to achieve the best accuracy of measurement. In a classical white-light interferometer the two parameters, the scanner speed and the mean wavelength of the detected fringes, are dependent on each other. Often the value of one is measured by assuming that the value of the other is well known and constant. However, these assumptions may not be correct and errors can be introduced into the measurement. Below, we first review current calibration procedures and different factors that influence the scanner speed and mean wavelength, then we present how these parameters can be measured independently. Our method allows us to measure these parameters at each moment of the scan, which then enables automatic, on-line calibration of the system during each measurement. This automatic calibration is achieved through the use of an internal length standard, namely the wavelength of the laser.

2.1. Scanner speed

The scanner speed can be calibrated to a calibration step height standard (SHS) with a certificate of traceability to NIST (National Institute of Standards and Technology)or other standards. The calibration takes place prior to measurement and the determined scanner speed is assumed to remain constant through a large number of scans. Any change in the scanner speed affects the measurement and reduces the system's repeatability and accuracy. If a scan is non-linear but has a repeatable and known behavior, this knowledge can be applied to the measurement algorithm which can account for scanner nonlinearity. In this case the absolute scanner position would need to be known to introduce proper corrections. In an alternate method, this information can be used for a hardware linearization of the scanner by monitoring the scanner position and using a hardware closed-loop system. These hardware solutions, which include capacitive sensors, linear variable differential transformers and linear encoders, are expensive or have rather limited resolution.

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Typically, ideal or repeatable scanner behavior is not achievable, especially over a large scanning range on the order of millimeters. Interferometric techniques can utilize the measurement fringes to introduce some correction into the measurement, but they do so by assuming that the mean wavelength for fringes is well known and constant. The frequency of fringes as sampled along the scanning direction will vary with a change in the scanner speed; an average scanner speed can be determined from the sampled fringe frequency. Other techniques measure the phase rate of the fringes at each scanning step and apply this information to the algorithm, thereby reducing artifacts in the measurement and improving its repeatability. Two problems exist with this approach: first, the fringes may not be visible during each moment of scan and thus information about scanner speed may not be delivered during these blind times; second, these techniques rely on the mean wavelength of the measurement fringes which can be affected by many factors. In the next section we describe factors that affect the mean wavelength.

2.2. Mean wavelength

Knowledge of the precise value of the wavelength corresponding to the registered fringes is critical for accurate interferometric measurements. For laser-based interferometers the wavelength of the source is determined with great precision by the energy difference between transition states of the lasing media. For interferometers based on broad-band sources, such as a white-light halogen lamp, the mean wavelength needs to be determined. Sometimes band-pass filters with a determined mean wavelength are used to select a part of the spectrum from the white-light source. However, the mean wavelength of the source may slightly differ from the mean wavelength corresponding to the period of detected fringes for different reasons and this fact needs to be accounted for. Knowledge of the detected mean wavelength is important because some algorithms for fringe analysis are designed for a specific fringe sampling frequency and a departure from the nominal value introduces errors into the measurements. Hence, it is important to accurately know the period of the fringes. The wavelength is also the scaling factor between the phase of the fringes and physical quantities such as distance or height.

The conventional approach to determining the mean wavelength is pre-calibration. The mean wavelength of the detected fringes is calibrated prior to measurement by a proper procedure (such as measuring a step height standard) and then one assumes that the period of fringes does not change more than the tolerance required by the algorithms used. The mean wavelength corresponding to the detected fringes may differ from that of the source for several reasons. First, the spectral characteristics of the source as detected are altered by the spectral characteristics of the detector and optics. Second, high numerical aperture objectives alter the mean wavelength of the detected fringes. For these reasons wavelength calibration is needed. Assuming that the measured mean wavelength is constant is overly optimistic, for factors such as aging of the light bulb, change in its working point, the optical properties and shape of the analyzed object all affect the mean wavelength of the fringes. One might think that additional wavelength changes can be measured if the scanner speed is constant and well known, but it is impractical to assume this. Thus, in a conventional system scanner speed and the detected mean wavelength (period of the fringes along the optical axis) are mutually dependent.

All of the above system calibration procedures are sufficient for most required measurement tolerances, but with the trend toward producing more precise parts an instrument that provides time-stable measurement becomes a necessity. Our optical profiler enables measurement to tighter tolerances, as we implement an internal length standard based on a laser interferometer with a highly stable wavelength independent of numerical aperture, sensitivity of the detector, spectral characteristics of the filter or sample, and spectral characteristics of the light bulb. In our system the mean wavelength of the measured signal and the scanner speed are determined separately, thereby achieving the highest measurement precision at each moment of the whole range of the scan.

3. WHITE-LIGHT INTERFEROMETER WITH REFERENCE SIGNAL

In this section we describe our white light interferometer with an embedded Michelson interferometer[3] (see Figure 1) that, because it shares the same focusing mechanism, is capable of monitoring the progress of the scanner. This reference signal interferometer uses a separate narrow-band light source with a well-controlled mean wavelength. The signal in the reference interferometer is acquired by detectors, such as photodiodes,

and is sent to the computer for processing. Data acquisition is rapid compared to the CCD camera and more detailed scanner motion data is provided. During a measurement both the reference signal and sample signal are acquired simultaneously as the scanning rate is the same for both interferometers. The CCD camera used to capture intensity frames is governed by an internal clock with a typical accuracy better than 30ppm. The reference signal is acquired using a general purpose, data acquisition board with a programmable scan rate. The comparison and synchronization of both signals is based on the time stamp associated with each acquired data sample.

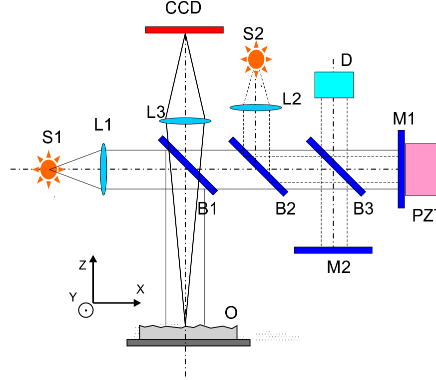

Figure 1. Basic arrangement of a optical profiler with internal length standard created by reference signal. S1 is low-coherence light source; S2 is the reference signal light source; L1 and L2 are collimators; B1, B2 and B3 are beam splitters; L3 is imaging lens; M1 is the scanner mirror; M2 is reference signal reference mirror; D is reference signal detector; PZT is the scanner transducer; O is object; CCD is camera detector.

In order to fully characterize the instrument we have built a prototype using a modified Wyko NT3300 Optical Profiler (Veeco Instruments Inc.) with a 20x Mirau objective and a 60 fps camera. As a light source we have used a regular tungsten light bulb. The reference signal interferometer was built using a He-Ne laser operating at its fundamental wavelength of 632.8 nm. The scanner used in the experiments was based on generic mechanical components and was driven by an electric motor without any feed-back loop. We have used the reference signal to characterize the scanner error position (speed) and applied it to WLI measurement of flats and steps. This software closed-loop solution increases measurement accuracy through the use of a reference signal that tracks the actual scanner position during the data acquisition process. Our setup does not correct the scanner motion; rather, we monitor the scanner motion and feed this information into the algorithm to achieve error-free surface measurements.

4. SELF-CALIBRATION OF WHITE-LIGHT INTERFEROMETER WITH REFERENCE SIGNAL

The reference signal allows us to measure the scanner position over the entire scan.[4] This obtained position information is based on the primary length standard - the wavelength of its light source, e.g., a He-Ne laser, and therefore, provides accurate position information during each scan. The influence of scanner errors is reduced or eliminated, and final result of the measurement yields a lower noise floor and more accurate height profiles. This position information can also be used to calibrate the period of the fringes during each measurement run and provide information about the mean effective wavelength registered by the camera. By direct referencing to a primary length standard, the uncertainties of step height standard can be avoided and significant increases in measurement accuracy can be achieved. No longer are step-height standards necessary for system pre-calibration since the relative stability of a He-Ne laser wavelength is at least an order of magnitude better than the step height standards used for pre-calibration. Obviating the need for system pre-calibration also reduces maintenance of the instrument.

The constant calibration of each system to the wavelength-based internal length standard during each measurement is much more reliable and accurate than current pre-calibration methods, thus allowing for better

system-to-system correlation. In essence the calibration process is reduced to setting the scanning speed to a nominal value that is within the tolerance of the algorithms. Any deviations from the ideal scanning speed or any change in the mean wavelength are corrected based on the information from the primary length standard delivered by reference signal. Thus the system is truly self-calibrating.

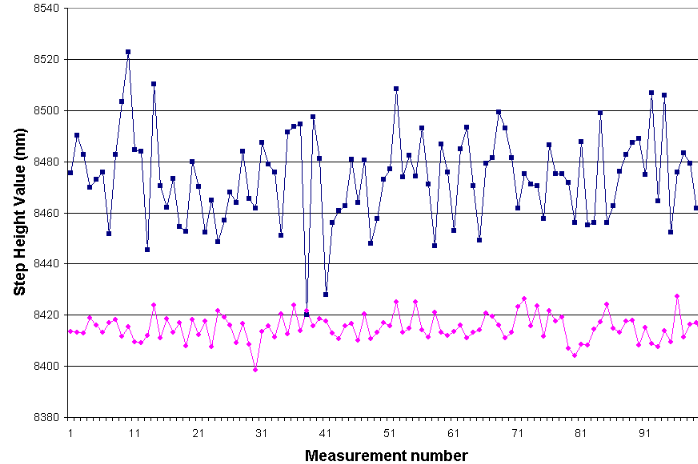

Figure 2. Step height standard numerous measurements with and without internal length standard

The reference signal interferometer yields highly accurate and repeatable results over a long scanning range, up to 8 mm, without resorting to using expensive capacitive sensors with often limited scan range. Even temperature and other environmental changes that influence system behavior are compensated for in this system. Figure 2 demonstrates the significant improvements in long-term repeatability of the reference signal interferometer. The measurement was performed using a WLI method with a reference signal using an inexpensive scanner without scan correction. The 60 nanometer offset was introduced between results for greater picture clarity. The correction of scanner errors improves system repeatability and helps maintain stable measurements over long time contributing to improved accuracy.

5. CONCLUSIONS

A practical self-calibration technique utilizes a reference signal interferometer, as an internal length standard, that directly measures the scanner motion during each scan and instantaneously applies information about scanner position to the algorithm. Thus, the measurement is traceable to the primary length standard - the wavelength of the laser and no step height standards are required for system pre-calibration. The system is insensitive to source wavelength drift, temperature and other environmental changes. Measurement linearity is guaranteed and resolution versus range dependencies is eliminated. The self-calibration routine reduces system maintenance and assures system-to-system correlation.

REFERENCES

1. M. Fleischer, R. Windecker, and H. J. Tiziani, "Theoretical limits of scanning white-light interferometry signal evaluation algorithms," *Appl. Opt.* **40**, pp. 2815–2820, 2000.
2. P. J. Caber, "Interferometric profiler for rough surfaces," *Appl. Opt.* **32**, pp. 3438–3441, 1993.
3. A. Olszak and J. Schmit, "High-stability white-light interferometry with reference signal for real-time correction of scanning errors." to be published in Opt. Eng.
4. C. Farrell, *New Algorithms for High Accuracy Phase Shifting Algorithms.* PhD thesis, University of Aberdeen, November 1993.