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WHITE-LIGHT OPTICAL PROFILER WITH INTEGRATED PRIMARY STANDARD

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Abstract – White light interferometry has become a common tool for measuring surfaces with large height ranges, slopes, and large roughness. The object is generally scanned through focus, varying the optical path difference between the light reflected from the object and from a secondary reference surface. The quality of the measurement is dependent on having a known and constant- velocity scan, as well as knowing the effective wavelength of the white light source at all times. In this paper we present a white light interferometer with an embedded second interferometer utilising a HeNe laser which provides an interferometric reference signal. This signal, based on the primary standard of the HeNe wavelength is used to monitor the scan and use the known scan positions in the height calculation algorithms. This yields improvements in the accuracy, and repeatability of topography measurements, allowing higher scan speeds without loss of data integrity.

Keywords: interferometer, surface metrology, profilometry, coherence scanning,

1. INTRODUCTION

White light interferometry (WLI), also known as vertical scanning interferometry (VSI) is a measurement technique based on the detection of the peak contrast position of fringes which are narrowly localized about the plane of best focus. All WLI techniques depend heavily on the data acquisition and are susceptible to errors in the scan mechanism[1]. The scanner controls the optical path difference (OPD) change between the test and reference beams, and most data analyses assume the rate of OPD change is calibrated and known throughout the acquisition of intensity frames. In practice, this assumption is never perfect, and both systematic and random errors result.

In most cases error is reduced by calibrating the system on a known surface and using high quality scanning devices such as closed-loop motors or PZT actuators. Calibration is generally accomplished using a step height standard certified to some degree. The scanning device, once calibrated to the step height, is assumed to have a known average speed throughout each scan. However, the scan mechanism may respond non-linearly and vary based on initial scanner position, scan length, or environmental effects such as temperature. Often the overall variation in scanner performance with position and speeds are mapped at the factory and corrected, but this correction may not remain stable with time. Delivering a high quality scan requires a significant investment and thus is not always a desirable situation. Further, random changes in the mechanism caused by vibration, dust, or other processes can greatly diminish the accuracy of the overall measurement.

Such inaccuracies may be reduced by monitoring the scanner position and using a closed-loop system to correct the scan. These hardware solutions typically suffer from high cost, limited resolution, or limited range. In this paper we present a system which uses an integrated optical reference signal to increase system accuracy, speed, and repeatability. By monitoring the scanner motion and using this information in the height calculation algorithm one may achieve a significant improvement in the measurement process. As the integrated reference signal incorporates a HeNe laser, this primary standard may also be used for calibration of all measurements without the need of step height or other standards. While Abbe error and other effects will limit the ultimate accuracy of the tool, these effects are significantly smaller than the typical 1.5% errors associated with commercial step standards.

2. INTERNAL REFERENCE SIGNAL INTERFEROMETER INTEGRATION INTO WLI

There are a variety of approaches to integration of a laser reference signal in a WLI system[2]. Figure 1 shows the method chosen by Veeco for final implementation in the NT8000, the most recent white light profilometer product. The design incorporates a HeNe laser for its long coherence length and stable operation. While the reference signal does not measure the total distance between the profiler and object, most errors are generated by the scanner motion and the effect is much the same. The advantages of independence from the object quality and numerical aperture of the objective, long allowable scan distance (over 8mm in the current scanner implementation), and simplicity of design make this the preferred method.

The reference signal employs a homodyne HeNe laser source separate from the broadband source used by the conventional WLI system. The reference signal can be acquired by one or more photodetectors, and is transmitted to the computer for further processing. The phase of the reference signal is calculated for each scanner position corresponding to the acquisition of a frame of data of the measurement signal. The phase may be calculated using any of the various techniques common to surface and distance measuring interferometry. In our set-up we have used a technique described by Farrell [3], where two signals in quadrature are used for accurate phase calculation.

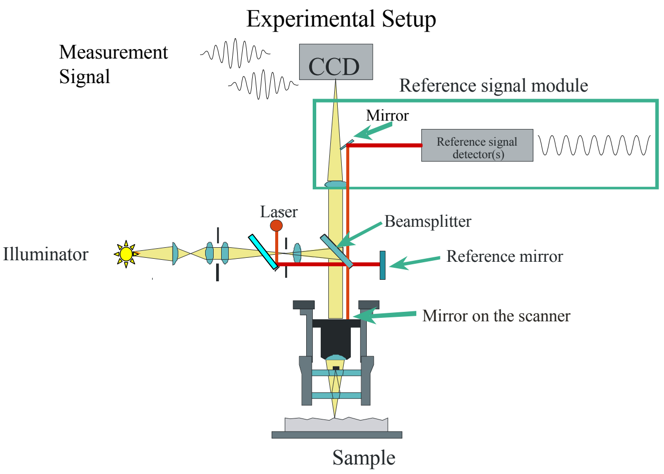

Figure 1. Example of a white light interferometer

Once the phase of the reference signal is known, one can easily employ this information in the white light algorithm used to determine surface height. We use a centroid technique to determine the position of the peak of the coherence envelope for each pixel. The reference signal calculation allows accurate correction of this technique over the scan, as shown below:

$$H(z)=\frac{\sum_{n+1}^{N-1} n*\Delta z_n[I(n+1)-I(n)]}{\sum_{n+1}^{N-1}[I(n+1)-I(n)]}$$

H(z) is the peak position along the z axis, *I* represents the intensity in the nth frame collected by the camera, and Δz represents an average step value between consecutive frames. The assumed nth frame position $n*\Delta z$ normally used in WLI calculations is here replaced by cumulative sum of Δz_1 through Δz_n, properly correcting the calculated height.

3. EXPERIMENTAL RESULTS

As mentioned previously, optical profilers are typically calibrated with step heights of a known value, with possible correction of overall scanner performance based on factory measurements. The goal of an integrated laser reference separate from the measurement path is to remove uncertainty in the system performance with environment, scanner starting position, scanner range, and other factors which can cause performance reductions. In addition, because of the known HeNe wavelength used for calibration, no external step standards are required for system calibration; the system is self-calibrating.

Several experiments were designed to test the performance benefits of an integrated standard for active calibration. These tests included errors from scanner non-linearity, long term stability of measurements, error correction with deliberate system miscalibration, and linearity retention over long scan ranges. Results are presented in the following paragraphs.

One test of correction ability was to build a deliberately non-linear scanner and measure the surface of a tilted SiC mirror, nominally flat within the field of view, both with and without reference signal corrections. With standard WLI algorithms, scanner non-linearities will cause a ripple across the calculated surface, while a well-corrected scanner will not evince this behaviour. Figure 2 below shows results from such a test, showing 180nm ripple from the uncorrected scanner. With the reference signal correction, errors reduce to less than 30nm. In addition, residual errors at this point were primarily due to the unstable nature of the breadboard setup.

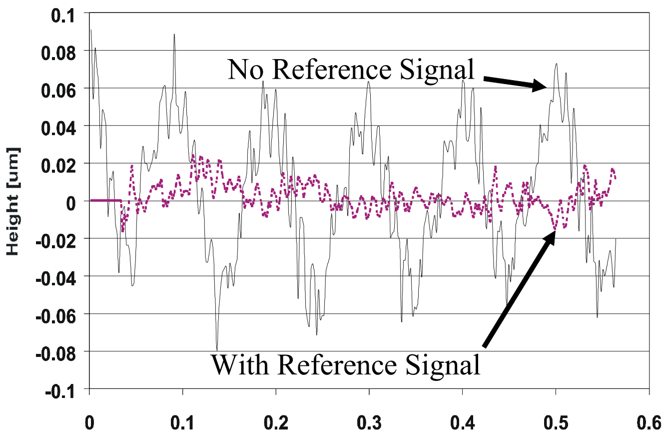

Figure 2. Trace across a measurement of a high-quality SiC mirror using a non-linear scanner.

Another benefit of reference signal correction involves long-term stability of measurement performance. Environmental fluctuations, wear, and other effect can change how the scanner functions. Thus, drift of step calculations or other parameters may occur over time. While such drift can be corrected by recalibration of the system, this is not desirable. Additional time is involved, and recalibration is not feasible for long-term studies of a part where handling the part or disturbing other aspects of the system to measure the step height affect the results.

Figure 3 shows measurements of an approximately 23μm high step taken over about eight hours. During this time, the room temperature was raised by 10 degrees Celsius over the initial condition, and then lowered to 15 degrees from the highest temperature. The upper plot shows a WLI algorithm with no correction, and the lower plot shows measurements with correction. Without correction, the step values drift by 60nm over the course of the test. In contrast, the corrected step values drift by less than 10nm, again about a six-fold improvement. The step itself is chrome-coated quartz, which would be expected to change height less than 1nm over this range of temperatures.

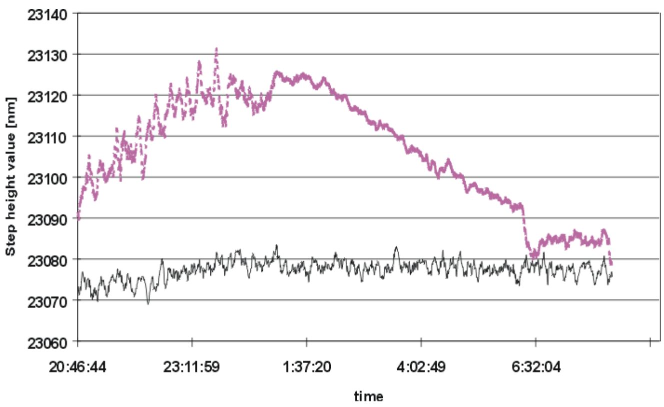

Figure 3. Calculated step height versus time as room temperature is cycled. Top line is without integrated reference signal and bottom is with reference signal.

A further test of the reference signal involves merely testing the performance of the integrated standard in the presence of known system miscalibrations at different scan speeds. Figure 4 shows calculated step height at two different scanner speeds when the system on a 49.8 µm high step. The system was scanner had been calibrated using a 10µm step height standard at 5µm/sec base speed the week previously, but not recalibrated prior to measurement. Even using the nominally calibrated scanner motion errors are seen in the data without reference signal correction. When the scanner motion calibration was deliberately changed by 10%, nearly 10% errors are seen without reference signal, as expected. However, all calculated step heights using reference signal agree to within 0.05% of one another, despite scanner miscalibrations.

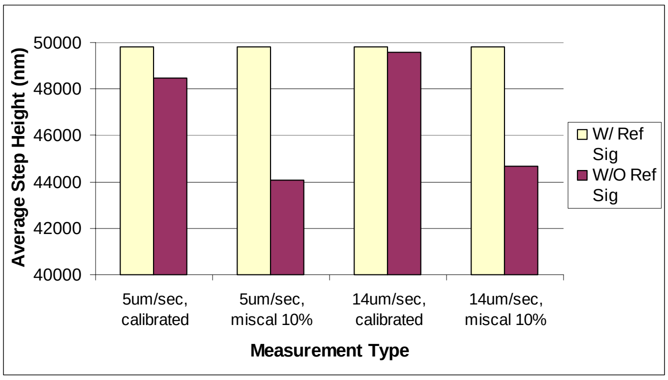

Figure 4. Calculated step height on a 49.8µm step with different scanner speeds and deliberate miscalibration, with and without applying reference signal correction.

In addition to improved accuracy, the integrated reference signal also maintains repeatability as scanner speed is increased. With increased scanner speed, causing sub-sampling of the detected fringes, WLI algorithms are increasingly sensitive to miscalibrations [4]. Figure 5, however, demonstrates that repeatability is not significantly affected with increased scanner speed on a 49.8µm step, even with deliberately induced miscalibrations. The maximum standard deviation is about 10nm, or 0.02% of the overall step value, even when the scanner is operating at 50µm/sec speeds (sampling one point every 900 degrees of phase) and 10% miscalibrated.

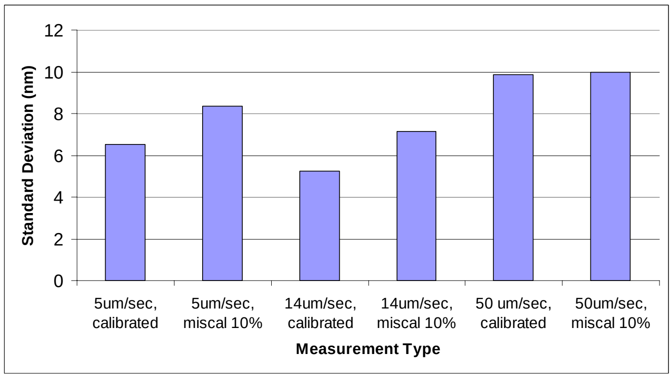

Figure 5. Standard deviation of measurements on 49.8µm step with different scan speeds, and deliberately induced scanner miscalibration.

A final test of reference signal performance was to determine its ability to linearize the scan over any arbitrary range. It is impractical to maintain many high-quality steps to cover any given range of heights for which the instrument is used, and to recalibrate the system according to the part being measured. Making a perfectly linear scan over many mm is difficult and expensive, leading many manufacturers to limit the basic scanner range so that they can maintain good specifications. With the integrated reference signal, however, perfect scanner linearization is not required.

To test this, the Veeco NT8000 was allowed to self-calibrate scanner motion using reference signal, but no height standard was used. Ten measurements were taken using reference signal correction on each of seven steps, ranging from 920nm to 5mm in height.. Results are presented in Figure 6, which plots the average measured step height versus the listed step height for each step, as well as a linear regression plot. The linear regression calculation shows linearity of 0.05% over the nearly four orders of magnitude studied. Also, standard deviation of each set of 10 measurements ranged from 0.007% to 0.05% of the step height value, showing high repeatability of the data. Further step standards are being obtained to achieve a more complete range of values.

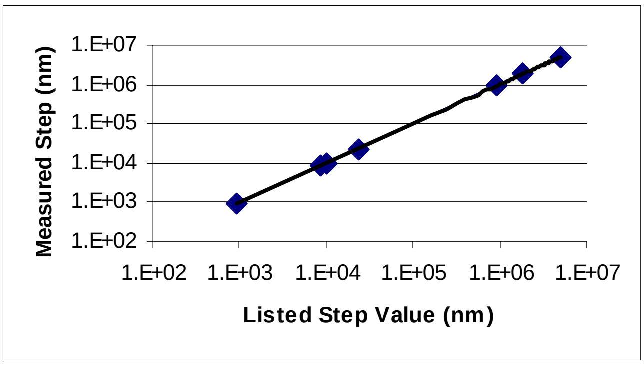

Figure 6. Measured step versus given step value, and associated linear regression line.

4. CONCLUSIONS

Standard commercial profilometers rely on calibration of a known step standard to obtain the correct scanner speeds for height calculations. Obtaining a high-quality, known scanner motion is difficult and costly, and mechanical wear or environmental factors can cause the behaviour of the system to drift with time. Through incorporation of a HeNe laser reference signal into a profilometer, significantly more stable performance can be obtained.

Integration of such a standard leads to real time correction for scanner non-linearities, increased insensitivity to environmental drift, and proper height calculations at varying speeds, calibration accuracies, and scanner ranges. While the laser reference standard is not perfect, such a standard is significantly more accurate than most commercial certified steps, which typically are certified to only about 0.1%. Step repeatability and scan linearization of better than 0.05% was achieved on steps from under 1µm to over 5mm in height.

The laser reference standard provided here has been incorporated into a commercial instrument, the Veeco NT8000, from which data for Figures 4 through 6 has been taken. Current work with the laser reference signal focuses on quantifying the potential error sources with Tony Schmitz of the University of Floriday. Effects of Abbe offset, cosine error, residual environmental drift, dead-path error, and other ultimate limitations on the technique will be studied, so that true traceability of the instrument can be claimed.

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