INVESTIGATIONS ON MEASUREMENT SPEED OF SPATIALLY DISPERSED SHORT COHERENCE INTERFEROMETER

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ABSTRACT

In recent times online surface measurement techniques have attracted widespread attention in research and industry enabling fast high precision measurement of engineered surfaces. In this paper we discuss an online metrology tool based on the spatially dispersed short-coherence interferometer using an SLD (Super Luminescent Diode) as a light source. The SLD is a broadband source which is spatially dispersed across a surface using a reflective grating and scan lens. The phase information which is related to the surface height is spectrally encoded. The Michelson interferometer technique was used for this experiment. The light reflected from the surface under test is interfered with a reference beam which the resulting fringes are interrogated by a spectrometer. In addition, phase shift interferometry is used to extract the spectrally encoded phase data by analysing four captured frames using a Carré algorithm; and in this procedure the surface height can be calculated across a profile of the sample. Environmental noise is an issue in any interferometer system, which degrades the performance of the device measurement results. Hence, the speed of capturing and analysing is one of the important factors to be considered in an online manufacturing process in order to reduce the effect of noise on the performance for instruments. In this paper, the application of high-speed phase shifting interferometry to detect surface information is presented. The PZT (piezo-electric transducer) settling time has been investigated to optimise speed of the system. The data acquisition speed has been substantially improved from 4s to 1s. Similar surface measurement results obtained when the system operated at higher speed exhibiting better performance in terms of speed and measurement reliability.

Keywords: Optical Metrology, Interferometry, Phase Shifting Interferometry, Surface Measurement

1 INTRODUCTION

Optical interferometry has been widely explored for surface measurement as a non-contact method. Interferometric methods have many advantages when compared to traditional contact stylus instruments. They do not contact the surface being measured and thus any damage can be avoided under normal circumstances [1-3]. Non-contact methods are generally faster and remain capable of high precision measurement. In the field of surface metrology there are many types of developed techniques including SWLI, PSI and wavelength scanning interferometry [4]. SWLI in particular is a powerful technique which can overcome the inherent phase ambiguity and is thus capable of measuring discontinuous surface features; as such it is the de facto optical profilometry technique in industrial use. However for many dynamic applications, such as the analysis of defects on moving subtrates, methods such as SWLI are not suitable due to the requirements of mechanically moving the objective lens in order to make the measurement. For dynamic application such as defect detection in roll-to-roll manufacture it is often enough to measure only a line profile on the surface because the second lateral measurement axis is provided for by the movement of the substrate. In this paper we introduce a spectrally resolved broadband interferometry technique to measure surface profiles at the nanoscale. A Michelson interferometer is setup and is illuminated with a broadband SLD light source. The light is spatially dispersed across a profile on the measurand using a grating and collimating lens. The resulting broadband interferogram is spectrally decomposed, and the optical phase is determined for each sampled wavelength simultaneously. This spectrally resolved phase information can be used for interferometric measurement of surface topography by virtue of its relationship to optical path length in the interferometer [5]. The spatially dispersed interferometer gives surface topography information across a profile on a measurand. The length and sampling resolution of this profile depends on the properties of the NA of the objective lens, the properties of the grating as well as the specification of the spectrometer [6.7].

2 THEORY OF OPERATIONS

Phase shift interferometry (PSI) is widely used in interferometry utilising monochromatic light sources. The limitation of the method is an inherent phase ambiguity because of the inability to determine the absolute fringe order. This means a limitation for this technique when used for surface profiling, in which the wavefront is reflected from the measurand surface; the height difference between two

sampled points should not exceed one quarter of the source wavelength. However, increases in height of greater than this limit may be tracked by using a phase unwrapping process as long as the maximum discontinuous height change condition is met across the whole measurement [8].

In this section, the principle of a spatially dispersed broadband PSI technique is explained. The experimental apparatus is based upon a Michelson interferometer configuration. The measurement arm is formed from a dispersive probe and the surface under test. The reference arm comprises a mirror mounted on a PZT to act as the phase shifting element. The intensity of the resultant interfered beam from an interferometer can be described as,

$$I = I_r + I_m + V\sqrt{I_r I_m}\cos(\phi) \tag{1}$$

Where I_r and I_m are the irradiance reflected from the reference mirror and object respectively and ø is the phase shift between them. The fringe visibility, V is defined as:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{2}$$

Where I_{max}, I_{min} are the maximum and minimum intensity respectively. The PSI method can be used to analyse collected intensity data to determine the phase. The intensity pattern is recorded as the phase in the reference arm is changed sequentially. The recorded interferograms are analysed electronically and a suitable algorithm recovers the phase. Examples of these algorithms are Carré, Schwider-Hariharan and 3 steps, although many more have been developed [9.10]. The Carré algorithm is potentially the most useful for the experimental apparatus in this work, because it does not require a specific value of phase shift, it only requires each shift to be identical which has benefit for a system operating at multiple wavelengths, where the physical movement of the optical path length to effect a wavelength dependent amount of phase shift. The Carré algorithm is given as,

$$\phi = \tan^{-1}\left\{\frac{\left\{\left[3(I_2 - I_3) - (I_1 - I_4)\right]\left[(I_1 - I_4) + (I_2 - I_3)\right]\right\}^{1/2}}{(I_2 + I_3) - (I_1 + I_4)}\right\} \tag{3}$$

Where four phase shifted measurement intensities: I_1, I_2, I_3 and I_4 are required in order to extract the original phase. In our apparatus each wavelength, λ which is discretised through analysis by the CCD spectrometer is mapped by the dispersive optical probe to a single position, x along a line profile on the surface under test. The phase of the interference fringes at any given wavelength is then a function of the OPD and thus the surface height, h at the position, x . This may be represented as,

$$I(x,\lambda) = I_r(\lambda) + I_m(x_\lambda) + V(x,\lambda)\sqrt{I_r(\lambda) I_m(x_\lambda)}\cos\phi(x,\lambda) \tag{4}$$

Where

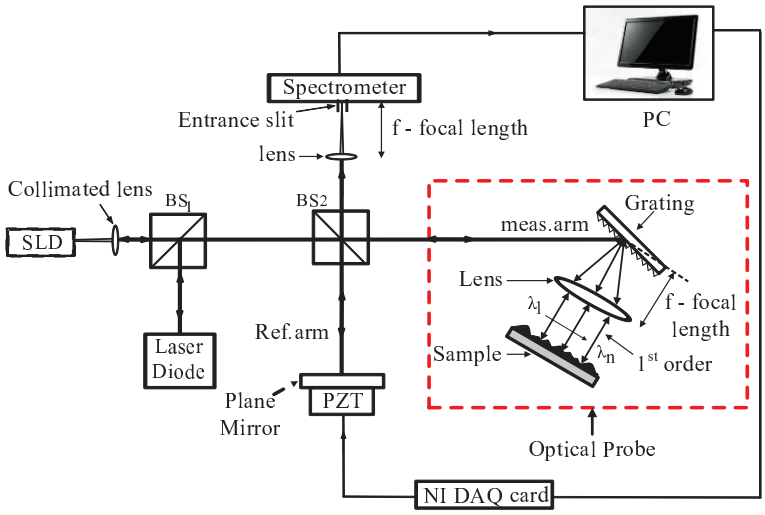
$$\phi(x,\lambda) = \frac{4\pi}{\lambda} h_x \tag{5}$$

Note that there is no x dependence in the reference arm intensity because it contains only a simple mirror. From equation (5), the surface height can be calculated for any continuous phase distribution. The phase difference between the reflected wave from a position on the measurand surface and the reference wave can be calculated by evaluating the fringe intensity. The interferogram is position encoded as a function of wavelengths. By determining the phase encoded at a given wavelength, the surface height of the position relating to that wavelength may be determined.

3 EXPERIMENTAL SETUP

The experimental apparatus configuration of the surface measurement is illustrated as in figure (1). A SLD (Exalos EXS8310-8411) is used as a broadband light source and features high spatial coherence while maintaining a short coherence length of approximately 20-30 µm. The SLD has an output power of 1.08 mW, bandwidth of 25 nm (FWHM) centred at 825 nm. The BS (Beam Spliter) acts as the main splitter/combiner for the Michelson interferometer . The interferometer experimental setup is a PSI comprising a Michelson interferometer which uses: a grating element and collimating lens in the measurement arm to produce a dispersive probe; a spectrometer to analyse the spectral interferogram generated; a PZT (piezo-electric transducer) in the reference arm to shift the reference phase. The measurement arm beam propagates through the optical dispersive probe, the reference beam to the PZT mounted mirror. This is shown in more detail in figure (1). In the dispersive optical

probe, the SLD beam is angularly dispersed by the grating. The dispersed light is then collimated and then focused as a line profile onto the surface under test by the objective lens.



Fig(1) Exprimntal setup

At the dispersive optical probe, the broadband SLD beam width is 8.3 mm, which angularly dispersed by the grating and thus dispersed light is then collimated and focussed onto the surface by the objective lens. In this experiment, the achromatic doublet lens (Thorlabs, AC254-050-B) was used which has the focal length 50 mm. The grating equation is,

$$m\lambda = d\left(\sin\alpha + \sin\beta\right) \tag{6}$$

Where *m* is an integer number, d is the grating pitch; λ is the wavelength of the incident light. α, β are the incident and diffracted angles respectively as shown in figure 2.

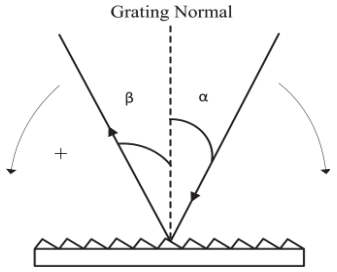


Fig (2) Utilised angle and sign conventio

The 1st order diffracted beam is used to probe the surface under test using the objective lens. The lateral range (line profile length), *S* of the incident light on the surface can be represented by,

$$S = f.\frac{\Delta\lambda}{d\cos\beta} \tag{7}$$

Where *f* is the effective focal length of the objective lens, and the diffraction grating is operating on the 1st order only. The rear focal position of the objective lens is aligned such that it is placed at the point of diffraction on the grating surface. The optical axis of the lens is aligned with propagation of the centre SLD wavelength (825 nm).The grating is set so that the incident angle of the measurement arm beam is 0°, resulting in a diffracted angle of 83.70° at the centre wavelength and a total angular dispersion of 0.01 rad/nm of the light from the SLD source (taken from FWHM =25 nm). The incident angle is critical in determining the angular dispersion and thus the overall length of the line profile cast upon the surface. The 1st order diffracted beam is diffracted by a diffraction grating and this beam hits collimated and focused by the objective lens onto the measured surface. In the reference arm, a PZT (PI, P.810.10) mounted mirror is used to generate phase shifts by moving the mirror through four positions along the optical axis. The spectral interferogram is recorded by a spectrometer (Solar Laser Systems, S150) after each mirror movement to provide the set of intensities required for applying the Carré PSI algorithm in (see equation 3). The spectrometer features a CMOS line array having 3648 pixels in total. The PSI operation is coordinated using National Instruments Labview software and a data acquisition (DAQ) card having an analogue output (National Instruments USB-6211). In the reference arm, the PZT is pushed in 4 steps by applying a series of 0.84 V steps using the DAQ card

analogue voltage outputs. The speed of capturing time has been minimized substantially reducing both the acquisition and the analysis times from 4s to 1s with the spectrometer camera speed (45 Hz) per frame. The spectrometer speed is still faster than 1s, which needs more investigation in order to achieve at the highest possible capturing speed according to the spectrometer specifications.

4 RESULTS AND DISCUSSION

A spectrometer is used in this experiment for analysing the spectral interferogram. The spectral interferogram generated through mixing the waveforms reflected from the surface under test and a reference mirror. A spectrogram was captured for each of four reference mirror positions, which relate to phase shifts of approximately 110^{o} at the source centre wavelength of 825 nm. The spectrometer uses a CMOS line array having 3648 pixels. In combination with the dispersive optical probe, each pixel of the spectrometer monitors interferogram intensity information retrieved from one specific position on the surface. The spectral interferogram data is transferred to the PC through a USB interface and analysed using National Instruments Labview software. The actual sample (diamond turned multi-step) having variable slope angles between steps was used for measurements of the steps. Figure 3 shows a surface profile of this sample obtained using a Taylor Hobson PGI stylus instrument and University of Huddersfield proprietary surface analysis software, Surfstand. In the experimental setup the optical probe was arranged such that the 4 leftmost steps (i.e. A, B, C and D) where imaged. Figure 4 shows the extract spectral interferograms at the 4 reference mirror positions using the multi-step sample.

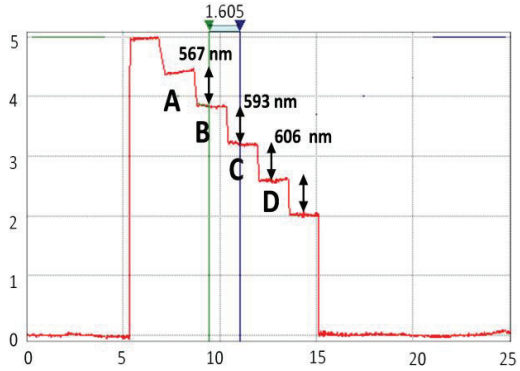


Fig (3) A diamond turned multi-stepped sample (Taylor Hobson PGI stylus profilometer)

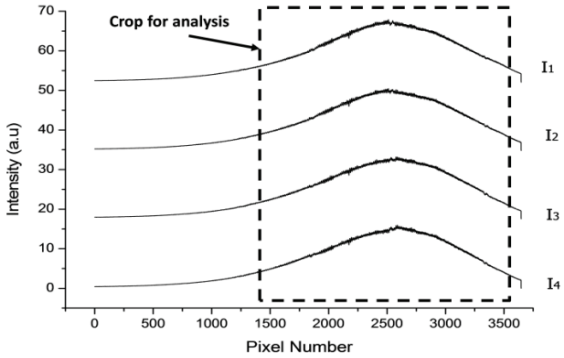


Fig (4) Phase shifted spectral interferograms

The retrieved data from the 4 acquired inteferograms were then evaluated by Carré phase shifting algorithm in order to extract the phase information related to the surface height along the profile. The raw data as figure (5) is used to evaluate the step height (i.e., unwrapped tracking) as in figure (6) any phase change more than π and adjusting the fringe order up or down as necessary. It is very important to refer that the step heights for the sample are particularly larger than the non-ambiguous measurement range of a proximity 206 nm (λ/4). The measurement step height for a sample height between step B and C was 613.51 nm compared to the Surfstand/PGI result as in figure(3) of 606 nm. Results revealed that the timing 4s for pushing of PZT and spectrometer capturing are resolved. High speed phase shift pattern interferometry with high speed capturing has been investigated to reduce the inherent environmental manufacturing noise. The reference mirror is moved in 1 s at each step where the data being read after a delay in ms to allow for mechanical settling. The mirror is mounted upon the PZT and the PZT results related to settling times due to the interaction with the mass and the stiffness of the PZT parts. To calculate theoretically settling time founded the settling time for the PZT if the percentage error is 2% as in the equation 8 and 9:

$$\omega_n = \sqrt{\frac{k}{m_{eff}}} \tag{8}$$

$$\tau_s = \frac{4}{\gamma\,\omega_n} \tag{9}$$

Where: ω_n is the resonant frequency, k is the stiffness of PZT 810-10 equal to 18.6 n/μm and m_{eff} equal to1.999 mg. The ω_n equal to 43.13 KHz, Y is the damping ratio = (1/2Q). The Q is the quality factor equal to10 then the damping ratio equal Y equal to 0.05. The calculated settling time is equal to 1.85 ms. The measured settling time (see the figure below) gives a settling time approximately 2 ms which is close to the theoretical calculation. Practically, the settling time is measured and the output results as shown in the figure (7) which is equal to 2 ms.

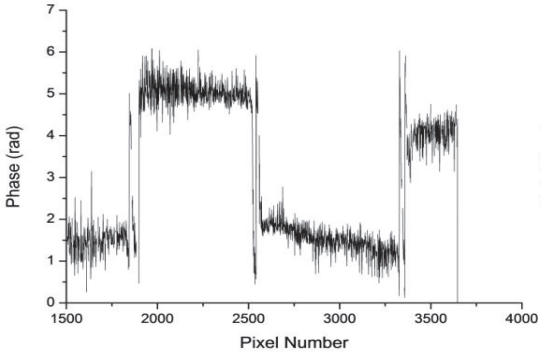


Fig (5) Raw phase profile calculated with Carré algorithm

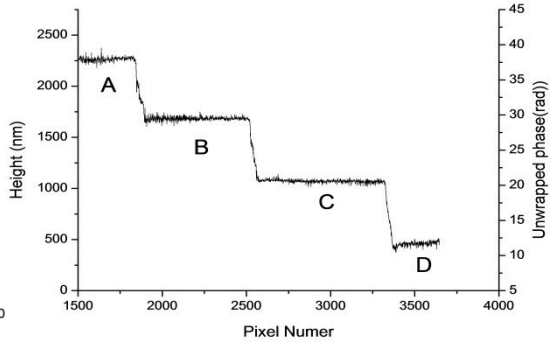
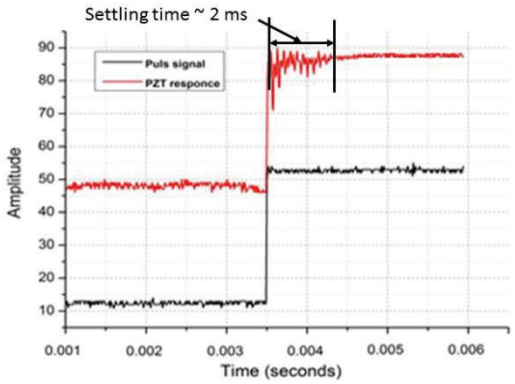
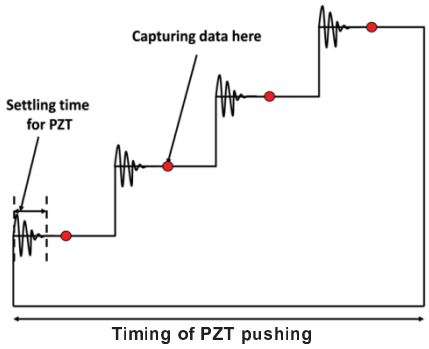


Fig (6) Step height profile

For the PZT, the degree of settling time is one of the important factors that should be considered. The capturing data are related at the settling time of the PZT when is set with the types of techniques and algorithm (Carré algorithm) for the mirror moved to different positions as shown in figure (8).

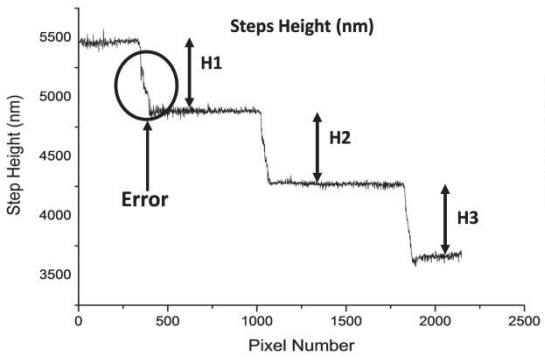


Fig(7) Practical measurment Settling time

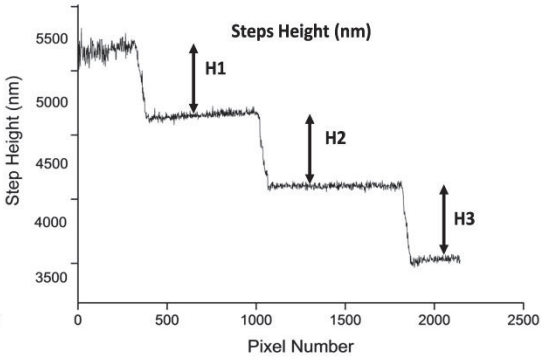


Fig(8) Settling time with capturing data time

The settling time is determined by measuring response PZT to a step excitation using function step pulse generator was applied on the PZT and this response of PZT relates to the Michelson interferometer setup. This settling time is much smaller than the capturing speed of the spectrometer for one frame which is equal to 22 ms. The initial capturing time for the spill dispersive short coherence interferometry is set to be 4s (including the four PZT movements), the capturing time has been reduced to 1s as shown in figure (9).



(a) Step Height measurement with 4s



(b) Step Height measurement with 1s

Fig (9) Step Height measurement with two different time reading

The measurement heights according to Taylor Hobson PGI stylus instrument were found respect to B and C. At the 4s speed of measurement, the heights of this letter was found at letter B the height equal (H2) to 613.15 nm with error 3.34% and at the C letter the height equal (H3) to 611 nm with error 1.3%. Meanwhile, with the increasing capturing time at 1s the height at the letter B equal to 571.82 nm with error 3.70% and at the letter C equal to 594.57 nm with error 1.41%. There is an error at step A with 4s reading meanwhile at 1s this error disappeared.

5 CONCLUSIONS

In this paper, a spatially dispersed short coherence surface profiling interferometry technique was used to obtain the surface profile of a multi-step sample. The method combines an SLD light source with a dispersive optical probe which spatially disperses the beam across the surface under test. The Carré phase shifting algorithm was used to extract the phase information from the recorded interferogram, and thus the surface profile is obtained. The step height obtained was in agreement with the measurement performed using a Taylor Hobson PGI stylus profilometer with some distortion, probably due to optical misalignment and aberration in the system. For higher accuracy, the device must operate at a maximum speed to negate environmental effects. Investigations on settling time of the PZT were performed to establish the maximum capturing speed with which the device can operate. The settling time of the PZT was calculated to be ~2ms. Moreover, the speed of the device is limited by the actual spectrometer camera speed (~22 ms). The device capturing time is reduced to 1s compared to the previous measurement time (4s) by modifying the labView code.

Further it is required to investigate and optimise methods of increasing the device speed close to the spectrometer camera capturing speed. This includes the LabView code development and implementation. In addition for a high resolution measurement it is required to replace the achromatic doublet with an optical coherence tomography (OCT) scanning lens in the current optical probe design and measure step height of a new sample. Evaluation of critical parameters such as resolution, uncertainty, repeatability, measurement rate is to be carried out. For single frame high speed measurement Fourier Transform of surface profilometry is to be investigated. Finally, to devise a modular, standalone optical fibre linked probe.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of the EPSRC Centre for Innovative Manufacturing in Advanced Metrology (Grant Ref: EP/I033424/1), European Research Council funding by the SURFUND Advanced Grant (228117) as well as a studentship funded by the Department of Laser and Optoelectronics Engineering at the University of Technology, Iraq.

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