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In-situ fibre-based surface profile measurement system using low coherence interferometer

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ABSTRACT

For many high-value manufacturing applications, advanced control systems are required to ensure product quality is maintained; this requires accurate data to be collected from in-situ sensors. Making accurate in-situ measurements is challenging due to the aggressive environments found within manufacturing machines and processes. This paper investigates a method to obtain surface profile measurements in a spectral-domain, common-path, low-coherence system. A fibre based Low Coherence Interferometer was built and was used to experimentally measure surface profiles. The fringes obtained from interferograms were transformed into the Fourier domain to obtain a trackable peak relating to the surface depth. This has been illustrated with ideal step height measurements and referenced specimens as well as more challenging surface roughness measurements, which have produced complex signal processing issues. This work opens up avenues for a metrology based system where both machining and measurement system can coexist on the same plane, in aggressive environments.

Keywords: Metrology, Sensor, Low Coherence Interferometry, In-situ, Water

1. INTRODUCTION

As technologies associated with the manufacturing of precision engineered surfaces continue to evolve and improve, so are their requirements to adhere to even tighter manufacturing tolerances. As a result, manufacturers of existing metrology platforms are continually improving and developing systems that are becoming more portable, robust and versatile, thereby reducing cycle times and increasing productivity. There are currently two conventional methods for measuring surface form and features; the first is a contact approach that passes a stylus probe across a surface allowing profiles to be traced. The second is a non-contact approach that records the form and features of a surface without physical contact with the object, and is fast expanding across a broad spectrum of fields from biomedical engineering to high-precision manufacturing. With advancements in high-precision manufacturing requiring an ever increasing need towards obtaining high quality surface measurements during the machining process, there is an industrial requirement for real-time shape and surface texture measurements for bespoke manufacturing.[1]

A simple and robust sensor that can provide for real-time shape and surface texture is one centred on an imaging modality known as Optical Coherence Tomography (OCT). Based on Low Coherence Interferometry (LCI) and originating from white-light interferometry, it's first application was reported by Fercher et al. in 1988, towards measurements of the corneal thickness of the human eye,[2] and soon afterwards by other researchers as a measurement tool for high-resolution profilometry.[3–6] The use of LCI to obtain high acquisition contactless, non-invasive measurements can be realised using a variety of configurations including the use of optical fibres and wideband fibre couplers in interferometer construction.[2,7,8] However, the use of fibre systems can be problematic due to factors such as chromatic dispersion. To circumvent such problems, designing an interferometer where both sensing and reference arm share a common path, hence the term common-path interferometer, has shown to promote interferometer stability.[9]

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In this paper, we describe a common-path Fourier domain (FD) OCT type system where signal is captured in the optical frequency domain from a broadband light source that is dispersed onto a CCD that measures the cross-spectral density. The sensor is designed for implementation as an in-situ measurement device that is deployable in confined spaces thus making it capable of on-machine measurements. We demonstratively show the measurement of surface topography using calibrated and traceable samples in conditions comparable to many manufacturing processes. We also present the possibility of measuring surface texture profiles.

2. EXPERIMENTAL SETUP

The experimental design of the common-path FD LCI type system is shown in Fig. 1. The system consists of a super-luminescent diode (EXS210068-01, Beratron GmbH), with a 3-dB bandwidth of 58 nm and an emitting power of 5.14 mW at 160 mA. A single mode fibre coupler with a splitting ratio of 50:50 was used for the beam splitting and coupling, with only one branch of signal output being used as the common-path for the signal and reference. The single-mode bare-fibre output leg was then placed into a fixed fibre clamp with the flat surface of the fibre tip adjusted parallel to the plane of the base of the translation stage. It is worth pointing out that the bare-fibre was placed as close as possible to the target, so as to prevent signal decay with increased imaging depth due to the highly divergent nature of light exiting the fibre tip, as reported by Liu et al.[10]

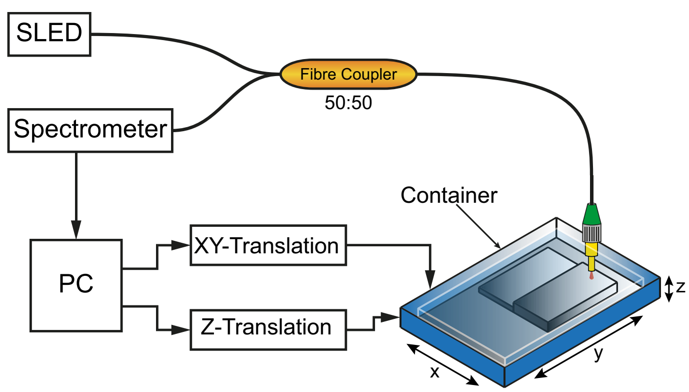

Figure 1. Experimental setup of common-path Low Coherence Interferometer.

A set of 3-axis stepper driven translation stages, (Zaber Technologies), with a manufacturer stated microstep size of 0.124 μm in the YZ direction and 0.0476 μm in the X direction, was used to move the sample laterally and vertically. The back reflected/scattered light from the reference and the sample leg was coupled back into the single-mode fibre and channelled by the coupler to a 2048 $\times$ 64 pixel array CCD spectrometer (MayaPro2000, Ocean Optics) that covered a wavelength range from 756 nm - 930 nm, with an average resolution of 0.21 nm. The targets used with the common-path configuration setup were: a pair of tungsten carbide slip gauges (Select Gauges, Cornwall, U.K.) stacked close together so as to provide a step height of 8.5 μm and a N6 shaping sample (Rubert & Co. Ltd, U.K.) with a stated Ra of 0.8 μm.

To obtain a step height measurement and initial roughness measurements, the modulated spectrum from the CCD detector was recorded over a single pass of the sample at discrete points. Using a custom built application in LabVIEW, the incoming signal from the spectrometer was recorded in the x-direction every 10 μm over a translational length of 2.5 mm for the slip gauge and 4 mm for the Rubert shaping sample. The exposure time on the spectrometer for each sample was set accordingly in order to get a signal without any clipping.

The same LabVIEW application was also used to compute a Fast Fourier Transform (FFT) with an applied 7-term Blackmann Harris window on the spectral interference pattern. This allowed for the signal in the spectral domain to be converted into a signal in the spatial domain that delivered the location of a peak at a frequency that corresponded to the scatterer location and hence a resolvable depth. Processing of the spectral domain signal was carried out in a custom built MATLAB program and involved composing a quadratic fit on a windowed region of the frequency domain signal in order to determine the centre peak position. Final analysis of the data was carried out using Digital Surf MountainsMap software where the sequence of data analysis in this software comprised of leveling using a least square line method and, where necessary, operations such as profile filtering and form removal.

3. RESULTS AND DISCUSSION

Step height measurements of the slip gauges were obtained from a common-path configuration type setup. All the results were processed in the frequency domain, with the laser source set to 160 mA, emitting an optical power of 5.13 mW and the capture rate on the spectrometer set to 7 ms.

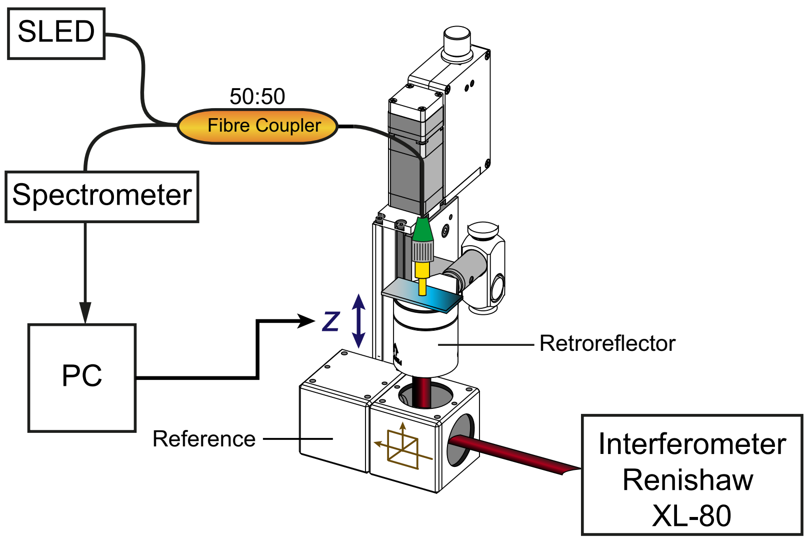

Figure 2. Experimental setup of the common-path LCI system with a Renishaw XL-80 interferometer for z-axis calibration.

In order to acquire quantitative depth measurements, the first step was to obtain a relationship between, the optical path length mismatch between the sample and fibre tip. This process involved incrementally stepping a slip gauge vertically via the z-axis of the motorised stage and recording the spectral domain signal as well as the stage position. To accurately monitor and record the z-axis stage position a Renishaw XL-80 interferometer was used as a traceable source, as shown in Fig. 2. Applying a least squares linear fit to this data provided a relationship between the z-axis movement and the tracked centre frequency of the frequency domain signal.

The second step of the experimental process looked at measuring the height difference between two tungsten-carbide slip gauges stacked side by side together. Two slip gauges with a step height of 8.5 μm were placed on a flat mirror surface with a perspex surrounding to allow for measurements in both air and water. Using LabVIEW to laterally sweep across the two slip gauges and MATLAB to transform the extracted centre frequency from the frequency domain signal to a depth, measured profiles from the LCI system in both air and water were obtained. In addition, results from more established metrology measurement techniques were gathered. This included a contact measurement instrument, a Talysurf CLI 2000 inductive gauge attachment holding a diamond stylus with a 2 μm radius and a non-contact measurement system, an Alicona G4 with a 20X lens attachment. These measurements were carried out to illustrate the variability between measurement processes, highlighting the fact that different processes will produce a range of measurement values for the step height depending upon transduction method. The results were analysed using Digital Surf MountainsMap software and are shown in Fig. 3.

For a nominal step height of 8.5 μm, the Alicona and the Talysurf recorded 8.44 μm (1.3% lower than expected) and 8.66 μm (1.88% higher than expected) in air respectively, whilst the LCI system recorded 8.61 μm (less than 1.28% larger than expected) and 9.93 μm in air and water respectively. It should be noted that the Alicona and Talysurf could not be used in water. It is anticipated that the LCI system will tend to overestimate depth measurements due to the dispersion characteristics of the fibre output and hence the introduction of potential cosine errors. It should be noted that dispersion will be dependent on the refractive index of the medium.

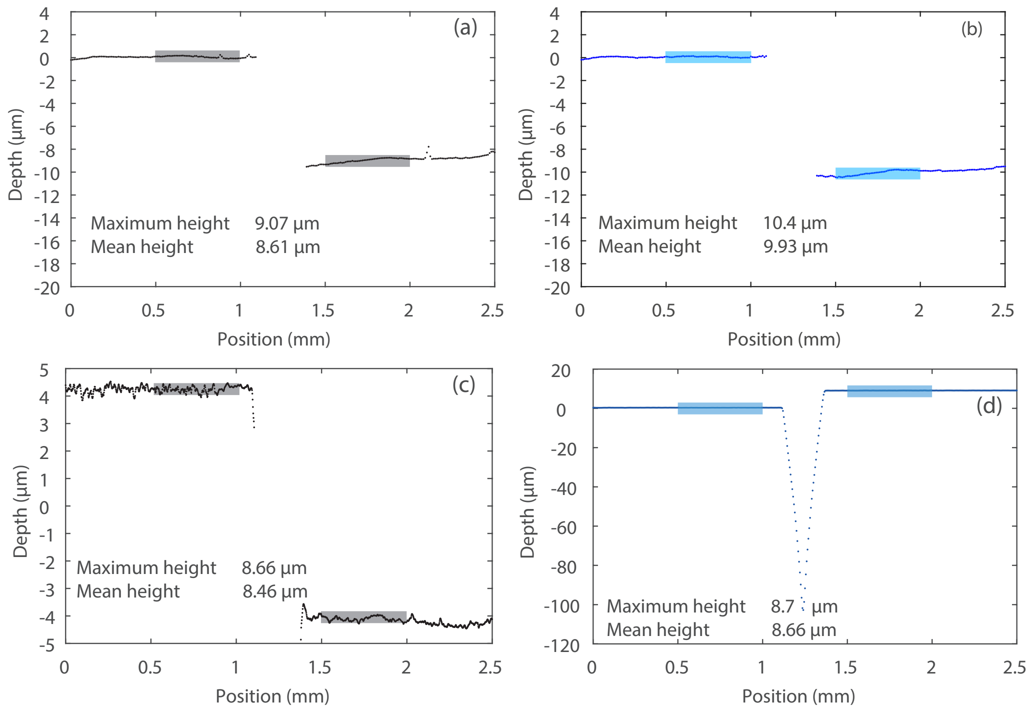

Figure 3. Step height measurements of a pair of tungsten carbide slip gauges with a step height of 8.5 μm obtained from (a) LCI system in air (b) LCI system in water (c) Alicona G4 non-contact traceable instrument and (d) Talysurf CLI 2000 contact traceable instrument.

In addition to the step height measurements, surface texture measurements were also carried out on the common-path LCI system. These more challenging measurements were carried out on an N6 shaping sample that exhibited various ranges of micro-roughness. Here, a set of 5 longitudinal scans with a 50 μm spacing were taken. These 5 longitudinal scans taken over a 4 mm length, were then averaged and analysed in Digital Surf MountainsMap software with a series of operator sequences including, profile filtering using a Gaussian filter with a cut-off of 100 μm and form removal. Following the optical measurement, stylus profilometer measurements were performed in a similar manner as with the common-path LCI system, again using the Talysurf CLI 2000 inductive gauge attachment holding a diamond stylus with a 2 μm radius. The results from both these measurement techniques are shown in Fig. 4.

The surface texture results from the LCI system and the Talysurf CLI 2000 reveal a similar pattern of events. Noticeably, for both the measurements over the same travel range of 4 mm there are similarities in both the number of peaks, peak spacing and the magnitude of peaks. A comparison of surface profile parameters are shown in Table. 1. The difference in the Rc values is a function of the current vertical resolution of each instrument.

Table 1. N6 shaping surface profile parameters

	Common-path LCI system (μm)	Talysurf CLI 2000 (μm)
Rc	2.88	4.40
RSm	359	337

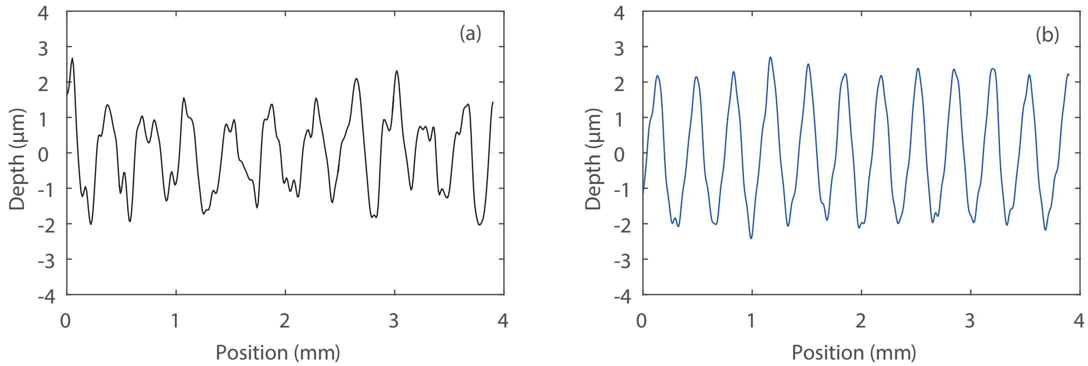

Figure 4. Surface texture measurements from an N6 shaping sample (Rubert & Co. Ltd, U.K.) carried out in air from (a) common-path low coherence setup and (b) Talysurf CLI 2000 with an inductive gauge stylus with a 2 μm radius.

4. CONCLUSION

This work explores the potential of LCI to be used as a real time robust online measurement sensor for surface topography measurements in harsh industrial environments. The high value manufacturing domain is often focussed around the production of micro-scaled structures with the need for traceability of conformance to design tolerances, the fibre based LCI system proposed in this paper has the capability to enable portable, in-process measurement during component machining for process control and assurance of surface topography.

It has been experimentally demonstrated that a common-path LCI system could be used for in-air and in-water based measurements of surface profile and surface texture. The advantages of a common-path LCI system are clear in that, it is unaffected by environmental factors, it is fibre deployable with a bare fibre output leading to a small probe footprint, making it attractive as a low-cost sensor system.

Initial work has demonstrated measurements of step heights on idealised reference slip gauges (8.5 μm) with in-air and in-water measurement results being 8.61 μm and 9.93 μm respectively, with differences currently being attributed to dispersion characteristics of the two media. In addition, preliminary work has demonstrated the potential for measuring engineering textured surfaces, but it is now found that the signal-to-noise range is more challenging as a function of surface scattering effects especially when measuring in water.

Further work will involve investigating the relationship between varying surface texture components and signal quality in various mediums, data processing, optimisation mechanics with the view to uniquely enabling real time manufacturing control as a function of surface texture.

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