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Carrier fringe analysis algorithms for three degree of freedom optical probing

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ABSTRACT

In this work, we present a fiber-delivered and fiber-detected, 3-DOF optical probe concept for measuring optical components to be used in conjunction with an optical coordinate measuring machine (OCMM). The optical probe uses a Michelson interferometer to produce carrier fringes and a high density fiber bundle to transmit interferograms that are recorded away from the probe head in a remote imaging system. We compare several different signal FFT processing techniques (parabolic interpolation, windowing, and zero padding) and a single-bin DFT technique to compute and enhance the resolution of the displacement, tip, and tilt of a moving mirror. We simulated varying signal-to-noise ratios and interference fringe contrast ranges to determine the algorithms' sensitivity to those parameters and compare our simulated values to measured SNR and fringe values. Based on this work, it should be possible to use a carrier fringe algorithm for fiber probing applications if the interferogram can be transmitted through the fiber bundle with sufficient contrast (40%) and SNR (30 dB).

1. Background and motivation

Freeform and conformal optical components are rapidly becoming more pervasive in semiconductor, defense, space, and consumer electronics applications [1]. Three critical aspects are needed for manufacturing freeform optics: (1) optical design software to specify tolerances with freeform optics, (2) manufacturing processes that can accommodate freeform surfaces, *e.g.*, magnetorheological finishing (MRF) [2] and UltraForm Finishing (UFF) [3], and (3) accurate metrology for quality control to ensure specifications are met or error maps for iterative manufacturing. In this work, we are addressing the third aspect by focusing on metrology tools for qualifying freeform optics, specifically an optical probe to be used in conjunction with a 5-axis optical coordinate measuring machine (OCMM).

Presently, many full aperture metrology systems lack the ability to measure steep deviations from spherical, cylindrical, or plano surfaces due to irresolvable fringes in the recorded interferogram [4]. Recently, a round robin comparison has been conducted to measure the surface figure and thickness of a toroid that used a variety of commercial and custom solutions [5]. Contact and non-contact probing of the toroid showed good agreement over the full figure and mid-spatial frequencies, while sub-aperture stitching interferometry showed good agreement for high spatial frequency content. One of the reasons for poor high spatial frequency metrology with the probing techniques is undersampling on the part. Thus, contact probing with a conventional coordinate measuring machine or non-contact optical probing with a 5-axis optical coordinate measuring machine [6,7] is one possible solution for high accuracy metrology. In this work, we are focused on optical probing because contacting the part can lead to local deformations.

Optical coordinate measuring machines have three main limitations: inaccuracies in the global positioning, insufficient resolution and local slope knowledge in the optical probe, and limited bandwidths that increase measurement times or cause undersampling in the spatial domain. OCMMs can incorporate air bearing axes/stages, high-resolution positioning encoders, massive granite blocks, as well as vibration isolators to minimize error in the global positioning by creating a more stable metrology frame with smooth axes/stage motions and accurate positioning sensitivity [6,7]. Additionally, uncertainty characterization can be applied to the OCMM by measuring a certified master part to error-map the metrology system positioning motions [6]. It is important to maintain the stand-off distance of the optical probe to the part surface for accurate metrology, minimizing relative motions between the two

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inducing drift in the measurement. The purpose of this work, however, is to address the latter two issues: insufficient resolution and local slope knowledge in the optical probe, and limited bandwidth capabilities of current probe systems. There are wide varieties of potential probe concepts [8–13] that use different sensing properties to measure the optical surface.

One probe technology is based on scanning white light interferometry (SWLI) [14]. SWLI utilizes a broad spectral width light source with a short coherence length to achieve high contrast interference fringes only when the optical path lengths of the measurement and reference legs are closely matched. To generate the interference pattern, however, one arm in the interferometer must be continuously scanned, leading to limited measurement bandwidths and vibrations present from either the measurement or reference arm oscillating. Additionally, the height resolution can be limited by the mechanical step resolution for the arm oscillations.

A similar surface measurement technology to SWLI is confocal microscopy [15]. By adding confocal apertures after the light source and before the detector, stray and out-of-focus light is prevented from entering the detector while light from the focal point is free to enter. The resulting image is high resolution with a high SNR [16], however requires a longer illumination or multiple exposures averaged at the same point to collect enough photons to minimize noise [15]. Additionally, tilt between the part and probe can cause light to be lost in the aperture, thus a confocal probe must be nominally normal to the local part surface.

Chromatic confocal microscopy introduces an objective with longitudinal chromatic aberrations into the measurement system to create multiple focal positions at different wavelengths of light [16]. The detector from the confocal microscope is replaced by a spectrometer to measure the wavelength of reflected light to determine the height of the measurement surface. The range of heights capable of being measured is determined by the chromatic aberration of the lens as well as the spectrum of the source [16]. This removes the need for a vertical scanning mechanism, however, measurements are still susceptible to tilt between the part and probe.

In this work, we address two limitations with current optical probes: the need to be nominally normal to the part, and bandwidth limitations that increase measurement time or reduce spatial frequency content. The optical probing concept we propose is a simple Michelson configuration that uses carrier fringes in the interferogram to simultaneously measure part displacements and local slope in two dimensions based on work by Strube [17]. A pair of orthogonal, high speed line sensors replaces a traditional CCD or CMOS detector to provide high bandwidth, and local slope knowledge allows for blind contouring where only the nominal part shape is known. This will lead to increased measurement bandwidth and higher spatial sampling, while using the slope information to maintain normal to the part. In this manuscript, we present the probe design and discuss the limitations for fiber delivery and fiber detection through an optical fiber bundle. Fiber delivery and detection is critical for developing a compact probe that has no local heat sources to affect the measurement accuracy. We detail the carrier fringe algorithms used to determine the local slope and displacement and model the effects of fringe contrast and signal-to-noise ratio (SNR). Additionally, we present SNR and fringe contrast data from measurements using an available fiber bundle to determine if the needed SNR and fringe contrast is achievable in practice.

2. Probe concept

The probe design is based around the operating principles of a Michelson interferometer as shown in Fig. 1(a) [17–19]. Light from a fiber delivered laser diode is collimated and is split equally at a

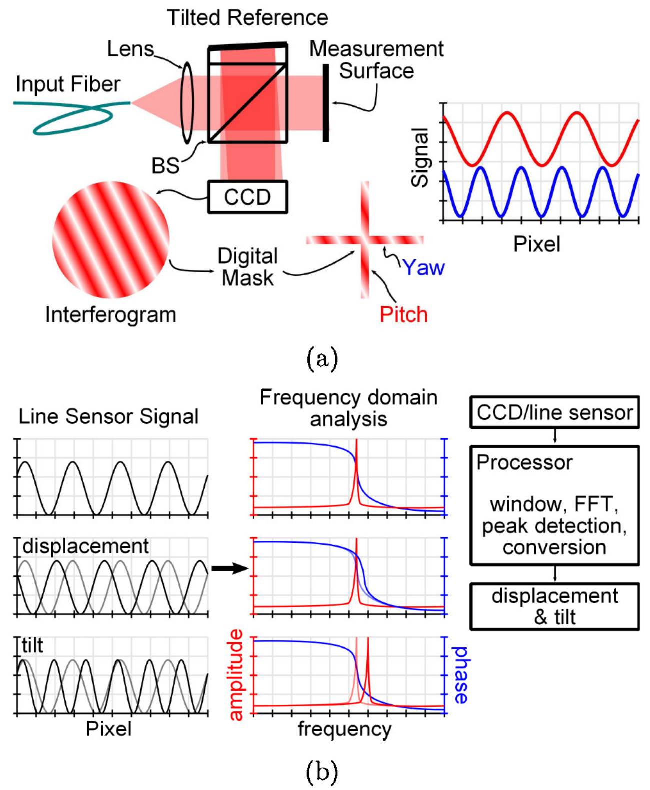

Fig. 1. (a) Schematic for measuring displacement, pitch, and yaw using a simple Michelson interferometer, CCD, and digital mask. The tilt fringes on the CCD are masked to create two line samples with a sinusoidal shape and are process using carrier fringe techniques. (b) Carrier fringe concept diagram using the Fast Fourier Transform. Changes in displacement lead to phase changes, while changes in angle lead to changes in the peak location in the Fourier Domain. Additional algorithms can be used to better determine the peak location.

50:50 beamsplitter (BS) with one beam traveling to a measurement surface while the second beam reflects from a fixed reference surface. Interference is created when the two beams recombine at the BS and is detected visually as a fringe pattern. The amount of fringes will vary dependent upon the relative tilt of the measurement and reference surfaces, and any other higher order aberrations present. A line sensor can be used to scan across the interferogram, which is then analyzed in the Fourier domain to determine the peak amplitude, nominal frequency of the fringes, and the phase, as shown in Fig. 1(b). If the slope of the measurement surface changes, then the frequency of the peak locations in the Fourier domain shifts while the phase remains constant at that location. If the distance to the measurement surface changes, however, then the relative phase of the signal will also change. This is also known as a ‘carrier fringe’ detection method [20].

There are three fundamental challenges of this particular probe: (1) minimize the overall size to increase the OCMM bandwidth, (2) accurately fiber-deliver and fiber-detect to remove unwanted heat sources from the area of the component to be measured, and (3) measure with a high bandwidth to limit thermal influence in the measurement of the component. While the optics required for this interferometer can be quite small, the detectors necessary are significantly larger and are a heat source. The focus of this initial research therefore is to investigate whether a carrier fringe analysis can be performed on an interferograms transmitted through a fiber bundle with high fidelity for this probe concept. The optical fiber bundle provides a flexible path for transmitting the interferogram from the moving OCMM to a stationary electronics box. However, because the fiber bundle will have a spatially varying noise distribution, the noise structure may prohibit the use of carrier fringes