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Multiwavelength Holography: Height Measurements Despite Axial Motion of Several Wavelengths During Exposure

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Abstract: In a typical interferometer, axial motion of half a wavelength reduces the contrast to zero. Our setup compensates this component of motion utilizing a piezoelectric actuator, demonstrating height measurements despite axial motion of 14 wavelengths.

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1. Introduction

Digital holography enables fast and highly precise 3D height measurements [1] even on moving objects. Previous work demonstrated the significance of the direction of motion: In case of motion perpendicular to the sensitivity vector, height measurements are possible even for object motions during exposure time exceeding one speckle diameter [2]. For axial motion - or, in the more general case, motion parallel to the sensitivity vector - interferometry is much more sensitive: motion of half of a wavelength reduces the contrast to zero [3]. Being able to measure objects moving in an arbitrary direction would open up a large field of applications, for instance gear metrology: Steep flanks require off-center measurement, with the optical axis of the measurement system aligned non-radially. If the gear is rotated during measurement, the velocity vector has a component in parallel to the sensitivity vector. In this work, we demonstrate that during continuous rotational motion and with known orientation of the setup with regard to the axis of rotation, a piezoelectric actuator can compensate this component, and height measurements can be performed.

2. Experimental Procedure

The experimental setup for measuring the rotating aluminum cylinder eccentrically with two-wavelength digital holography is shown in Fig. 1. Two fiber-coupled diode lasers emitting light at 632.65 and 634.53 nm (synthetic wavelength of 214 µm [4]) are used. The light of each laser is split by a fiber-based beam-splitter into object and reference beam. In the object beam path, a fiber-based beam-combiner merges the two object beams, so they illuminate the object from a common source point. Two cylindrical lenses collimate the illumination beam into a line. The light scattered by the cylinder passes the rectangular aperture and is guided by a lens onto the camera. The reference beams are tilted to the optical axis to achieve spatial phase shifting [5]. The mirror reflecting both reference beams onto the camera is mounted on a piezoelectric actuator, which adjusts the path length of the reference beam by applying a voltage signal. The camera records the superposition of the two incoherent superimposed holograms at the two slightly different wavelengths. As the cylinder is rotated with constant speed, the object path length is changed linearly over time, so the piezoelectric actuator is driven with a voltage ramp (see Fig. 1 bottom right). To reduce the effects stemming from the hysteresis of the actuator, the ramp starts 0.5 ms before camera exposure. The cylinder (R = 46.2 mm, see Fig. 2 a)) is rotated with 1.5 °/s, which equals a circumferential speed of 1.2 mm/s. The exposure time is set to 30 ms. The rotation axis is parallel to the *y*-direction. The optical axis of the setup is shifted by a_{ax} = 12 mm to the axis of rotation, so the cylinder is moved 9 µm in

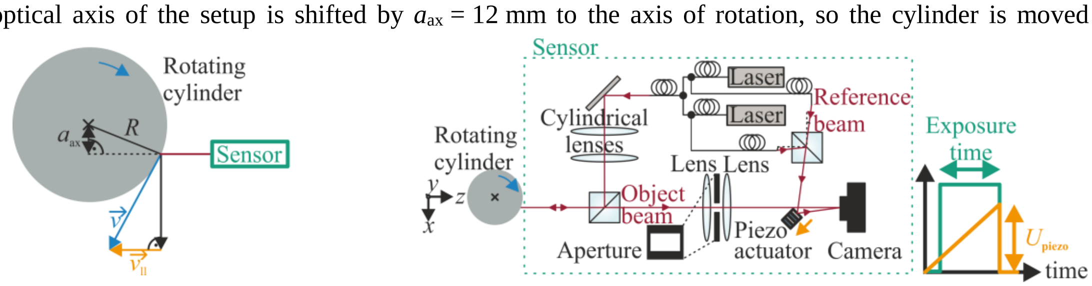

Fig. 1: Left: Sketch of eccentric measurement arrangement: The off-center distance a_{ax} between the axis of rotation and the optical axis is non-zero, so that there is a velocity component $v_{||}$ parallel to the optical axis. Right: Two-wavelength holographic setup using spatial phase shifting: The piezoelectric actuator in the reference beam compensates the velocity component $v_{||}$. Therefore, a voltage ramp is applied to the actuator as depicted on the bottom right.

parallel to the sensitivity vector during exposure time. At this speed, measurements are not possible without the piezoelectric actuator and just phase noise would be measured if the compensation is not active. The optimal slope of the voltage ramp applied to the piezoelectric actuator is found by maximizing the interference contrast of the single holograms.

The single camera frames (5120 px × 512 px, 10 bit) are processed individually as in [2]: The raw image is Fourier transformed, for each of the two wavelengths one side band is cropped out and shifted to the center. The inverse Fourier transform of each cropped region results in the phase information of one wavelength. The phase difference for the two single wavelengths equals the phase of the synthetic wavelength.

Out of all frames, the mean curvature of the cylinder is calculated and subtracted from each single frame. The single slices are then stitched together according to the frame rate and the speed of rotation in order to get the unwound cylinder surface. Consecutive images are laterally overlapping each other and are thus pixel-wise averaged to increase the measurement accuracy. The deviation to the nominal shape is calculated by subtracting the best-fit cylinder of the whole shell surface.

3. Results

The deviation to the nominal shape ΔR of the eccentrically measured cylinder is presented in Fig. 2 a), a zoom is shown in (b). Evaluating five measurements leads to the map of the pixel-wise standard deviation in c). These results show that it is possible to measure defects of the cylinder eccentrically that are as small as some µm with a mean reproducibility of σ_z = 2.1 µm despite of a circumferential speed of 1.2 mm/s and an axial movement of 9 µm (14 single wavelengths) during exposure time. Furthermore, the reproducibility data demonstrates a good synchronization of camera, piezoelectric actuator and motor.

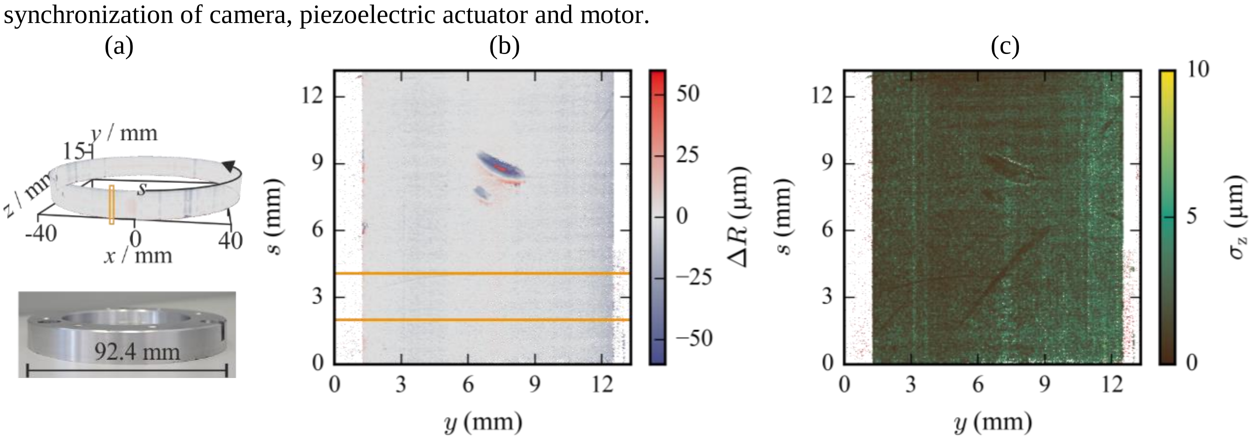

Fig. 2 a) Deviation ΔR from the nominal shape of the cylinder measured at a rotation speed of 1.5 °/s, the orange rectangle indicates the measurement spot of the setup and a photograph of the aluminum test cylinder. b) zoom of a), the orange rectangle indicates the size of one single frame, c) Map of pixel-wise standard deviation calculated out of 5 measurements.

4. Conclusion and Outlook

We demonstrated that height measurements on moving objects with an axial motion component are possible by compensating the axial motion by a piezoelectric actuator. The dependences on rotational speed, object radius and measurement position will be investigated in future studies.

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