Multiwavelength digital holography in the presence of vibrations: laterally resolved multi-step phase-shift extraction

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Abstract: With the application of multiwavelength digital holography in rough environments such as machine tools, we cannot rely on the complete absence of vibrations. The evaluation of temporal phase-shifting in sections allows to determine and take into account random sub-wavelength tilt of the sensor with respect to a work piece. In this regard, measurements inside a machine tool are evaluated and discussed.

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1. Introduction
The demands placed on machine tools are constantly increasing and can often not be reliably met by modern machining centers – measuring each individual part has become inevitable [1]. Our sensor HoloCut measures topography using digital holography. It measures directly in the machine tool and resolves even short-wave irregularities of freshly machined parts [2]. Multiwavelength digital holography is an established technology for nondestructive testing in industrial applications [3]. However, as an interferometric measurement principle, digital holography is very sensitive to vibrations [4]. In order to compensate imperfect phase shifts in temporal phase-shifting, Cai et al. introduced a generalized approach of phase shift extraction for unknown phase shifts [5]. However, a single phase difference is assumed for the entire interferogram. In this paper, this algorithm is extended to evaluate multiple interferogram sections. A laterally resolved phase shift map is calculated and not only used to assess the quality of each single measurement, but also applied for improved hologram reconstruction.

2. Experimental Procedure

Fig. 1. Left: HoloCut optical design with two-dimensional beam arrangement, for center of gravity mount using temporal phase shifting induced by a piezo actuator – mirrors are not labeled. Right: Schematic integration of HoloCut measuring a work-piece inside a Hermle C32U 5-axis machine tool with critical axial movement visualized by orange arrow.

The experimental setup for digital holographic measurements inside a machine tool is shown in Fig. 1. For a detailed description of the sensor head, see [2]. A laser system, consisting of multiple fiber-coupled grating-stabilized diode lasers, guided to a fiber switch, sequentially couples single lasers to the sensor. Temporal phase-shifting is applied by a piezo actuator in open-loop mode: For each wavelength, three interferograms are recorded with phase shifts of approximately $2\pi/3$. In addition, a combination of lateral [4] and critical axial oscillations (orange arrow in Figure 1 right) due to the closed-loop position controller of the machine tool superimposes the phase shift introduced by the piezo. Cai et al. describes calculation of global phase shift between single interferograms using the mean modulation between images [5]. With our approach, this calculation is applied to multiple sections of each interferogram. The resulting laterally resolved phase shift maps yield information of the rigid body movement between sensor and object.
Up to a certain relative deviation, this movement can be compensated by a plane fit and enables pixel-correct phase shift reconstruction. Height information is extracted after calculation of the synthetic wavefronts [2].

3. Results

![Phase shift maps](image)

Fig. 2. Phase shift map for single phase shift at $4\pi/3$. Left: Coin measurement with smooth phase map without any artifacts. Right: Coin measurement with irregular phase map and strong artifacts.

Fig. 2 shows two coin measurements, recorded inside a Hermle C32U machine tool. 25 regions of interests (ROIs) were evaluated and used to fit a plane for pixel-perfect phase reconstruction. The left measurement was taken with disabled, the right measurement with enabled spindle control. For the latter, the height map is marked by strong artifacts. The underlying 3D plots show a laterally resolved phase shift map of the second phase shift at $4\pi/3$ – other phase shifts show a similar behavior within the respective measurement. A high standard deviation of individual phase shifts around the plane fit can be observed and prevents us from reconstructing this measurement correctly. This deviation is a good measure for existing vibrations during measurements. On the left, phase shifts are distributed very narrowly around the plane fit resulting in a smooth height map without any artifacts. Cai et al.’s $c$ value yields information about the modulation of the interferograms. It is normalized and inversely used as weight for the fit.

4. Conclusion and Outlook

We demonstrated that holographic height measurements are possible even in rough environments such as machine tools. Occurring vibrations can be detected and considered using a laterally resolved phase-shifting approach. This method for detection of phase shift errors occurs early in data processing: An interferogram stack can be discarded (and re-recorded) before numerical propagation, combination of multiple wavelengths and subsequent filtering take place. The limits of vibration compensation under the influence of vibrations will be further investigated in the future.

References


