Application of the Moiré-effect in digital holography

Andreas Walter Stark, Daniel Weigel, Holger Babovsky, Armin Kiessling, Richard Kowarschik

Institute of Applied Optics, Friedrich Schiller University of Jena
Abbe Center of Photonics

andreas.stark@uni-jena.de

In this paper we present a technique to reconstruct object information from free space digital holograms with the application of the Moiré-effect leading to an increase in the resolvable angle by a factor of 2 compared to phase shifting methods. To do so the spatial frequencies causing the Moiré-structures are repositioned in their proper position and this way increase the image quality.

1 Introduction

Holography [1] gives the opportunity to reconstruct amplitude as well as phase information of an optical wave field. The numerical access to the data allows meanwhile a plentitude of applications [2]. In this paper we want to focus on a special problem: the limited resolution of the sensor. The pixel pitch of the detector determines in free space holography the resolvable angle, under which an object can be recorded. If the maximum angle is exceeded the holographic structure is under sampled and Moiré-structures (Moirés) occur. This problem can be solved by shifting the sensor under the holographic pattern and taking multiply records [3] or, as we propose, by moving the holographic structure by phase shifting the reference beam.

2 Concept

Since Moirés are known for reducing image quality in the first place, it is an important fact that they contain real object information. This object information is displaced in the spatial frequency domain due to the Whittaker-Shannon sampling theorem. To shift the frequencies back to their proper position they have to be distinguished from the already correctly placed information. Therefore a phase shifting method can be applied. By taking for example 3 digital holograms differing only by a phase shift in the reference beam by 120°, the resolvable angle in free space holography can be doubled compared to a single digital hologram. In principle also other methods are possible to reduce the number of necessary phase shifting steps [4].

One has to take into consideration that the modulation transfer function (MTF) of the CCD has a sinc-shape in the one dimensional case as seen in Eq. 1 and Fig. 1.

$$MTF(f) = T\left|\frac{\sin(0.5\pi fDT)}{0.5\pi fDT}\right| = T\left|\mathrm{sinc}(0.5\pi f DT)\right| \quad (1)$$

f is a normalized spatial frequency to be observed by the detector, T the fill factor and D the length of the light sensitive part of each pixel.

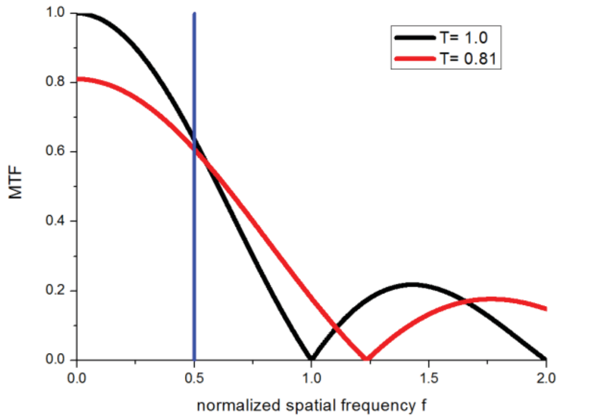

Fig. 1 *MTF of an electronic sensor for different fill factors, the blue line represents the resolution limit by the Whittaker-Shannon theorem*

3 Experimental Setup

In a first step we implemented the off-axis setup shown in Fig. 2 to make use of the Moiré-effect.

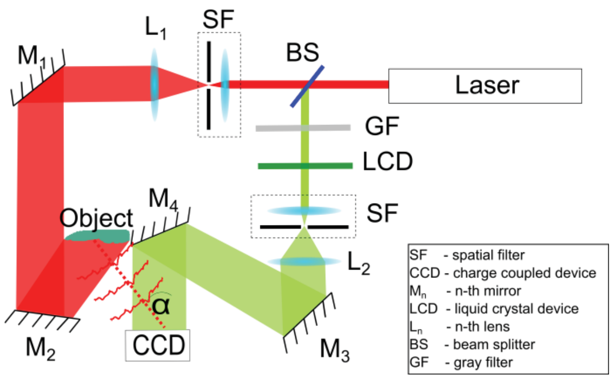

Fig. 2 *Digital holographic off-axis setup; red beam (after BS): object beam, green beam: reference beam*

The beam of a helium-neon laser was divided by a beam splitter in a reference beam and an object beam. The reference beam was intensity adjusted by a gray filter, phase shifted by a LCD and then collimated and reflected on to the recording plane. The object beam was collimated and projected on

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the object. The interference pattern created by the scattered light and the reference beam was recorded in the plane of the CCD (AVT Marlin, pixel pitch: 4.65 µm) under the doubled classical maximum angle. In a second step we varied the setup to an in-line setup with an even larger object. To make sure that the object information came only from a known area, the object was illuminated partially.

4 Results

At first an object was recorded under the doubled classical maximum angle. Hence the reconstruction suffered from the overlapping of object structures and Moirés, in this case the twin image as seen in Fig. 3 (a), a phase shifting method was applied to distinguish the twin image from the interesting object information. The result is shown in Fig. 3 (b).

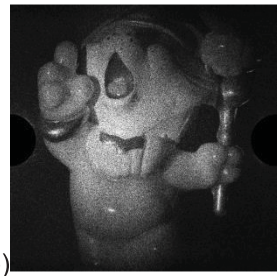
(a)  (b) 

Fig. 3 *Comparison of Moiré affected reconstruction (a) and a Moiré unaffected reconstruction with phase shifting (b); object seen under an angle of 3.9°*

As clearly visible in Fig. 3 (a) and (b) the contrast of the reconstruction and the amount of details was increased.

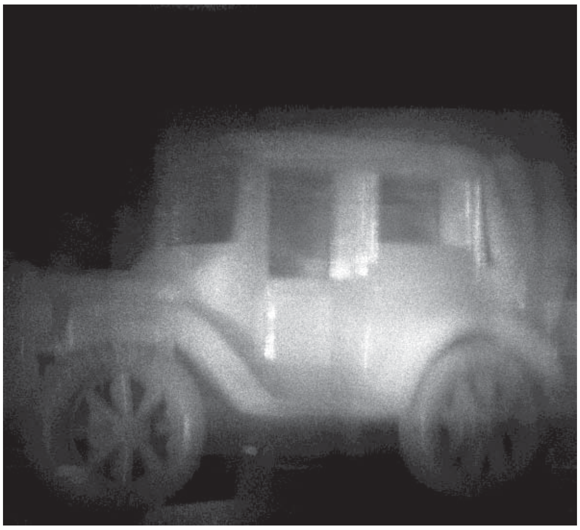


Fig. 4 *Reconstruction of a digital hologram of an object taken under doubled resolvable angle in vertical as well as in horizontal direction*

In a second step another object was illuminated under the doubled angle (7.8°). It was not possible to reconstruct the information by applying a three-step phase shifting method. Therefore only parts of the object have been illuminated while applying a phase shift. This way not only three holograms had to be recorded, but 15 since 5 different parts of the object have been illuminated.

Fig. 4 shows the reconstruction of the hologram resulting from this process. The resolvable angle has been increased to 7.8°, the doubled maximum angle. On the boundary the intensity seems to decrease. This happens due to the shape of the MTF of the sensor element. The reconstruction can be processed to reduce this error but the image noise is going to be increased.

5 Conclusion

We were able to show that the Moirés caused by under sampling of the holographic structure can be used to retrieve real object information. As a conclusion the maximum resolvable angle can be doubled, compared to phase shifting digital holographic methods (see Tab. 1).

Method	Number of used holograms	Resolvable angle
Class. dig. holo.	1	1.95°
Phase shift dig. holo.	3	3.9°
Moiré-technique	12-15	7.8°

Tab. 1 *Comparison of different digital holographic methods*

On the downside the number of necessary digital holograms is increased. This process is further limited by the MTF of the sensor element, since the SNR might drop too much, so that no object information can be reconstructed. Applications of the presented method could be found in digital shape measurement and holographic microscopy.

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