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Full field deformation measurement of centimeter sized objects using optical phase retrieval

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ABSTRACT

Most papers in the field of optical phase retrieval either consider only the intensity (or amplitude) profile of the object under inspection (or scatterer location in the X-ray version), or a uniform tilt/rotation of the object beam. However, phase retrieval is able to recover the phase profile of the object (beam) as well, which theoretically makes the observable interference of phase retrieved object waves possible. In this paper we demonstrate this principle experimentally on centimeter sized deformable reflective objects (as large as 40 mm by 40 mm) and corresponding simulations are also presented. When the CCD camera is moved along the optical axis in the Fresnel region, the interference fringes of the displacement field have low contrast. On the other hand, when an imaging setup is built, and the camera moves near the image plane, high fringe contrast can be obtained. These fringes however suffer from some phase error. In our work the iterative modulus projection algorithm was used as a simply implementable phase retrieval method.

1. Introduction

With the appearance of high resolution digital cameras, spatial light modulators and powerful desktop computers digital holography became a well established experimental and measurement tool in optical non-destructive testing [1–3]. The holographic principle, which encodes the phase of a beam into intensity modulation, opens many ways of digital wave manipulation techniques to improve interferometric applications, such as direct phase difference calculation instead of phase stepped intensity fringe processing, comparative measurement of two real objects [4], comparison with an ideal simulated object [5], or tilt compensation in shape measurement. The cost of a holographic optical setup is however the vibration free environment needed within an interferometric precision range.

Another possibility of obtaining the phase of an optical beam using a digital camera is to record multiple intensity patterns of the same beam. These intensities can be Fourier pairs, Fresnel pairs, which require a lens in the optical setup, or a sequence of intensities within a limited range of motion along the main propagation direction of the beam. Processing these recordings in the computer one can estimate the corresponding phase of the beam numerically [6,7]. The physical picture behind these calculations is clear: the same intensity pattern with two different phase patterns results in different intensity patterns at a distant location due to wave propagation, while intensity and phase together, or better said the complex amplitude is what propagates.

Once the phase of the beam is known, it can be propagated using numerical diffraction formulas in the computer and focusing may occur, which will tell the location of point sources ("bright pixels"), e.g., the object amplitude or intensity profile can be reconstructed. Another application is tilt or direct angle measurement of plane or spherical beams, which is sometimes called as wavefront sensing [8], and the setup usually contains a small iris.

For the estimation of the beam phase several algorithms are known in the literature. In most cases an iterative approach is used due to their relatively simple implementation. When only two constraints (image plane and Fourier plane intensity measurements) are used, more sophisticated combinations of them are also known, such as the hybrid input–output (HIO) algorithm [9], or the relaxed averaged alternating reflections (RAAR) algorithm [10]. The constraints or projection can also vary: a relaxation parameter can be introduced, and noisy or saturated pixels can be omitted. A direct solution to phase retrieval is also known when two axially displaced intensity patterns and thus the corresponding first derivative is known [11].

The aim of this paper is to demonstrate another possible use of phase retrieval. Interferometric fringes of a centimeter sized diffuse object are produced from two sequences of intensity recordings made before and after the surface of the object is deformed/displaced due to an applied load. Simulation and experimental results are presented, and the optical setup and its parameters are discussed.

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2. Overview and details of the optical setup

Imagine the simple optical setups in Fig. 1. An expanded and collimated beam is illuminating the object having a matte white paint surface, and the scattered objective speckle field is recorded in multiple (10–20) positions of the camera along the optical axis. After the phase retrieval calculation the objective speckles will also have a corresponding phase, and by applying a discrete Fresnel transform the obtained complex amplitude can be back propagated into the object plane, and an image of the original object will be seen. Now thinking of continuous signals, if the phase of the optical wave is known somewhere far away from the sources (the object surface), it is also known in the object/image plane by some extent. Considering also the aperture effect of the finite sized CCD camera, the phase in this plane must have a general curvature due to this aperture, and a superimposed random phase which can be related to the object surface itself. Displaying this phase distribution as a wrapped grayscale image will not show any information useful for the human eye or an image processing algorithm. Having geometrical parameters typical in digital holography, when the object size is several centimeters, the sampling distance (pixel size) in the object plane will be several tens of micrometers due to the discrete Fresnel transformation, which means that the optical wave itself is not really resolved, i.e., the output of the Fresnel transform cannot be further propagated.

But the same conditions hold for digital holography as well, yet interferometry is possible there, if the diffraction orders of the digital hologram are separated in the reconstruction plane due to the non-in-line (but small angle) arrangement. If one records a set of intensity patterns in an initial state of the object and another set after a load is applied, and the object is deformed (surface elements are displaced), the two sets can be the input of a phase retrieval calculation, and the two output complex amplitudes in one of the camera planes will be the intermediate result. These two phase retrieved waves (complex wavefields) added or subtracted, i.e., their interference field can be propagated back to the object plane, and there an interferometric fringe system will appear. (Of course the addition or subtraction of the waves can be performed in the object plane as well, but since the Fresnel transform/free space propagation is linear, the previous method is advantageous.) Considering the subtraction of the two resulting waves, the general wavefront curvature due to the aperture effect of the CCD will be canceled, and only the object related phases and their difference will influence the final fringe system.

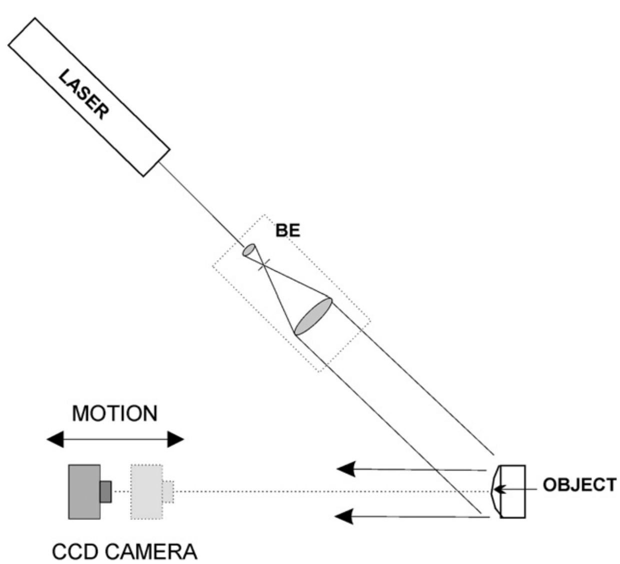

Fig. 1. Optical setup of the non-imaging (lensless) case of phase retrieval (BE = beam expander).

The interpretation of the fringes will be the same, as in holographic interferometry. The illumination and the observation directions define a sensitivity vector, and according to other known arrangements out-of-plane, in-plane displacement fields, or also shape could be measured [12]. The main question regarding fringe patterns generated this way is that how perfect phase retrieval is, when not only the amplitude of the object is important (location and strength of the point sources), but (relative) phase as well. The effectiveness of phase retrieval naturally depends not only on the applied method but also on the input intensity patterns. If the measurement aims several centimeter sized objects, and a naked CCD camera is used, many experimental limiting factors will restrict our possibilities.

Given a CCD pixel size of approximately 5 μm, the minimum object-to-camera distance should be much larger than the object size—typically more than 50 cm—to fulfill the sampling condition. The required mechanical tolerance of the motion stage in the direction perpendicular to the motion should be negligible, i.e., smaller than the pixel size. This limits the range of the motion itself pretty much: in our experiments this was within 5 cm. To avoid stagnation during the iterative phase retrieval in the setup in Fig. 1, more than two recordings are needed. The more the input patterns available, the better the results expected, but the runtime of the iteration is increasing, so recording more than 20 images is not practical. The stepping distance of the motion stage also has an ideal value. If it is too small, successive recordings show almost the same objective speckle pattern; thus, the change in the information content of the patterns is small. At least half the longitudinal size of the objective speckles is advised, or a distance close to the entire size. If the steps of motion are too large, we may not be able to record enough patterns within the available range of motion.

One important measure of the setup is the ratio of the motion range to the minimum object-to-camera distance. If this ratio is higher, much more is seen from the "propagation" of the beam, and phase retrieval will be more accurate. Considering this principle an ideal setup would be where the camera starts directly next to the object, or even if the camera would move around the object symmetrically, intersecting it in the middle of the motion range. Naturally, in these cases one of the recording planes would coincide with many or all of the point sources of the beam, so their location would be known exactly, but there will be even more information available, while a corresponding phase will be retrieved using all the other recordings. As a conclusion, having such a "near-field" arrangement a really good result may be expected, or thinking of the interferometric measurement we are aiming, the visibility or contrast of the final fringe system will be high.

In fact, such experimental setups are impossible to make, but it is possible to model it in a computer. Another experimental option is to image the object using a lens, as shown in Fig. 2, and to move the camera near the image plane. Recording defocused images and possibly one focused image is already known in the literature to reconstruct an object [13], but to our knowledge this method was not used to laser illuminated diffusely scattering objects. The obvious advantage of the imaging setup is that the image formed by the lens can be considered a secondary object, which is of course band limited according to the F# of the lens, but if the magnification of the imaging geometry is set properly, the object is will be sampled at many points. In this picture we may say that the camera scans the "near field" of this secondary object, and the location of the secondary point sources will be known precisely, and hopefully also their phases. Another advantage is that the original size of the object is no longer a matter, but the size of its image is what counts. As the speckle field behind the lens is subjective, to fulfill the sampling criterion the F# is typically set to 11 or 16. Both the lensless and the imaging setup has a limiting aperture, the CCD detector and the lens aperture correspondingly; thus, for a given amount of load on the object the correlation of the speckle fields passing the apertures and the highest value of the final fringe contrast will be limited. As the presented optical setups are similar to those of digital holography and speckle interferometry