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Quasi-common path three-wavelength holographic interferometer based on Wollaston prisms

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ABSTRACT

This article presents a digital three-wavelength holographic interferometer based on the use of two Wollaston prisms. This provides an in-line setup with quasi common-path and as a consequence there is no additional independent reference wave to be added. Thus, immunity to external perturbations such as vibrations or thermal perturbations is achieved. Furthermore, the set-up exhibits a single shot and real time capability which is very useful to study dynamic events. By using the two Wollaston prisms in an astigmatic configuration, spatial carrier frequencies can be adjusted both in amplitude and orientation. The digital hologram processing is based on Fourier processing and filtering around the carrier spatial frequency so that phase shifting is not required. The use of three wavelengths leads to visualizing directly the zero order fringe and regions for which there is no air density variation in a dynamic flow. Experimental proof of concept is demonstrated with a supersonic jet when the injection pressure varies.

1. Introduction

In the past decade, phase imaging has developed at an accelerating pace and impacted a wide range of domains, such as microscopy (also known as quantitative phase imaging or interferometric phase microscopy) [1–15], fluid mechanics [16–18], or photomechanics [19–23]. Phase imaging measures the optical path length map associated with transparent specimens (transmission illumination) or opaque surfaces (reflection illumination) and translates this data into relevant information. In such a way, biomedical imaging [7,8,10,11], topology at nanoscale [9,19], flows and vortices [16,17], material properties [19], surface shape [20], polarization imaging [21], displacement field [22,23], vibrations [24–27], particles tracking [28–31], measurement of temperatures or thermal exchanges in flames [32,33] were investigated. Off-axis methods provide the fastest acquisition rates, because the phase information is extracted from a single recorded hologram. As a general rule, phase extraction from in-line holograms is performed with phase-shifting [34]. In off-axis digital holography, the reference wave is shaped to provide a spatial separation in the reconstruction plane or in the Fourier plane of the hologram (slight tilt) [1,16,35,36]. Tilting the object and reference waves (i.e. adding a spatial carrier frequency to the hologram) can be performed according many different ways: tilting one mirror in a Michelson [1,10,16] or a Mach-Zehnder interferometer [19,24], using a Lloyd mirror [4], or using a diffraction grating associated to a spatial filtering [5,7,9]. A Michelson set-up is quite easy to implement and to experimentally adjust. In that case, the transparent object is crossed twice by the probe beam. Thus, the measurement sensitivity is two times that of a Mach-Zehnder and that can be very advantageous for weak phase changes. However, if the object exhibits high density gradients, a shadow effect may be superimposed on the hologram fringes, thus reducing their visibility. As a common feature, in a Michelson and a Mach-Zehnder set-up, the optical paths are quite different. When using a diffraction gating, the optical paths are quasi-common, but the filtering induces losses which reduce the light efficiency of the set-up. Note that the use of an independent reference wave induces sensitivity to external perturbations such as vibrations, temperature changes, etc., and leads to an increase in the set-up complexity. So as to get a reference wave removed or quite commons optical paths, the pure in-line configuration is well adapted [15,30], but the faculty for a direct phase contrast recovering has to be developed.

The use of multiple wavelengths in digital holography was initially proposed by Yamaguchi [37,38]. At the same time, Demoli presented the first study on fluids using digital color Fourier holography using a monochrome sensor with a sequential recording of three laser wavelengths. Qualitative results were obtained to

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visualize convective flows induced by the thermal dissipation in a tank filled with oil [39]. Quantitative results were obtained to analyze the variations in the refractive index induced by a candle flame [16] and for the gas density on a subsonic near wake flow downstream a circular cylinder [18]. The use of three different wavelengths is a powerful approach to determine the absolute zero order in the field of view. The absolute zero order is found by observing the synthesized color fringes whereas it cannot be found by considering the calculated unwrapped phase data. Indeed, each unwrapped phase map is obtained with an unknown value multiple of 2π. However, it can be found by considering the wrapped phase: the zero order fringe is that for which all the three wrapped phase values are identically null [16]. Since then, an increasing number of important applications have relied on the possibilities of using digital color holography to record and reconstruct colored objects at high precisions using a simple optical setup [40–56].

Thus, this article presents a digital three-wavelength holographic interferometer based on the use of two Wollaston prisms that aims at overcoming the major drawbacks of the previous techniques. The proposed set-up is based on a "Z" architecture and the use of two Wollaston prisms. This provides an in-line setup with quasi common-path and as a consequence there is no additional independent reference wave to be added and no losses in the light transmission. Thus, immunity to external perturbations such as vibrations or thermal perturbations is achieved. Furthermore, the set-up exhibits a single shot and real time capability that is quite useful to investigate high speed transient flows. The article is organized as follows: section 2 establishes the basic principle of the optical set-up and section 3 describes the digital hologram processing. In section 4, experimental results are provided and section 5 draws conclusions to this study.

2. Basic principle

2.1. Optical set-up

The optical set-up is described in Fig. 1 and is based on a "Z" configuration. The light source is constituted of three different DPSS lasers (660 nm, 532 nm and 457 nm). The beams are spatially filtered with a microscope objective associated to a micrometric pinhole. Then, the beams are extended and focused in the first large field Wollaston prism (8° angle). A linear polarizer is used to adjust the input polarization. The prism is localized at the focal point of a spherical mirror. The two beams emerging from the first Wollaston prism are orthogonally polarized. After reflection by the spherical mirror, the beams are parallel and one half of the expanded beam crosses the test section whereas the other one constitutes the reference beam. This configuration provides immunity to external perturbations such as vibrations or thermal perturbations. In addition, the "Z" configuration leads to a quite common-path holographic interferometer, having the capability of fully transmitting the light issued from the source to the sensor. After reflection on the second spherical mirror, the beams are focalized in the second first large field Wollaston prism. This second prism is mounted "upside down" with the first one. An analyzer is then placed behind the second prism in order to produce interferences between the orthogonally polarized beams. A lens localized in front of the camera creates the image of the test section at/or nearby the recording plane. The sensor is based on a 3CCD cooled digital color camera equipped with three CCD chips, including 1344×1024 pixels sized $6.45\ \mu m \times 6.45\ \mu m$. The colors are separated using a dichroic prism.

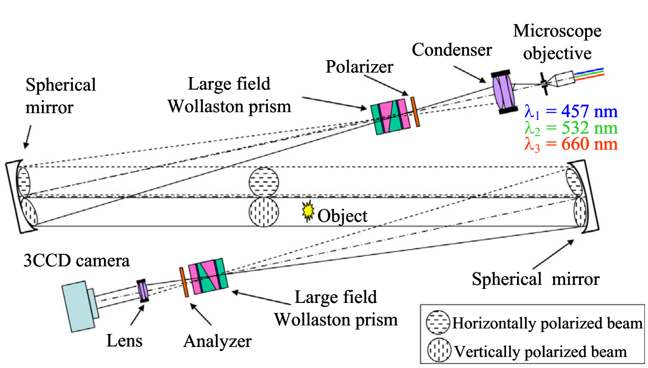

Fig. 1. Optical set-up with two Wollaston prisms in "Z" configuration.

2.2. Characteristics of the Wollaston prism

Large field Wollaston prisms which strongly separate the two interfering beams were designed. This means that each prism has to generate a distance between the two interfering beams that is greater than the dimension of the field of view to be measured. The hologram is constituted with two beams: the first one does not pass through the phenomenon (reference beam) and the second one crosses the phenomenon under interest (see Fig. 1). For a spherical mirror with diameter $D=250$ mm, a curvature radius $R=2.5$ m, the distance dx between the two interfering beams should be about 125 mm. If n_e and n_o are respectively the extraordinary and ordinary refractive index, $\Delta n=n_e-n_o$ is the crystal birefringence, α is the bonding angle of prism, then the birefringence angle ε is given by:

$$\epsilon=2.\Delta n.tan(\alpha) \tag{1}$$

and dx can be expressed according to the following relationship:

$$dx=\epsilon.R=2.R.\Delta n.\ \tan(\alpha) \tag{2}$$

By choosing calcite as material, the bonding angle is found to be:

$$\alpha=tan^{-1}\left(\frac{dx}{2.R.\Delta n}\right)=8^{\circ}27 \tag{3}$$

2.3. Astigmatic properties of the optical set-up

The "Z" optical path generates astigmatism because the two spherical mirrors work in an off-axis configuration. The first prism is located at the focal point of the first spherical mirror, so that the two optical rays which are reflected onto the second spherical mirror may be parallel. The second spherical mirror refocuses the light into the second Wollaston prism. Note that due to astigmatism in the set-up, the second focusing point in the front of the sensor is not unique. Fig. 2 illustrates how the optical beams are focused on the two small focal lines separated by a few millimeters along the optical axis. The first focal line is due to the focusing beam in the horizontal plane (tangential image), and the second one is the sagittal image, and it is due to beams focusing in the vertical plane. This particularity of the set-up leads to straight and parallel interference fringes in the field of view, i.e. the set-up includes in an automatic manner a set of spatial carrier frequencies. Fig. 3 illustrates this particular feature. Interference fringes are shown in Fig. 3, according, both to the position of the prism

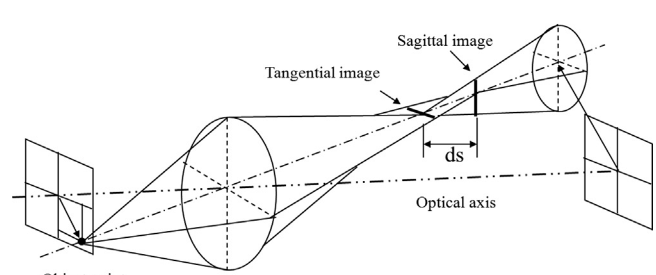

Fig. 2. Astigmatism represented by sectional views.