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Aberration compensation of holographic particle images using digital holographic microscopy

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Characterisation of small and large-scale vortices in turbulent flows demands a system with high spatial resolution. The measurement of high spatial resolution, three-dimensional vector displacements in fluid mechanics using holography, is usually hampered by aberration. Aberration poses some problems in particle image identification due to low fidelity of real image reconstruction. Phase mismatch between the recording and the reconstruction waves was identified as the main source of aberration in this study. This paper demonstrates how aberration compensation can be achieved by cross-correlating the complex amplitude of an aberrated reconstructed object with the phase conjugate of a known reference object in the plane of the hologram (frequency space). Results favourably show significant increase in Strehl ratio and suppression of background noise that are more pronounced for particle images of 10 and 5 microns. It is clear from the work conducted that wavefront aberration measurement and compensation of holographic microscopic objects are now possible with the use of a variant digital holographic microscope.

Keywords: aberration; digital holography; digital holographic microscopy; holographic microscope; compensation; holographic particle image velocimetry

1. Introduction

Swirls, tornados and cyclones are interesting examples of turbulent flows that exist in nature. Turbulence plays some important roles in many industrial applications particularly to increase rate of mixing and heat transfer, that in turn depend on the formation of vortices (eddies) which appear on many different length scales. Turbulent flows are highly complex and inherently three-dimensional. In order to characterise the physics which underpin various turbulent phenomena, it is important to resolve both large- and small-scale vortices. Of many optical diagnostic tools, holographic particle image velocimetry (HPIV) is a promising technique to probe into the flow structures since it is a truly whole-field, three-dimensional three-component (3D-3C) displacement and velocity measurements technique [1]. It works by seeding the flow with neutrally buoyant particles which are assumed to faithfully follow the flow. Upon interaction with coherent light, both amplitude and phase of the particles would be modulated and eventually recorded on to a holographic glass plate emulsion in the form of an interference pattern (or hologram). Interestingly, one is able to reconstruct the entire three-dimensional (3D) volumetric field of the recorded event by illuminating the hologram with a conjugate of the coherent light.

A number of developments pertaining to HPIV techniques have concerned off-axis holography. It offers reasonably high signal-to-noise ratio as compared to the in-line holography because there is no superposition between the image (signal) of interest with virtual image waves, the directly transmitted reconstruction wave and the autocorrelation term [2]. In addition to signal-to-noise ratio criterion, another important factor that influences characterisation of both small- and large-scale vortices is spatial resolution. The spatial resolution of any HPIV system is however, determined by particle number density, n_s. For particles uniformly distributed in a spherical volume, the mean distance between particles can be assumed as the smallest vortex size, η, such that [3]

$$\eta = \left(\frac{3}{4\pi n_s}\right)^{1/3} \tag{1}$$

For this reason, it is desirable to acquire high particle number density across the measurement volume since the former parameter influences the smallest resolvable vortex while the latter determines the largest measurable vortex. Experimentally, the achievable particle number density varies from several tens [4–9] to 300 [6] particles/mm^3.

Acquisition of high spatial resolution in off-axis HPIV is usually hampered by the inherent noise originated from the increase in particle concentration [10–13] and aberration [14]. It is noted that the latter issue is the subject of this study. Aberration in the imaging system should be corrected to differentiate reliable images from

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