An advanced off-axis holographic particle image velocimetry (HPIV) system

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Abstract Holographic PIV (HPIV) is the most promising candidate for the next generation full-field velocimetry that can measure high spatial resolution instantaneous three-dimensional (3D) velocity fields. To explore the maximum performance capabilities of HPIV including spatial resolution, off-axis holography based HPIV has become a major direction of development. A fully automated off-axis HPIV system based on an injection-seeded dual-pulsed YAG laser and 3D data processing software has been implemented in the laser flow diagnostics lab (LFD). In our system, 90-degree particle scattering, dual reference beams, in situ reconstruction/data processing, and 3D velocity extraction based on a fast “concise cross correlation” (CCC) algorithm are utilized. The off-axis HPIV system is tested for an acoustically excited air jet and the wake of a surface-mounted tab in a water channel flow, giving instantaneous 3D velocity fields for both flows. Experimental data of instantaneously measured 3D flow structures using this technique show great promise.

1 Introduction
Over the past decade particle image velocimetry (PIV), which measures two components of velocity in a 2D plane based on photographic imaging, has become the state-of-the-art experimental technique for fluid velocity measurement (Adrian 1991). It employs laser light sheets and planar imaging media (e.g. photographic films or video CCD cameras) to measure the two in-plane components of fluid velocities in a planar domain in a flow, or three components in a planar domain if a stereoscopic imaging technique is used (Arroyo and Great 1991; Prasad and Adrian 1993). The establishment of PIV clearly marks a significant advancement in experimental fluid mechanics from single-point to multi-point velocity measurement (Adrian 1996; Adrian 1997). This progress, however, is only half way towards full-field three-dimensional (3D) measurement of turbulent flows, and by far the easier half. Attempts have been made to generalize these 2D planar PIV techniques into 3D volumetric field measurement through scanning (Guezenec et al. 1994; Bruecker 1995; Bruecker 1997) with severe limitations in spatial and temporal resolutions. Hence, planar PIV techniques are unable to provide detailed space- and time-resolved experimental data in highly transient and three-dimensional turbulent flows needed for understanding, modeling and controlling of turbulent flows.

Recent advancements in both experimental and computational fluid dynamics research has increased the demand for instantaneous full-field 3D flow velocity measurements resolved in space and time. Measurements of turbulent and complex flows require good accuracy and high resolution in a relatively large volumetric domain. The requirement for information capacity is far beyond any photography-based technique. By capturing the phase information of light waves scattered off the object of interest, holography is an instantaneous 3D imaging process that offers an enormous storage capacity suitable for 3D information recording. It is thus an inherently better solution to 3D measurements than any other available technique. HPIV records the 3D information of a large quantity of particles in a fluid volume on a hologram instantaneously and then reconstructs the particle images in a 3D space. From the reconstructed image field, we can retrieve the 3D positions (as well as size and shape information) of these particles. Furthermore, by finding the 3D displacements of the particles in the image volume between two exposures separated by a short time lapse, the instantaneous 3D velocities of these particles in the volume can also be obtained.

The key problems that any HPIV system faces are reduction of speckle noise, handling of huge quantities of data, extraction of 3D velocity in presence of large gradients/fluctuations, and system complexity vs. user-friend-
liness. While the strategies of handling all these issues make each setup unique, HPIV configurations can be broadly classified into two kinds based on the nature of the holographic scheme: “in-line”, where only one beam is employed to produce both the object wave and the reference wave, and “off-axis”, where separate object beam and reference beam(s) are introduced. Many variations of these two basic schemes are possible, often blurring such distinctions.

Classical in-line holography (also known as Gabor holography) has been traditionally the standard holographic method to diagnose particle fields (Trolinger et al. 1973; Thompson 1974; Belz and Menzel 1979) and thus was employed in holographic PIV (Weinstein et al. 1985; Meng and Hussain 1991; Scherer and Bernal 1997). While enjoying simplicity of optical geometry and low requirements for laser coherence and energy, standard in-line method, especially when used in HPIV where the particle density is usually large, faces a severe problem. Due to the superposition of the real image, virtual image and reference waves, excessive speckle noise is produced to interfere with recognition of particle images (Meng et al. 1993). Another problem with in-line HPIV that affects the measurement accuracy is the large depth of focus in the reconstructed particle images. This is caused by the small effective numerical aperture (N.A.) formed by the forward particle scattering. Efforts have been made to address these problems to improve the practicality of in-line HPIV while maintaining its merits (Simmons et al. 1993; Zimmin et al. 1993; Zimmin and Hussain 1994; Meng and Hussain 1995a). Among these methods the in-line recording off-axis viewing (IROV) technique appears to be an efficient way to suppress the speckle noise and improve the signal to noise ratio (SNR) of the reconstructed particle images. At the same time, only one beam is used in hologram recording, thus retaining the advantages of in-line HPIV. Holographic PIV based on IROV has been successfully applied to instantaneous 3D flow measurements (Meng and Hussain 1995a, b; Sheng and Meng 1998).

With the innovative IROV approach, in-line HPIV has reached a certain level of applicability. Indeed, its optical simplicity makes it attractive for many applications including holographic 3D flow visualization, and hence it is one of the major HPIV techniques this and other labs are currently pursuing (Sheng and Meng 1998; Meng et al. 1998). However, at a seeding density of no more than a few particles per mm², which is a de facto limitation of IROV, the achievable spatial resolution of in-line HPIV is still far from fully resolving turbulent flows. In the pursuit of high spatial resolution measurement, off-axis holography becomes the logical choice. With this scheme, the real, virtual images and the reference beam are no longer superposed, eliminating the major source of speckle noise inherent in in-line HPIV.

2 Rationale of the off-axis HPIV technique

Compared with in-line techniques, off-axis holography tolerates higher seeding densities and offers a much better image SNR, since the directly transmitting wave, the virtual and real image waves are naturally separated during reconstruction. By utilizing wide-spread side scattering rather than the narrow central-lob forward scattering of particles, the effective numerical aperture (N.A.) of imaging is drastically increased, thereby reducing the depth of focus and yielding higher measurement accuracy. Also the directional ambiguity problem inherent in double-exposure in-line HPIV can be solved by employing dual reference waves at different angles. These make off-axis HPIV a desirable configuration despite the optical complexities and the high requirements on the laser power and coherence. However, the particle scattering characteristics require a trade-off between the achievable effective N.A. and the laser energy utilization, since most of the laser energy scattered by the particles is carried by the narrow-angled forward scattering. Side scattering is much weaker than forward scattering and near-forward scattering, thus calling for much higher laser power/energy than what in-line versions require.

Various off-axis methods have been proposed and reported since the early years of HPIV development (Barnhart et al. 1994; Meng 1994; Liu and Hussain 1995; Zhang et al. 1997), addressing the problem of laser energy utilization and effective N.A. Encouraged by the high scattering efficiency of the forward scattering, Zhang et al. (1997) constructed a hybrid HPIV system, where forward scattering is combined with off-axis holography. In the configuration an optical high-pass spatial filter is utilized to avoid the directly transmitting wave in the object beam. In contrast, Barnhart et al. (1994) implemented a phase conjugate HPIV system, where two separate channels of near-forward scattering are combined to achieve an effective large N.A. of particle images. To compensate for the severe optical distortion and aberration imposed by the complex optics, a phase conjugate reconstruction system is required. These two approaches exemplify compromises between the laser energy utilization and the effective N.A.

Such compromises in off-axis HPIV often come with undesirable problems. In the system of Zhang et al. (1997) the employment of the central-lob forward scattering and long recording distance results in low effective N.A. To make up for the large depth of focus, an extra hologram has to be placed in the orthogonal axis to provide velocity component in depth direction. Such a system involves not only doubling the amount of optics and data processing, strict coordination of the two orthogonal holograms, and synthesis of 3D vector map, but also requires the flow domain to be optically accessible from two orthogonal directions through four windows. On the other hand, the phase-conjugate off-axis HPIV system by Barnhart et al. (1994) involves a different type of practical restriction. In spite of the low f-number lenses, the two-channel optical system used for collecting scattering works effectively as a low-quality imaging system, introducing excessive optical aberrations that prohibit the reconstruction of particle images. The only remedy is to employ the so-called phase-conjugate reconstruction, i.e. extract back tracing of optical waves from the hologram to the particle images. This requires placing everything, including the original flow medium and its wall, that appeared between the particles and the hologram during the recording, back into the