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ATOMIC, MOLECULAR & OPTICAL PHYSICS | REVIEW ARTICLE

A review on noise suppression and aberration compensation in holographic particle image velocimetry

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Abstract: Understanding three-dimensional (3D) fluid flow behaviour is undeniably crucial in improving performance and efficiency in a wide range of applications in engineering and medical fields. Holographic particle image velocimetry (HPIV) is a potential tool to probe and characterize complex flow dynamics since it is a truly three-dimensional three-component measurement technique. The technique relies on the coherent light scattered by small seeding particles that are assumed to faithfully follow the flow for subsequent reconstruction of the same the event afterward. However, extraction of useful 3D displacement data from these particle images is usually aggravated by noise and aberration which are inherent within the optical system. Noise and aberration have been considered as major hurdles in HPIV in obtaining accurate particle image identification and its corresponding 3D position. Major contributions to noise include zero-order diffraction, out-of-focus particles, virtual image and emulsion grain scattering. Noise suppression is crucial to ensure that particle image can be distinctly differentiated from background noise while aberration compensation forms particle image with high integrity. This paper reviews a number of HPIV configurations that have been proposed to address these issues, summarizes the key findings and outlines a basis for follow-on research.

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PUBLIC INTEREST STATEMENT

Holography is commonly associated with the arts of displaying objects that seemingly appear realistic in three-dimensional space. In engineering and medical fields, holography has been used as a non-invasive tool to (1) record the dynamics of three-dimensional fluid flow phenomena, and (2) replay the same event afterward for further analysis. Nonetheless, the recorded holographic images often appear distorted with poor image quality, making analysis considerably difficult. This article reviews a number of key techniques to address this issue.

Subjects: Applied Physics; General Physics; Laser & Optical Engineering; Optoelectronics

Keywords: holographic particle image velocimetry; flow diagnostics; fluid flow; digital holographic microscopy

1. Introduction

Over the past two decades, a number of unique experimental holographic particle image velocimetry (HPIV) configurations have been proposed to acquire high-spatial three-dimensional (3D) displacement and velocity measurements. The first review by Royer (1997) discussed some fundamental requirements (energy per pulse, repetition rate and coherence of laser) and limitations (time-consuming image analysis) in the early developments of HPIV techniques. Another reviews concerning state-of-the-art optical, digital and hybrid HPIV techniques were later covered in Hinsch (2002), Meng, Pan, Pu, and Woodward (2004), which clearly demonstrate the advantages of CCD sensors over holographic films through numerical reconstruction and digital image processing.

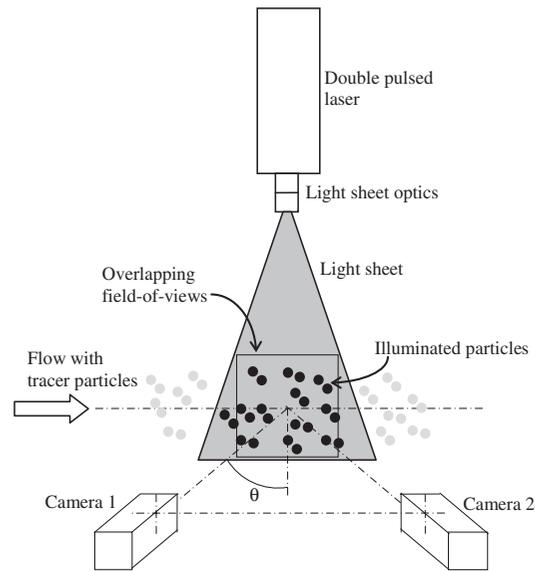
This paper specifically deals with the HPIV techniques to overcome noise and compensate for aberration in order to acquire high-spatial resolution in all dimensions, which are discussed in Section 2. The content in this paper is structured in such a way that it first introduces the transition from two-dimensional (2D) imaging technique using particle image velocimetry (PIV) to three-dimensional (3D) imaging technique using HPIV. Section 3 compares the performance of the proposed techniques based on a number of criteria, whilst Section 4 highlights the superiority of holographic films over CCD sensors in terms of information capacity. The application of digital holographic microscopy to overcome noise and aberration is discussed in Section 5.

HPIV is essentially the application of holography in particle image velocimetry. Historically, PIV was initiated from the original work of Dudderar and Simpkins who introduced the laser speckle photography (LSP) technique in 1978 to measure fluid flow (Dudderar & Simpkins, 1977; Simpkins & Dudderar, 1978). LSP was established as a method to measure in-plane surface deformation requiring rough material surfaces to efficiently scatter the incident light to produce a speckle modulated image. In fluid flow measurement, the surface is simulated using a laser light sheet and it is possible to control the scattered light by varying the concentration of seeding particles. It was found that if individual particle images could be distinctly recognized one could acquire reliable flow velocity (Adrian, 2005). This was realized by Adrian and Yao (Adrian & Yao, 1984) in the USA and Pickering and Halliwell (1984) in the UK who independently called the technique “particle image velocimetry”.

As shown in Figure 1, PIV set-up employs a planar light sheet of few millimetres thick which illuminates neutrally buoyant particles that are assumed to faithfully follow the flow and efficiently scatter the light. The light scattered by such particles is then recorded using a camera or photographic film that is placed orthogonally to the light sheet. If the time is known between multiple exposures it is possible to estimate the local fluid velocity based on individual or ensemble particle displacement. The technique is however, limited to two-dimensional two-component (2D-2C) in-plane flow measurements.

To extract the out-of-plane motion of seeded particles, the stereo-PIV technique was proposed (Arroyo & Greated, 1999; Prasad & Adrian, 1993; Westerweel & Van Oord, 2000). Similar to the original PIV technique, stereo-PIV utilizes two cameras to simultaneously record distinct off-axis views of the same flow region of interest (Figure 1). Before any measurement can be taken, the positions of the camera with respect to the interrogated region have to be calibrated using a calibration plate to remove misalignment in the system. The overlapping area of the defined by the field-of-views is however restricted by the off-axis angle θ . Finally, the true three-dimensional displacements of a particle are extracted from a pair of two-dimensional displacements as measured by the left and right camera, respectively. This is effectively solving four equations with three unknowns. Although

Figure 1. Basic experimental PIV set-up uses one camera while stereo-PIV set-up employs two cameras for the same flow measurement.

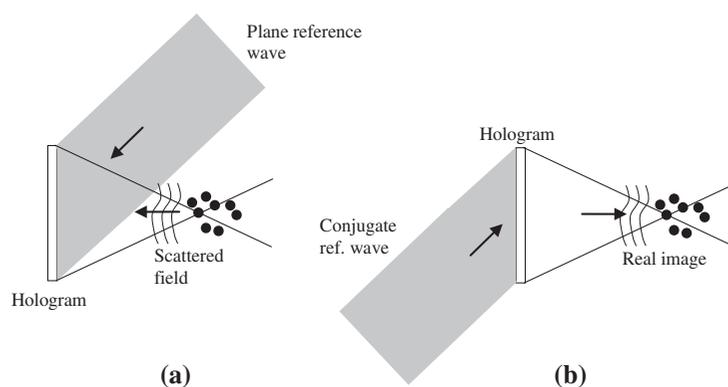


the technique extracts three components of the velocity, it does so across a 2D field defined by the light sheet and is known as two-dimensional three-component (2D-3C) technique (Prasad, 2000).

HPIV is undoubtedly the key to three-dimensional three-component fluid flow measurements. A hologram records objects in the form of complex interference fringes and contains useful amplitude and phase information that provide the means to make three-dimensional three component (3D-3C) measurements. Pioneering work by Thompson, Ward, and Zinky (1967), Trolinger, Farmer, and Belz (1968) Trolinger, Belz, and Farmer (1969) on particle holography demonstrated that both particle size and particle dynamics can be measured using holography. Displacement of particle images in a double or multiple-exposed hologram can be extracted by focusing the images using a travelling microscope. In the early studies, particle concentration was limited to a relatively low concentration level (several particles/cm³) in which each individual particle image can be reliably tracked since noise is proportional to the number of particles present. It is clear however, that this results in low spatial resolution of the flow under investigation.

Figure 2 shows a basic off-axis set-up used to record and reconstruct the position of seeding particles using a traditional silver halide holographic plate. There are several points to note. First, a hologram can be considered to measure the phase and amplitude of the scattered wavefront at the time(s) of exposure and the hologram plate is strictly two-dimensional. It cannot be said to be a three-dimensional image of particles for certain, but merely appears to be—it could be a totally different way of creating the same wavefront, a computer-generated hologram for example. The point here is that the observer is using a priori knowledge of similar images to identify that the complex

Figure 2. Basic off-axis holographic (a) recording and (b) reconstruction setups.



wavefront is similar to that originating from a set of scattering particles. Second, it is clear from the figure that the size of the plate and its distance from the seeding particles define the numerical aperture of the system. The numerical aperture varies from particle to particle but is usually in the range of 0.3–0.6 for typical holographic geometries (Hinsch, 2002). The numerical aperture has a major influence on the ability to retrieve three-dimensional displacement data as it strongly influences the depth of field. These fundamental limitations will be returned to later in Section 2.

2. The development of HPIV

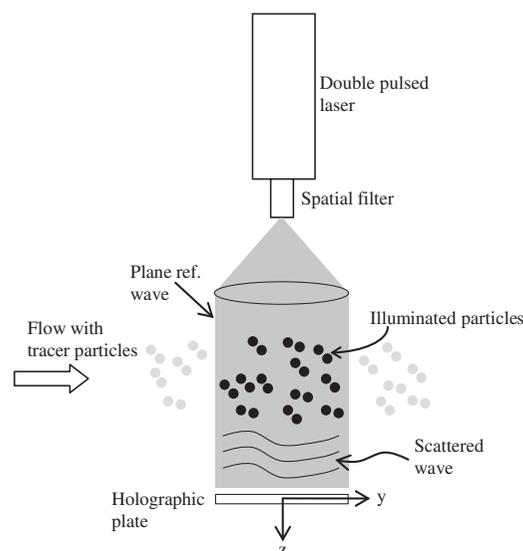
Noise and aberration have been considered as major hurdles in HPIV in obtaining accurate particle image identification and its corresponding 3D position. Major contributions to noise include zero-order diffraction, out-of-focus particles, virtual image and emulsion grain scattering. Noise suppression is crucial to ensure that particle image can be distinctly differentiated from background noise, while aberration compensation forms particle image with high integrity. There are many variations of HPIV that have been proposed over more than 20 years to address these issues which are now considered in detail.

2.1. Forward-scatter in-line holography

Holography was invented by Gabor to correct for the spherical aberration of the electron lenses by means of two-step imaging process (Gabor, 1948). The set-up employed in his original work is now known as in-line or Gabor holography and it is the most straightforward holographic geometry. As shown in Figure 3, an object is illuminated with a defined reference field. If the light scattered by the object and the reference beam are mutually coherent, an interference pattern can be recorded on a traditional silver halide holographic plate. The advantage of in-line holography lies in its simplicity since a single illuminating beam is simultaneously employed as an object and a reference beam thereby lessening the need of high laser coherence.

The first instantaneous three-dimensional measurement of a velocity was reported by Meng and Hussain (1991). The same set-up was employed to capture the wake of vortex ring flow in an oil-filled tank that was seeded with 10 μm polystyrene spheres. A volume of $10 \times 10 \times 25 \text{ mm}^3$ was interrogated revealing a particle density of 3 particles/ mm^3 . Although the preliminary result was crude with a significantly large depth-of-focus, they still managed to acquire the axial component of particle displacement. However, there are some fundamental disadvantages of such a system. First, in addition to the desired reconstruction, unwanted artefacts and other sets of particle images appear in the image. In particular, the unscattered object beam and the undiffracted reference beam provide a bright background. Second, particles scatter more efficiently in the forward direction resulting

Figure 3. Typical optical recording arrangement for in-line particle holography.



in a forward-scatter lobe that for the case of particles that are significantly larger than the wavelength, significantly reducing the effective numerical aperture of the system.

For these reasons, Meng and Hussain (1995a, 1995b) later proposed a near forward scattering geometry with off-axis viewing of the reconstructed particle images. In this technique, a CCD was tilted such that the undiffracted reference beam was avoided while recording the high frequency lobes of the ring fringes (Figure 4). In this way, it was found that the speckle noise due to out-of-focus particle images was significantly suppressed, resulting in 10 dB of increase in signal-to-noise ratio (SNR) for tilted angle of 20° as compared to conventional in-line holography. In addition, they reported an order of magnitude increase (400–40 μm) in depth resolution for particle size of 20 μm .

In 1997, Scherer and Bernal demonstrated a holographic technique to characterize axisymmetric turbulent jet flows in a water tunnel (Scherer & Bernal, 1997). The flow region was recorded from two in-line setups (Figure 5) where the optical configuration resembles stereo-PIV set-up. It was proposed fundamentally to alleviate depth-of-focus problem normally associated with the single in-line

Figure 4. Off-axis viewing of an in-line hologram [after Meng and Hussain (1991)].

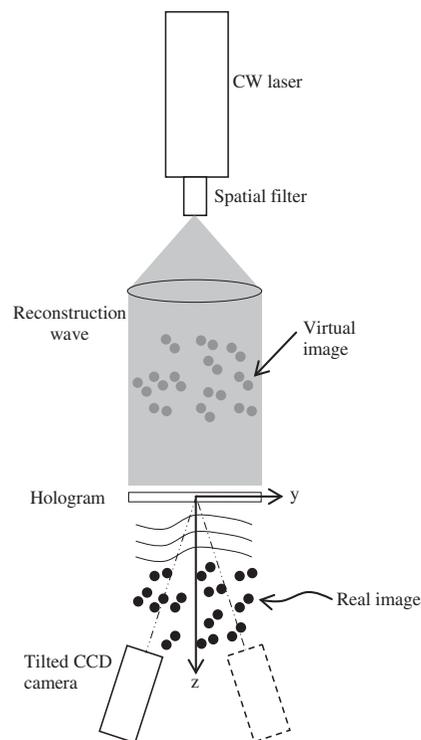
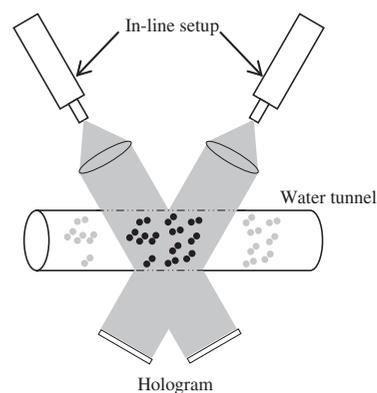


Figure 5. Stereo-HPIV [after Scherer and Bernal (1997)].



technique. To record the flow, two holographic films were placed outside the water channel for reason of convenience. Based on the schematic diagram given in their paper, it can be assumed that the optical window consisted of two separate Perspex round collars of considerable thickness, each of length more than 173 mm; allowing 150 mm beam illumination to incident on the holographic film at 30° with respect to channel wall. They reported that the speckle noise was of size similar to the particles, causing difficulty in selecting good particle images. This could be attributed to significant aberrations introduced by the optical window. The images were averaged and subsequently notch-filtered to remove speckle noise and non-uniformity in background noise due to reconstruction wave. With the contributing noise they still managed to obtain turbulent flow velocities in three components with a spatial resolution that comparable to PIV standards.

2.2. Forward-scatter off-axis holography

Although in-line holography is practically simple the reconstructed image of interest is heavily degraded by noise from other images as well as noise from the reconstruction beam. For this reason, work in the field of holography remained slow for nearly two decades until Leith and Upatnieks in 1962 unintentionally rediscovered Gabor's idea about holographic principle when working on secretive optical processing of side-looking radar. Using an off-axis holographic geometry, they managed to separate the undiffracted reconstruction beam and unwanted images from the image of interest (Figure 6) (Leith & Upatnieks, 1962, 1964). Although marginally more complicated to implement it offers a greater degree of control allowing the intensity of the reference and object beams to be balanced to boost the SNR.

In a forward-scatter off-axis geometry, the reconstructed particle signal is inherently overshadowed by a bright and unscattered object beam as shown in Figure 6(b). To counter this, Liu and Hussain successfully demonstrated the use of a Fourier transform lens that was positioned at about a focal distance away from the film plane (Liu & Hussain, 1995). A collimated object beam illuminating the particle field was then converged and would over-blacken a spot on the plate. Hence, the hologram not only served to record the flow but also worked as a high pass filter in the reconstruction process. As a result, the illumination would not be recreated in the reconstruction process and leaving behind clearly visible particle images. The main disadvantage of this set-up was reflection from the front and rear surfaces of the lens. Each surface created two secondary bright spots in the back focal plane of the lens. This was a hindrance for imaging large-scale flow because the flow has to be avoided being placed in the region of these secondary focal points. Later on, Liu and Hussain (1998) modified the original set-up by placing a fabricated Gaussian-shaped high-pass filter in between two Fourier transform lenses (Figure 7). This simple modification avoided the aforementioned problems associated with their original set-up.

A comprehensive flow velocity measurement utilizing forward-scatter off-axis geometry with high-pass filtering was reported by Zhang, Tao, and Katz (1997). Two perpendicular holograms of the same turbulent flow field inside a square duct were recorded. As a result, they managed to eliminate depth of focus problem and at the same time obtained equally accurate data for all spatial

Figure 6. Forward-scatter off-axis holographic particle (a) recording and (b) reconstruction setups.

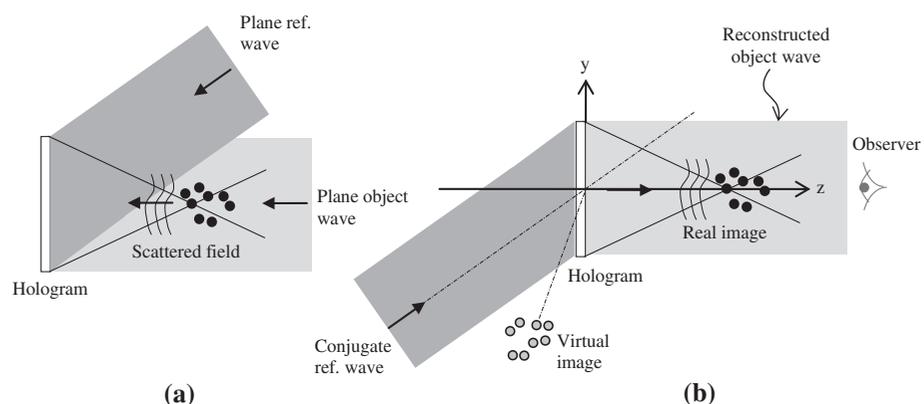
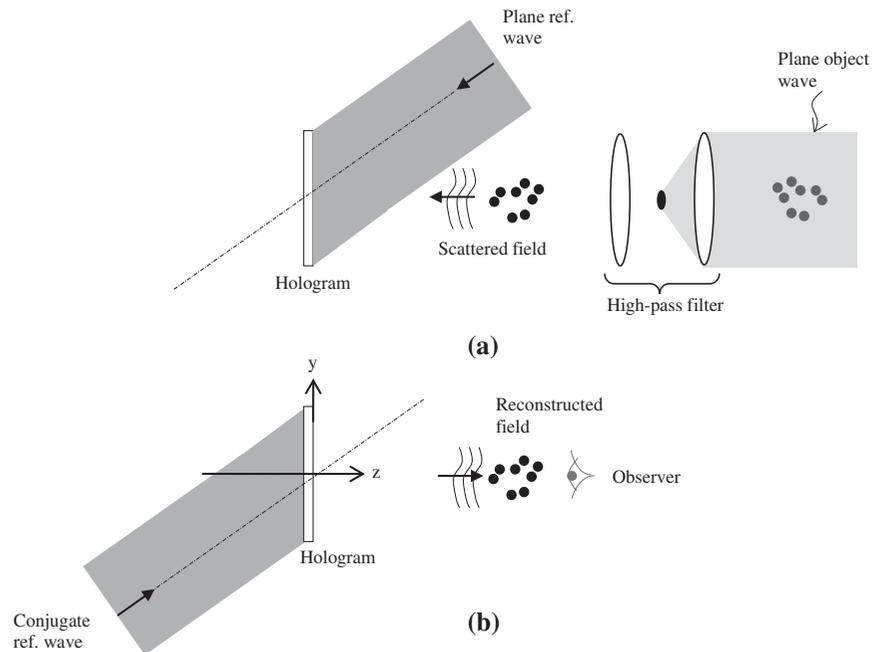


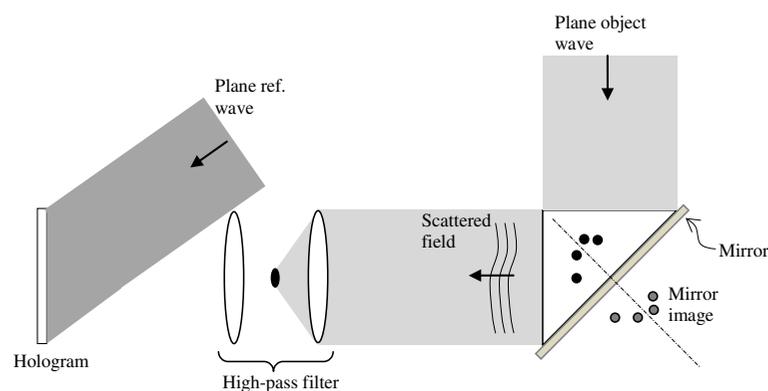
Figure 7. (a) High-pass filtering technique used in the holographic recording of forward-scatter off-axis geometry. (b) Holographic reconstruction eventually results in the suppression of the illumination beam [after Liu and Hussain (1998)].



dimensions. The main limitation of this approach is complexity since it requires four windows (two for each hologram). As the number of holograms is doubled, the aberrations introduced by the holograms and the system also significantly increase. Nevertheless, the result was impressive with more than 800,000 extracted vectors in $\sim 64 \text{ cm}^3$. Using the same optical recording and reconstruction methods, Tao, Katz, and Meneveau (2002) subsequently managed to achieve a much improved result with more than 2.2 million vectors from the same interrogation volume.

Following the limitations imposed by this optical arrangement, Sheng, Malkiel, and Katz (2003) realized the need to simplify the optical configuration while preserving the advantages offered by recording two orthogonal views. The original system was modified by utilizing a triangular tank with a mirror attached on its hypotenuse (Figure 8). This effectively means that only a single hologram is sufficient to simultaneously record an object and its “mirror image” from a single illumination path. Hence, this modified version contains only one window and one recording system. As a result, the spatial resolution was increased by a factor of four. The resolution is determined by the depth-of-focus in the direction perpendicular to the hologram (Sheng et al., 2003). However, the system was incapable of resolving direction since it recorded and reconstructed the two exposures simultaneously. This can be overcome by tilting the reference beam between exposures using a rotating mirror (Zhang & Eisele, 1995) or having reference beams at different orientation for each exposure (Barnhart, Adrian, & Papen, 1994).

Figure 8. Optical arrangement that utilized triangular tank with a mirror to simultaneously record an object and its mirror image [after Sheng et al. (2003)].



Adrian, Barnhart and their group (1994) were the first to report a successful implementation of HPIV to obtain full volumetric 3D velocity components. Their novel technique is known as phase-conjugate off-axis HPIV. The aim was to obtain quantitative and qualitative measurements comparable to 2D photographic PIV. The optical system used a stereo holographic-recording technique to achieve accurate particle centroid identification and, different reference beams for each exposure were used to resolve directional ambiguity of particle displacement. In essence, two images were recorded from two different angular directions and each image was reconstructed separately using the corresponding conjugate reference beam. To obtain the 3D displacement vector of a particle, stereo-PIV procedures were employed and enhanced by automated parallel processing technique to provide fast data acquisition rate. The technique was considered to be good for analysing small-scale flow but the configurations demand accurate experimental set-up and custom made prisms and lenses. The results revealed some large non-uniform magnification of particles images (original particles used were 0.5–1.0 μm); approximately 30 μm in the horizontal and 15 μm in the vertical directions whose length ranges between 100 and 700 μm . These characteristics can be attributed to the small recording NA of a near-side scattering geometry that is mainly due to the distance of the hologram plane with respect to the test volume. In addition, the analysis was performed without three-dimensionally tracking individual particle; instead the two-dimensional projections of a small flow region were correlated with 50% overlap.

Barnhart et al. (1994) also utilized a near forward-scatter geometry in which a complete beam stop was placed in between the flow volume and the holographic film (Figure 9). To record the scattered light from the particles, a pair of relay optics consisting of two plano-convex lenses and prisms were utilized to negotiate the light by both sides of the beam stop.

Unlike previous methods of blocking the undiffracted beam using a high-pass filter (Liu & Hussain, 1995, 1998; Sheng et al., 2003; Svizher & Cohen, 2006; Zhang et al., 1997), Fabry placed a black strip in the middle of the holographic film in his light sheet off-axis HPIV experiment (Fabry, 1998) (Figure 10).

The width of the strip was of similar size to the thickness of the light sheet. The remaining area of the holographic film is essentially recording the near-forward particle scattering light. Hence, this configuration not only removes the zero-order term but also enables the use of high particle concentration of small tracer particles within the light sheet. Another novel feature is his method of image analysis, which used an oriented right-angle prism (hypotenuse's face was in parallel with the hologram plane) that was placed in the reconstructed real image volume (Fabry, 1998) (see Figure 11). Instead of using two separate cameras which require precise calibration in the physical space; the

Figure 9. Schematic diagram to suppress the DC effect [after Barnhart et al. (1994)].

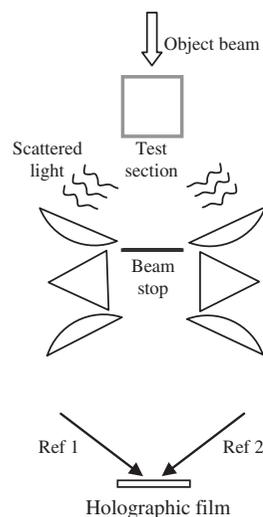
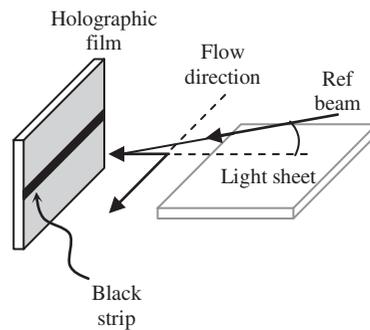


Figure 10. Holographic recording set-up utilizing light sheet object beam [after Fabry (1998)].



prism simultaneously refracted the real image through two surfaces angled at 45° from the optical axis. This produced a stereoscopic pair of holographic images on a single camera. To capture these images, the camera aperture was reduced to f#12 as a result of significant image aberration. One of the reasons could be the mismatch between recording (Argon laser, 488 nm) and reconstruction (HeNe laser, 633 nm) wavelengths.

Von Ellenrieder, Kostas, and Soria (2001) initially developed a side-scatter geometry to measure turbulent separated flow in a water tank. The set-up was similar to Lozano, Kostas, and Soria (1999). Since the light scattered in the side-scatter direction was insufficient, the object beam was tilted at about 16° with respect to the optical axis of the holographic film. This results in better light scattering while simultaneously deflecting the intense object light from incident on the holographic film. Two sets of holograms were recorded on a single holographic film utilizing two different polarizing reference beams. The geometry is reproduced as shown in Figure 12. A multi-grid cross-correlation digital PIV technique was employed to determine the displacement components. However, determination of the out-of-plane component using a stereoscopic method was not possible owing to the small NA of the hologram. This is because the separation distance between the flow vessel and film plane had to be compromised to allow sufficient space for the oncoming reference beams. This results in reduction of effective NA and scattering efficiency.

2.3. Side-scatter off-axis holography

Another important geometrical set-up in HPIV is side-scatter geometry. In essence, the geometry solves the noise problems inherent in forward-scatter geometry at the expense of less light

Figure 11. Use of a prism in the reconstruction geometry to produce stereoscopic pairs of particle images [after Fabry (1998)]. The 3D particle displacement, s is determined such that $s = \sqrt{s_1^2 + s_2^2}$.

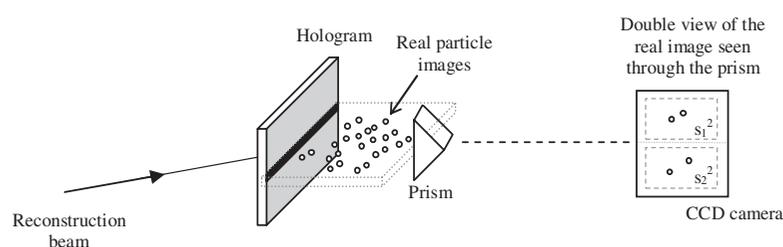
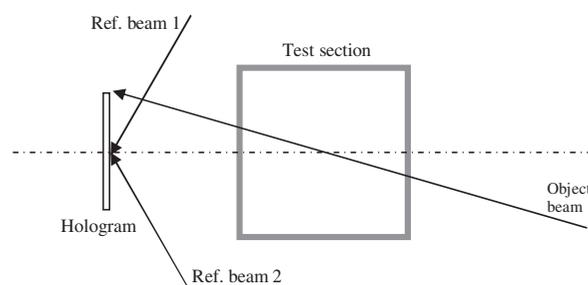


Figure 12. Hologram recording with a tilted object beam to suppress zero-order diffraction [after Von Ellenrieder et al. (2001)].



scattering (Figure 13). To compensate for this shortcoming, generally more than 70% of energy is supplied in the beam path (Pu & Meng, 2000) and considerably large particle size (>50 μm) (Alcock, Coupland, Garner, & Halliwell, 2003; Barnhart, 2001) are often employed. Additionally, an object can be placed closer to the hologram plane thus giving sufficiently large numerical aperture.

An attempt was made by Lozano et al. (1999) to quantitatively compare three-particle velocimetry techniques: DPIV, planar HPIV and volumetric HPIV using single experimental configuration (Figure 14). A conventional side-scatter PIV geometry exactly fits this purpose and was employed to measure swirling flows. To ensure accurate digitization of holographic images, a novel method was devised by placing a fine grid “floating” at an arbitrary distance in between the holographic film and the flow.

Another version of the lensless side-scatter experimental set-up was developed by Pu and Meng (2000). The system utilized dual reference beams to obtain a separate frame for each of the exposures, fundamentally to eliminate directional ambiguity. Once chemically processed, the hologram was flipped by 180° and placed at the same recording location utilizing the same reference beams alignment and laser wavelength. The real particle images were then captured via video microscope. An innovative feature here is that the reconstruction set-up was fully automated for particle image identification and correlation. A 3D stack of images was collected by scanning the flow volume and then particle centroid identification was performed.

The technique of flipping the hologram to reconstruct real particle images, however, had been the concern for many groups. For example, Lozano et al. (1999) realized the difficulty of positioning the plate after rotating it by 180° about the vertical axis and thus did not pursue with the flipping technique. This is because once rotated, the emulsion thickness variation cannot be cancelled out and particle image would suffer severe aberrations (Barnhart, 2001). In addition, it is difficult to judge the

Figure 13. Side-scatter holographic particle (a) recording and (b) reconstruction setups.

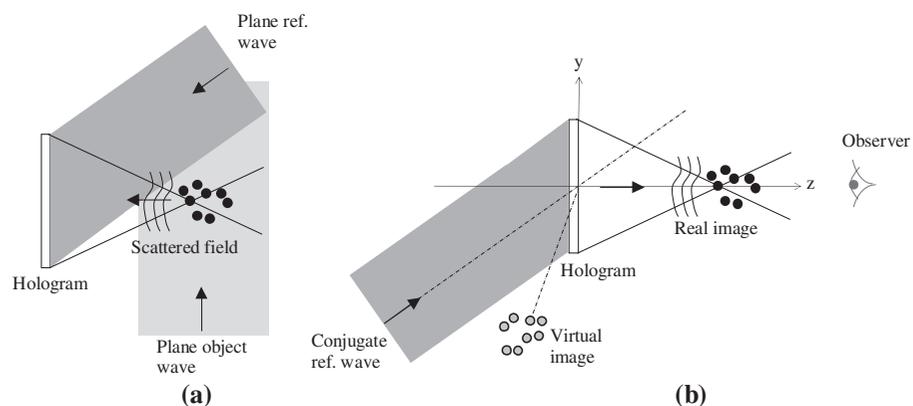
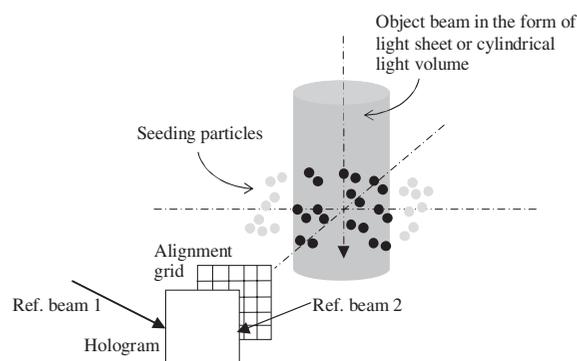


Figure 14. Employment of cylindrical light volume and alignment grid in side-scatter geometry. Planar HPIV setup employs a light sheet in place of the existing cylindrical light volume [after Lozano et al. (1999)].



merit of this system since no mention was made on chemistry involved and the quality of the reconstructed particle images. Nonetheless, the results were quite impressive showing 92,000 vectors and relatively high particle density of about 30° particles/mm³. Accordingly, there were more than 2 million particles in the interrogation volume of ~ 80 cm³.

2.4. Light-in-flight holography

The work of frameless motion pictures from holograms of ultrafast phenomena was first initiated and developed by Abramson (1978, 1983, 1984, 1985, 1991), Abramson and Spears (1989) in 1978. About 20 years later, a similar approach in HPIV was developed by Hinrichs et al. that permitted its application for the study of deeper flow fields and was demonstrated applicable for fluid flow visualization (Hinrichs, Kickstein, & Böhmer, 1997). Commonly known as light-in-flight holography (LiFH), this technique was based on holographic recording with short-coherence laser light or, alternatively, with short laser pulses to effectively “freeze” wavefronts in space (Herrmann, Hinrichs, Hinsch, & Surmann, 2000).

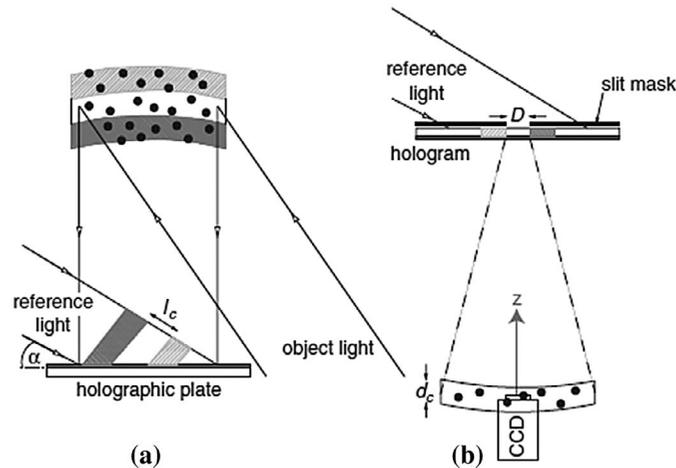
In 2004, Herrmann and Hinsch (2004) further explored the LiFH technique for particle tracking in a wind tunnel application. They employed a similar recording geometry to and as reported earlier by Hinrichs et al. (1997). The reconstruction was done however, on a separate optical configuration which demanded accurate alignment. In the experiment, they utilized low seeding density in order to acquire considerably larger cross-sections of the measurement volume in the wind tunnel although particle concentration comparable to HPIV is possible. The laser energy output could be one of the limiting factors in this experiment. This is because high seeding density demands very high laser energy for the same measurement volume to ensure efficient light scattering.

As shown in Figure 15(a), when a hologram is recorded using an off-axis reference wave, each particular section on the hologram would only register interference patterns corresponding to the light scattered in object space that falls within the coherence length. In the reconstruction stage, the real particle image can be reconstructed using a conjugate reference wave. The first advantage of using a short-coherence laser light is that the reconstructed depth volume is considerably less than that of typical HPIV and was measured to be about 1.5 times the coherence length (Hinrichs et al., 1997). Since the out-of-focus particle images did not fall within the coherence length, the corresponding noise is effectively suppressed (Herrmann & Hinsch, 2004). The second advantage is that one can independently choose the 3D location of the reconstructed object by selectively positioning a slit mask on the hologram. As shown in Figure 15(b), the slit mask is effectively blocking the scattered light originating from the emulsion noise at the expense of a reduced hologram aperture. Unfortunately, reduction of the hologram aperture would result in large depth-of-focus and hence poor longitudinal resolution (Herrmann & Hinsch, 2004). These considerations explain how LiFH could facilitate background noise reduction by suppressing the emulsion grain noise and out-of-focus particles. However, the need to move the slit over the hologram for the reconstruction procedure was also reported to be time-consuming (Herrmann & Hinsch, 2004).

2.5. Application of bacteriorhodopsin film in HPIV

One of the foreseeable commercial HPIV systems was demonstrated by Chan et al. (2004), Barnhart et al. (2004), Koek, Bhattacharya, Braat, Chan, and Westerweel (2004). Instead of using typical silver halide films, they utilized bacteriorhodopsin (bR) as a recording medium for the time-series HPIV measurements since bR did not require cumbersome chemical processing. bR is a real-time, volatile storage medium where the amount of information that can be retrieved from a bR film is heavily influenced by its photo and thermal properties (Barnhart et al., 2004). This is considered as the foremost advantage of bR including information capacity (5,000 line-pairs/mm) considerably higher than that of high-resolution photographic film (Barnhart et al., 2004). Its reversible photochromic protein characteristic allows bR to be repeatedly used within certain time limit before the recorded data experiences photo-induced erasure (Koek et al., 2004). Thus, its multiple storage capacity is deemed useful for providing stable turbulence statistics measurement.

Figure 15. (a) Holographic recording and (b) reconstruction using light-in-flight holography technique [after Herrmann et al. (1997)].



To record and reconstruct the hologram, they employed a polarization multiplexing technique that allows independent recording and reconstruction of two particle field instances using a single beam path. This indeed solves one of the practical hindrances in HPIV. However, bR's sensitivity to light is an order of magnitude less than that of silver halide film (Barnhart et al., 2004), justifying the use of relatively large 100 μm solid spheres as seeding particles in their experiments. The flow (10 mm in size) was illuminated with a converging beam such that the undiffracted beam would converge onto a metallic film located on the bR plane. The approach to suppress the zero-order diffraction is similar to Fabry (1998), except that the latter allowed whole-field flow measurement. Since the ratio of the illuminated flow region to beam stop size was 10:8, the experiment required much larger bR film to record the near-forward light scattering.

3. Comparison of HPIV techniques

A number of experimental HPIV systems have been described evaluating their advantageous and limitations; with the primary objective to maximize the number of independent image vectors that can be extracted from reliable experimental setups. As the number of vectors directly corresponds to the spatial resolution, however, there are three important interdependent parameters that fundamentally determine the performance of a HPIV system, namely: (a) particle number density, n_s ; (b) particle diameter, d ; and (c) axial depth, L . The overall relationship was first articulated by Royer who defined the shadow density, s_d as a means to quantitatively determine the image degradation of a particular hologram (Royer, 1974). The shadow density can be expressed as:

$$s_d = n_s d^2 L \quad (1)$$

In general, the shadow density increases in proportion to particle number density and axial depth, while it increases quadratically with respect to particle diameter (Tamrin, Rahmatullah, & Samuri, 2014a). Similarly, the shadow density can be thought of as an extended volume that can be accommodated by a number of particles of size d . As noted by Royer, a hologram is considered to have severe image degradation if the shadow density is greater than 10%. On the contrary, a hologram with a shadow density in between 1 and 10% is deemed marginally degraded. On the basis of this empirical criterion, one is able to evaluate and compare the performance of successful HPIV systems previously reviewed, as compiled in Table 1.

Based on Table 1, it is evident that HPIV measurements using off-axis configuration is superior in all aspects when compared with the in-line geometry. Of those concerning off-axis configurations, Sheng et al. (2003) reported the highest shadow density, vector density and particle number density. These could be attributed to a smaller flow field size of 20 mm as compared to others. Earlier studies by Tao et al. (2002) and Zhang et al. (1997) reported about twice the number of extracted particles in a flow field of about 40 mm, and this consequently results in reduced particle number density and

shadow density. On closer inspection, Sheng et al., Tao et al. and Zhang et al. reported more vectors than the particles and this trend is not consistent with the other findings. This clearly indicates that the same particles must have been measured more than once and shows that they do not know with any certainty where in the flow a given vector originates.

In addition, the shadow density reported by Sheng et al. and Koek et al. are anomalously high. In the case of Koek et al., its high shadow density can be attributed to a considerably large particle size of 100 μm used in the flow (Chan et al., 2004; Koek, 2006), but to the disadvantage of poor spatial resolution. In the case of Sheng et al., it is suspected that the same particles could have been detected more than once or noise could have been mistaken as particle images. This is because, at shadow density level of about 160%, the particle images are believed to be unrecognizable.

Since it is desirable to acquire high-spatial resolution, Barnhart et al. and Herrmann et al. demonstrated the employment of small particle sizes ranging from 0.5 to 3 μm and still managed to get reasonably high particle extraction and particle number density (Barnhart et al., 1994; Herrmann & Hinsch, 2004; Hinsch & Herrmann, 2004). In short, the performance and the achievable spatial resolution of any HPIV system are found to be dependent on the shadow density criterion.

4. Transition from film-based to digital holography

The previous section shows that the application of HPIV has been limited to laboratory-scale experiments particularly due to the requirement for complex, intensive holographic recording and reconstruction procedures and development of film-based hologram. The employment of bR film for HPIV work offered numerous advantages over traditional silver halide photographic film. Generally, a film-based hologram was employed to work as a temporary holographic buffer before digitization of images using a CCD sensor because of superior information capacity of the former. The space-bandwidth product (SBP) is a useful measure to compare the performance of an optical hologram and CCD sensor because it is directly related to information capacity. SBP of a CCD device is defined as the product of the dimensions of the device and the pixel frequency (Kreis, 2006). Table 2 compares the performance of several recording media and indicates that the information capacity of the silver halide photographic film is at least three orders of magnitude greater than that of the CCD sensor. This was considered to be the major drawback of CCD sensors that made them unsuitable for HPIV.

On the contrary, however, there has been considerable published work on digital holography in recent years and cumulatively in much greater in number than that of optical holography. Its application in digital recording and numerical reconstruction of microscopic objects has been most remarkable in the field known as digital holographic microscopy (Kim, 2010).

5. Application of digital holographic microscopy in HPIV

A microscope is a typical instrument normally used in laboratory for imaging purposes. The depth-of-field of a conventional microscope objective is governed by its magnification where high magnification results in limited depth-of-field (Hecht, 2002) given by

$$\text{DoF} = \frac{\lambda n}{\text{NA}^2} \quad (2)$$

where λ is the illuminating light wavelength, n is the refractive index of a medium and NA is the objective numerical aperture. In such limiting conditions, digital holographic microscopy offers the possibility to investigate three-dimensional microscopic object with ease. Similarly, cumbersome hologram wet processing and laborious optical reconstruction procedures, are effectively eliminated.

One of the pioneering works in digital holographic microscopy was described by Haddad et al. (1992). They demonstrated the principle of Fourier transform holographic microscope to study biological microorganisms. The microscope utilized a tiny glycerol drop of measurable (several hundred microns) sizes, acting as a Fourier transform lens and at the same time to create a spherically

Table 1. Performance comparison of HPIV systems and chronologically tabulated in reverse order

System	Type	Particle diameter (µm)	Volume depth, mm	Observation volume (mm ³)	Number of recorded particles	Particle number density (mm ⁻³)	Velocity vectors	Vector density (mm ⁻³)	Shadow density (%)
Chan et al. (2004), Koek, 2006	Off-axis	100 (solid glass sphere in water)	-	~70	1.12 × 10 ³	16	1160	16	64
Herrmann and Hinsch (2004), Hinsch and Herrmann (2004)	Off-axis	1–3 (DEHS, di-2-ethyl-hexyl-sebacate)	29.1	13,129	<170 × 10 ³	12–13	16,640	1.3	<0.34
Sheng et al. (2003)	Off-axis	20 (polystyrene in water)	20.0	1,785	>357 × 10 ³	200–300	644,160	360	<160
Tao et al. (2002)	Off-axis	20 (polystyrene in water)	44.5	93,323	<747 × 10 ³	4–8	2,263,040	24.2	<14.2
Pu and Meng (2000)	Off-axis	5 (water droplets)	32.0	78,848	2,400 × 10 ³	30	92,000	1.2	2.4
Zhang et al. (1997)	Off-axis	15 (polystyrene in water)	42.25	91,748	<742 × 10 ³	1–8	818,583	8.9	<7.6
Scherer and Bernal (1997)	In-line	24 (in water channel)	-	-	-	0.4	-	-	-
Meng and Hussain (1995)	In-line	20 (polystyrene in water)	11.0	3,234	74 × 10 ³	8	10,824	3.3	3.5
Barnhart et al. (1994)	Off-axis	0.5–1 (oil droplets in air)	60.0	36,015	360 × 10 ³	10	425,943	11.8	0.06
Meng and Hussain (1991)	In-line	10 (polystyrene sphere in oil)	25.0	2,500	7.5 × 10 ³	3	-	-	0.75

diverging reference wave. To refocus the image at different object planes, a numerical lens was added by multiplying the hologram with a spherical phase function. Although aberrations (due to coma and the optics used) were noticeable in the reconstructed image, this simplest form of microscope has allowed measurement of biological specimens with longitudinal resolution that is comparable to a compound microscope of the same NA.

Following this, Schnars and Jüptner (1994) made a significant improvement in digital holography by demonstrating full digital recording and reconstruction of a Fresnel hologram. To record an off-axis hologram of a considerably large object (size ~ 10 mm³), the object was positioned about 1 m away from the CCD plane such that the reference and the object beams subtended an angle of few

Table 2. Comparison of information capacity of three dissimilar recording media

Recording medium	Specification	Resolution, line pairs/mm	SBP
Bacteriorhodopsin (bR) film	100 × 100 mm	5,000	100 × 100 × 5000 ² = 25 × 10 ¹⁰
Silver halide photographic film	100 × 100 mm ²	3,000	100 × 100 × 3000 ² = 9 × 10 ¹⁰
CCD sensor	7 µm square pixel 4000 × 2000 pixels	71.4	4000 × 2000 × 0.007 ² × 71.4 ² = 2 × 10 ⁶

degrees. The off-axis angle is limited by the CCD resolution that should conform to sampling theorem (Goodman, 1996). The proof-of-principle result appeared crude but was viewed as an important breakthrough. Interestingly, in such an application wavefronts can also be reconstructed from under sampled CCD data (Coupland, 2004). In 1997, the first application of digital holography to record scattered light by microscopic particles in a flow were reported by Adams, Kreis, and Jueptner (1997) and later by Murata and Yasuda (2000).

Recently, Tamrin, Rahmatullah, and Samuri (2015a, 2014b, 2014c) demonstrated the applications of digital holographic microscopy in HPIV. In a typical HPIV set-up, a standard video microscope was usually mounted on a three-axis translation stage and scanned across the flow volume to detect reliable particle images. This method unfortunately resulted in loss of useful phase information. An integration of a purposely built digital holographic microscope in the HPIV reconstruction set-up successfully recovered both phase and amplitude of the holographically reconstructed particle images (Tamrin et al., 2014b).

In comparison to digital techniques, conventional recordings using silver halide emulsion are often subjected to severe aberration introduced in the reconstruction set-up (see Section 2). This makes identification of individual particles difficult and severely restricts the number of velocity vectors that can be obtained from a recording. In a different study, a similar digital holographic microscope was successfully employed to compensate for the aforementioned aberrations (Tamrin et al., 2015a) and eventually resulted in the increase of signal in the particle images.

6. Summary

In order to acquire as greater number of independent fluid velocity vectors as possible thereby offering increased spatial resolution, care must be taken to consider the effects of noise and aberration. A survey of research work pertaining to optical techniques to overcome noise and aberration in HPIV has been presented (see Section 2). In addition, a number of experimental configurations have been compared in terms of shadow density, particle number density and the obtainable particle number (Table 1, see Section 3). These parameters have direct implication on spatial resolution and essentially depend on identification of particle images that are characterized by SNR level and image fidelity. However, such identification is not a straightforward process since particle images were often degraded by noise and aberrations. Section 5 discussed the application of digital holographic microscopy for compensating aberration inherent in the reconstructed particle images through digital wavefront processing. Similarly, the proposed technique could be useful to suppress noise (Kim, 2010; Yu, Hong, Liu, & Kim, 2014), allowing identification of individual particle images in noisy background (Tamrin, Rahmatullah, & Samuri, 2015b) without the needs for complex experimental set-up. In short, careful integration of digital holographic microscopy in HPIV could offer limitless opportunities for future high-spatial resolution 3D displacement and velocity measurements of large-scale fluid flow behaviour which have been previously restricted by noise and aberration.

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