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## SINGLE PORT ACCESS HOLOGRAPHIC PARTICLE IMAGE VELOCIMETRY

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### ABSTRACT

An optical system, which requires only a single optical window mounted on a test volume, is proposed for holographic particle image velocimetry (HPIV). The optical system is a derivative of the double-exposure, double-reference-beam, off-axis HPIV system, but the innovative idea behind the system is to use back scattered light from the particles as the object wave. A 45° beam splitter inserted in front of the window serves to admit the illuminating beam and extract the back scattered light. This concept can be of great engineering interest because optical access is often limited to one window in practical devices. The preliminary results of the technique appear quite promising, with current studies aimed at defining the optical resolution capabilities.

### INTRODUCTION

Unsteady turbulent flow phenomena require fully three-dimensional, temporal measurement techniques to overcome the limitations of currently available point-probe and in-plane techniques. Representatives of the two latter techniques are laser Doppler velocimetry (Drain, 1980) and particle image velocimetry (Adrian, 1991), respectively. The two techniques are very valuable and widely used in experimental fluid

dynamics. Neither of the techniques, however, may be appropriate to investigate complex unsteady, three-dimensional flow fields. Three-dimensional global measurement techniques such as holographic interferometric tomography (Cha, 1992) and holographic particle image velocimetry (HPIV) have shown utility in experimental fluid dynamics. The first technique measures refractive index gradients induced by physical properties such as temperature and/or density. The second, HPIV, provides instantaneous three-dimensional, three-component velocity measurements of fluid flows at a resolution suitable, both spatially and temporally, for unsteady turbulent flow studies.

During the past few years, a variety of optical systems have been developed for HPIV, but some of them are difficult to apply in engineering environments. Those techniques often require complex and expensive optics and sophisticated test sections such as four transparent walls, etc. Basically, the optical arrangements for the technique can be classified into two groups: in-line (Weinstein, 1985) and off-axis (Coupland and Halliwell, 1992) holography. The in-line approach, as shown in Fig. 1, uses a single collimated beam of coherent light which passes through a test volume populated by seeded particles. A portion of the beam is diffracted by the particles, and the rest passes undiffracted. These two waves interfere and form fringe patterns on a holographic film plate. When the recorded fringe patterns are illuminated with reconstruction beam, images of the particles, virtual and real, are reconstructed. The approach uses forward scat-

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tered light from the particles, which has the highest light scattering efficiency, and thus low laser pulse energy is required. The in-line system can be implemented in a simple way, hence it can be less susceptible to facility vibration and is free from the constraint of the coherent length of the light source. However, particle images reconstructed from an in-line hologram are intrinsically noisy due to speckle. During reconstruction, the virtual image, real image, reconstruction beam, and recorded cross-interference pattern of particle diffraction emerge together in the same direction and interfere with each other (Cha, *et al.*, 1994). Since there is only one beam path, it is not easy to control the reference-to-object beam intensity ratio which is crucial to record good quality holograms. In addition, the small forward scattering angle leads to a large depth of field, which causes the particle images to be elongated along the longitudinal direction. This practically restricts velocity measurement to the two transverse components (Zimin, *et al.*, 1993). Therefore, stereoscopic views have been practiced to determine the out-of-plane velocity component (Weinstein, *et al.*, 1985; Blackshire, *et al.*, 1994; Barnhart, *et al.*, 1994). Recently, some innovative in-line approaches for overcoming those drawbacks of conventional in-line holography, by utilizing a multibeam technique (Zimin, *et al.*, 1993) or by employing raster devices and a conical filter (Zimin and Hussain, 1994), have been reported.

In off-axis holography, two separate beams of coherent light are used, as shown in Fig. 2. One beam illuminates seeded particles in a test volume, and either side scattered or near-forward scattered light from the particles serves as an object wave. The other, reference, beam is expanded and directed to a film plate to interfere with the object wave. For reconstruction, it is ideal to use the reference beam as a reconstruction beam. These two beams can be either collimated or spherical; however, it is convenient to have a collimated beam for practicing the phase conjugate reconstruction technique (Vest, 1979; Barnhart, *et al.*, 1994). During reconstruction, the virtual image, real image, and reconstruction beam are spatially separated, and thus the speckle noise associated with the in-line approach can be greatly minimized. By the use of off axis particle scattering, which has a more uniform angular distribution than forward scattering does, the hologram records a scattering aperture much larger than that of an in-line hologram. Therefore, the reconstructed particle image has a smaller depth of focus

(Zimin, *et al.*, 1993). However, a laser source for the off-axis holography requires some special features including high pulse energy and long coherence length. High energy is required because the light scattering efficiency of the off-axis setup is lower than that of the in-line counterpart (2 to 3 orders of magnitude). The use of a separate reference beam requires the laser to have long coherence length so that the set-up can be more flexible. Modern laser technology has already provided a suitable laser<sup>1</sup> (Barnhart, *et al.*, 1994), and will hopefully provide a better laser at a lower price. One interesting setup reported was off-axis HPIV with forward scattered light (Zhang and Katz, 1994).

As a natural extension of existing HPIVs using the forward, near-forward, and side scattering, we propose a new optical system for HPIV which uses the backward light scattering from the particles. The technique, termed single port access HPIV, requires only a single optical window mounted on a test section, and thus can be of great engineering interest.

## HOLOGRAPHY SYSTEM

The HPIV system being developed for this effort is shown in Fig. 3. The system is a derivative of the double-exposure, double-reference-beam, off-axis HPIV (Cha, *et al.*, 1994), but an innovative idea behind the system is to use back scattered light from the particles as the object wave. A 45° beam splitter inserted in front of a single optical window mounted on a test volume serves to admit the illuminating beam and extract the back scattered light. A frequency-doubled Nd:YAG laser with an energy of 200 mJ per pulse and pulse width of 5 ns or an argon-ion laser operating at 514.5 nm is used as the light source. Initially, the argon-ion laser is chosen to serve as a reconstruction laser, but is also used for recording during preliminary tests. The laser beam is split into two; the illumination beam (about 92 % of the output energy) and the reference beam (the rest of the output energy). The illumination beam, expanded by a negative lens, transmits through the 45° beam splitter, and illuminates particles in the test volume. A portion of the backscattered light of the particles is reflected by the beam splitter to the holographic film plate. A relayer

<sup>1</sup>Frequency-doubled Nd:YAG laser; 300 mJ pulses @ 532 nm; coherence length of > 1 m.

(Thompson and Malyak, 1985) consisting of two identical achromat lenses, 10.2 cm in diameter, sits between the test volume and the film plate. The relayer forms real images of the particles in front of the plate with one-to-one lateral and longitudinal magnifications. The relayer was used to enhance the collection efficiency of the back scattered light from the particles. Even without the relayer, stronger back scattered light can be achieved by moving the holographic film plate closer to the test section. However, there are limiting factors for the distance between the two, for example, the angle between the reference and object beams, discussed below, and the physical construction of the test section. Another way to keep the distance short may be to utilize reflection holography instead of the currently employed transmission holography. The reference beam is spatial-filtered, and directed to the holographic film plate at an angle of 20° relative to the normal to the plate. This angle satisfies a requirement regarding the resolution limits of the emulsion of the film plate (Newport, 1994). To accommodate a laser with a short coherence length, a delay line in the reference beam path is used to match that optical path length to the object beam pathlength. To optimize the holograms, two high power variable attenuators are incorporated to adjust the intensity ratio of the two beams. The intensity ratio of the reference-to-object beams was about 7:1 for most runs in this study. The holograms are recorded on Agfa-Gavaert 10E75 10.2x12.7 cm<sup>2</sup> photographic plate, and processed in a standard procedure.

An argon-ion laser, with 514.5 nm wavelength, is used for the reconstruction of the particle images, because its wavelength is close to that of the Nd:YAG laser, 532 nm. However, a frequency-doubled Nd:YAG laser operating in cw mode would be a better option for the reconstruction. Change in magnification in the longitudinal direction and distortion in the lateral direction due to the wavelength difference between the two lasers (Collier, *et al*, 1971) will be corrected. Imperfections in the relayer may result in additional aberrations which will have to be corrected. The virtual images of either the particles or their real images can be reconstructed depending on whether the relayer is employed. The virtual images can also be formed behind the plate with a different relayer setup.

In single port access HPIV, the displacement of each particle over a certain time interval can be captured on a single film plate at two moments with two different reference beams. To utilize this double-reference-beam technique, corresponding optics to generate the second reference beam are to be added

to current system shown in Fig. 3. The particle images at each moment can be independently reconstructed, and the reconstructed images are to be captured by an image acquisition system for further processing to extract the three-dimensional displacement. The image acquisition system is a CCD camera with macro optics mounted on a three-axis translation stage to scan the three-dimensional images. The real images of the particles can also be reconstructed using the conjugate image technique.

## RESULTS AND DISCUSSIONS

There are several experimental parameters which govern the success of this HPIV technique, including the coherence length. A longer coherence length laser can allow one to not only make the optical system flexible but also increase the size of the test volume which can be recorded. Since the coherence length of the recording Nd:YAG laser to be used is quite short, approximately 5 cm, an argon-ion laser with a much longer coherence length has been used to both record and reconstruct the test holograms. After the rest of parameters are well characterized, tests for this concept will be continued as originally planned, using the Nd:YAG laser. For the same reason, two solid test objects were used instead of particles.

The first test target was a screw with a washer sitting on a post, as shown in Fig. 4. Its typical reconstructed virtual image obtained from the present system (minus the relayer) is shown in Fig. 5 (a). The image was captured with an image acquisition system consisting of a CCD camera and a PC interfaced by a frame grabber board. Due to the backward scattering the central part of the image is bright. The hemispherical image around the target images is the ground glass edge of the beam splitter. This image is brighter than the target image because of the forward scattered light from it. Figure 5 (b) shows a reconstructed virtual image of the same target with the system employing the relayer. Since the relayer setup was not perfect, the image is distorted and demagnified.

The second target consisted of four pins, around 0.8 mm in diameter and of different heights for identification. Their relative positions are shown in Fig. 6. Our interest in this experiment was whether the technique can resolve images of the pins located in different places, especially along the longitudinal direction. In a similar manner, a hologram of the target was taken without the relayer. Its reconstructed virtual image was relayed by an achromat lens located behind the holo-

graphic plate, and captured by the image acquisition system. The CCD camera lens, used for the first target, was not employed in this run, thus the relayed image appeared directly on sensing array of the CCD camera. By translating the camera along the optical axis with a precision stage, we grabbed the relayed image of the reconstructed virtual image of the four pins at different longitudinal locations. Figure 7 (a) and (b) are the reconstructed images grabbed at sections A-A and B-B in Fig. 6, respectively. As shown in the figures, the image of the pin sitting on each section, P1 for section A-A and P2 for section B-B, is more distinct (in-focus) than those of other pins (out of focus). It is believed that the technique utilizing the backward light scattering from the target can reconstruct a three-dimensional image of the target, thus being able to be used for measuring the out-of-plane velocity component. The reconstructed images of the two test targets obtained with the proposed system are clear and distinctive from their backgrounds. Other characteristic studies are under way and currently, the plane wave, which provides more uniform intensity, is being used for both illumination and reference beams.

**FUTURE WORK:** To test the proposed technique, images of a cluster of fine particles will be recorded. The particles (less than a few microns in diameter) will be embedded in a transparent plastic material. A parametric study will be conducted to find the optimal density of the particles as functions of particle sizes and depth of field. To extract a three-dimensional velocity, the technique can be combined with the transplacing-window cross-correlation and cross-product algorithm (Cha, *et al*, 1994). In order to test the applicability of the HPIV technique in a flowing system, a lab scale film cooling jet will be investigated.

## CONCLUDING REMARKS

A single optical access port concept for HPIV has been introduced and tested. Preliminary results show that the concept is feasible. The technique recorded the holograms of the test targets using backward light scattering. Three-dimensional images of the targets were reconstructed. The resolution limits of the technique are under investigation and will be reported in the future.

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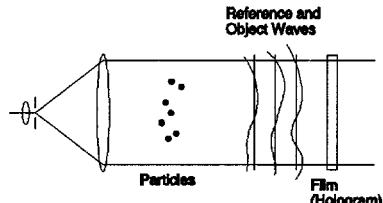
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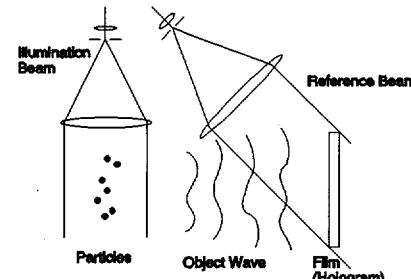
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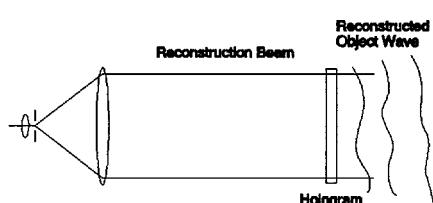
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(a)



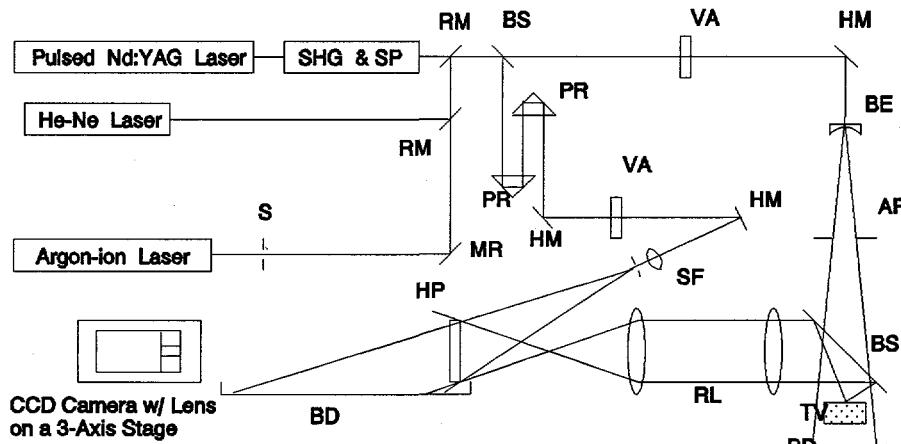
(a)



(b)

Figure 1. Schematic of in-line holography for HPIV: (a) recording the hologram of the particles and (b) reconstructing the object wave.

Figure 2. Schematic of off-axis holography for HPIV: (a) recording the hologram of the particles and (b) reconstructing the object wave.



SHG & SP: 2nd harmonic generator & separator; S: shutter; VA: variable attenuator; RM: removable mirror; BS: beam splitter; PR: prism; BE: beam expander; SF: spatial filter; MR: mirror; HM: high power mirror; HP: holographic plate; TV: test volume; RL: relayer; BD: beam dump; AP: aperture

Figure 3. Optical arrangement of single port access holographic particle image velocimetry.

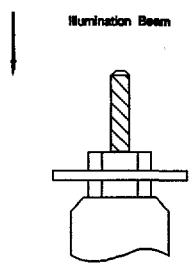
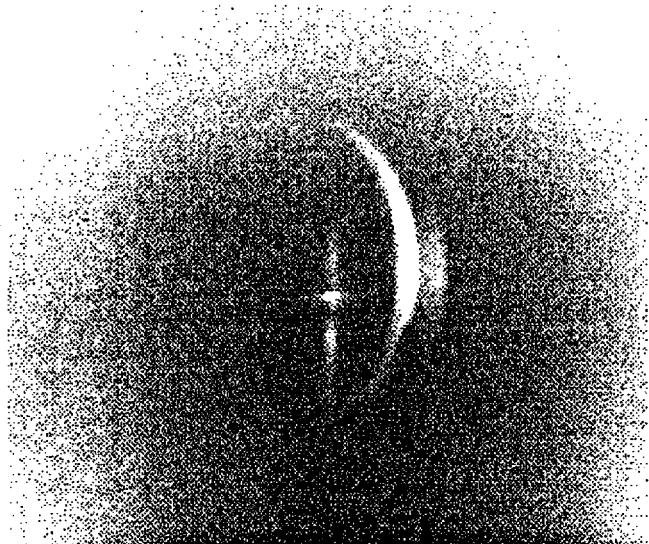
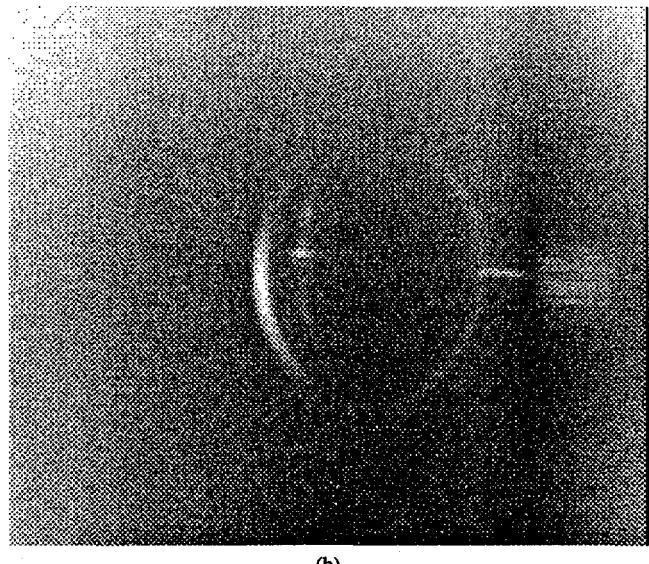


Figure 4. Sketch of the first test target: the screw with the washer sitting on the post.



(a)



(b)

Figure 5. Reconstructed virtual images of (a) the test target and (b) the real image of the test target with backward scattered light.

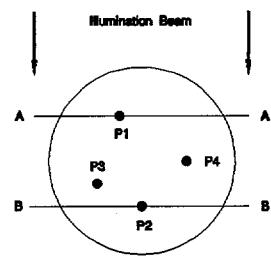
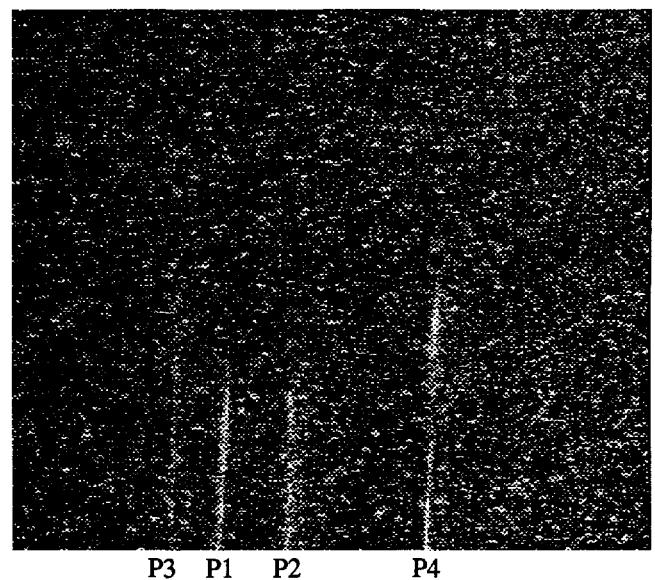
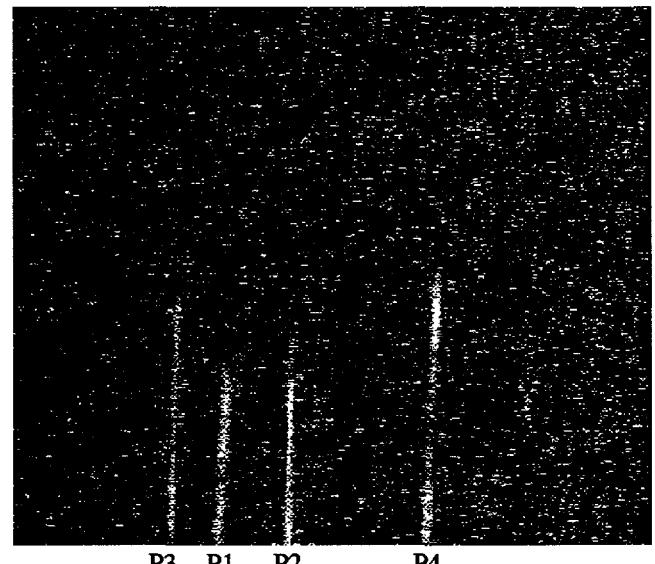


Figure 6. Top view of the four pins test target.



P3 P1 P2 P4  
(a)



P3 P1 P2 P4  
(b)

Figure 7. Reconstructed images of the pins at (a) section A-A and (b) section B-B in Fig. 6.