Note: Scanned multi-light-emitting-diode illumination for volumetric particle image velocimetry

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(Received 29 January 2010; accepted 26 July 2010; published online 16 September 2010)

We describe the development of both multilevel two-dimensional and grid-based three-dimensional illumination systems for volumetric particle image velocimetry (PIV) that uses a single camera and an arbitrary number of low powered lasers. This flexible system is robust and capable of capturing results over a range of spatiotemporal scales determined by the choice of camera, the depth of field of the lens, and the laser power. The system is demonstrated on a rotating spin-up experiment where we extract high fidelity velocity fields at up to 62 frames/s at a spatial resolution of 2352 $\times 1728$ pixels. The flexibility and economy offered by this system—approximately one-tenth that of a comparable commercial package—may make it attractive to many laboratory users. © *2010 American Institute of Physics.* [doi:10.1063/1.3480544]

Clearly, because the space-time evolution of the velocity field provides the solution to the momentum equation, it is of fundamental interest across a wide range of flows studied in science and engineering. Hence, particle image velocimetry (PIV) has been used extensively to investigate fluid flow. In the most common modality, PIV is used across a single laser illuminated plane that must either be considered as representative of the flow of the entire fluid body under examination or only locally representative. Whereas conventional PIV measures two velocity components, recent advances have made progress in overcoming this limitation including holographic,[1–3] translational stereoscopic,[2] dual plane,[4] and angular stereoscopic[2,5–7] approaches. While each of these developments significantly extends the capability of the original two velocity component PIV, they do not provide the ability to continuously record the velocity field in three dimensions at multiple locations within the flow. A method of volume illumination has been demonstrated,[8] but the results reveal that the particle concentration must be chosen judiciously in order to balance the desired spatial resolution against the signal-to-noise ratio of the particle image field. The commercially available solutions, including three-dimensional (3D) and tomographic PIV systems, are often fixed in their spatial and temporal resolution and are typically at least an order of magnitude more expensive than the approach described herein.

Here we describe the development of a robust PIV system that allows the user to acquire data at multiple locations within the fluid and to construct either a multilevel two-dimensional (2D) horizontal/vertical stack of velocity field measurements [Figs. 1(a) and 1(b)] or a 3D velocity grid [Fig. 1(c)].

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In this first genesis two essential design constraints were considered. First, and most importantly, we demand rapid (62 Hz) vertical and/or horizontal scanning of the lasers. Second, a small and flexible footprint is required for access to a variety of flow cell configurations and placements, such as upon a rotating table. The first requirement, rapidly changing from vertical to horizontal scanning, eliminates the possibility of the obvious choice of using a single laser with an oscillatory mirror.[9,10] Moreover, the required scanning speed makes the use of linear laser stage unfeasible. Although for both the 2D and 3D studies the number is arbitrary, in this stage of development we used up to ten low powered lasers. Images were captured at up to 62 frames/s, but we emphasize that this, too, is arbitrary and is constrained by the choice of camera. The PIV interrogation analysis requires image pairs; at maximum frame rate a sweep of the volume using all ten lasers takes approximately 1/3 s. While the utility of a particular scan rate is typically constrained by the phenomena under observation, the scan rate of this system can be increased or decreased to a value determined by the camera and lasers available to the researcher.

Each laser is a low powered unit (output <5 mW) with a cylindrical lens mounted in front of the light source to generate a light sheet. We seed the fluid volume with neutrally buoyant reflective particles (for the example discussed herein they are 100 μm silver coated hollow glass microspheres) then illuminate the fluid using the lasers and record image pairs. The difference between the system discussed here and standard two component PIV systems is that we use multiple lasers and hence generate multiple light sheets. This approach allows us to examine a range of velocity fields at distinct spatial locations throughout the fluid. The use of economical low powered lasers results in the need to amplify the intensity of the light in the volume being examined. This is accomplished by placing a mirror on one side of the fluid container (Fig. 1). The associated light reflection improves the uniformity and intensity of illumination throughout the measurement volume. However, the uniformity of the light

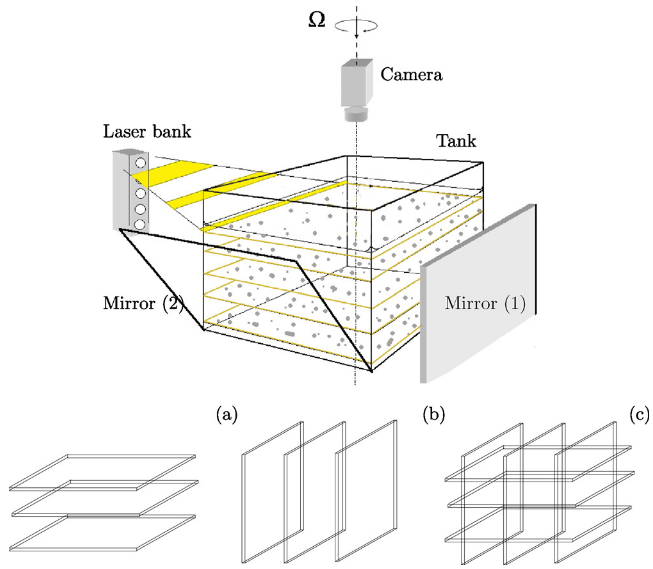

FIG. 1. (Color online) Schematic showing the experimental setup in the top panel and (a) 2D horizontal, (b) 2D vertical, and (c) 3D velocity grids. Mirror (1) is used to amplify the laser intensity and, as described in the text, mirror (2) is used for 3D velocity extraction.

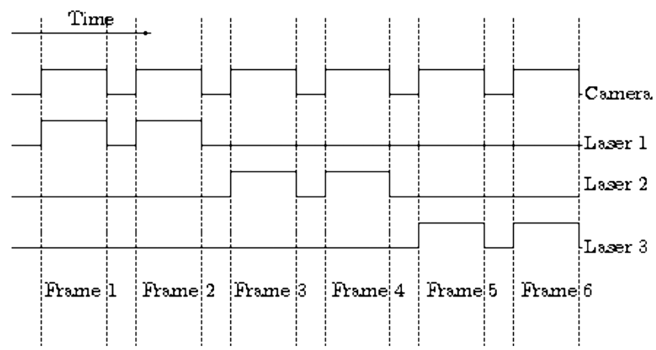

FIG. 2. Timing diagram over 6 frames showing the firing sequence of the camera and three lasers, the full 3D PIV system typically cycles over ten lasers and 20 frames. While this shows three lasers, in principle the system has no limit.

sheet is a function of the seed particle density and a matter of trial and error for the experimentalist.

The images for all PIV measurements should be sharply focused. The speed with which the volume is being scanned eliminates the possibility of automatically refocusing the lens at each vertical level. Therefore, we aim to exploit the fact that a lens has a depth of field (DOF) that provides us with a spatial domain (i.e., distance from the camera) within which to operate. A simple rule of thumb for the DOF is that for a given format size, the DOF is approximately determined by the subject magnification and the aperture. For a given aperture, increasing the magnification, decreases the DOF and decreasing the magnification increases DOF. For a given subject magnification, decreasing the aperture diameter increases the DOF, and increasing the aperture decreases the DOF. While reducing the aperture diameter increases the DOF, it also reduces the amount of light transmitted and increases diffraction, placing a practical limit on the extent to which the DOF can be increased by reducing the aperture diameter.

Balancing aperture and focal length of the lens is crucial to the success of this technique. Our test experiments have the commonly desired need to provide sufficient light to illuminate the seeding particles within the fluid while at the same time, ensuring that there is a sufficient depth of field in order to produce sharp images over the levels being scanned by the lasers. As each laser sheet is located at a fixed distance from the camera, there is a different linear mapping used during post-processing to convert pixel size into units of length.

The use of a single camera to capture three-dimensional grid data requires that a mirror be mounted at one side of the tank at an angle of 45° to the camera (Fig. 1). Images of particle movement in the vertical plane are then recorded from the mirror rather than from the fluid volume itself. Clearly, for the 2D multilevel system this mirror is superfluous.

The camera used is a Dalsa 4M60 capable of recording at either 8 or 10 bit depth with a resolution of 2352 (H) $\times 1728$ (V). The camera has four taps resulting in a maximum data transfer rate of 4×80 MHz, which provides a maximum of 62 frames/s. We note that although the frame rate can be further increased by a reduction in the vertical resolution, this was not carried out during this study. The camera is attached to a Bitflow Karbon PCI Express frame grabber (KBN-PCE-CL2-F) using the camera link interface (CL). This board can service either a base, medium or full CL camera. The frame grabber is in turn housed in an octal core SuperMicro workstation with a dedicated small computer system interface raid array used to store data directly from the camera.

The PIV system requires that the camera records a frame at the same time that a laser illuminates the flow, and hence two lasers cannot fire during the same frame. To ensure the correct timing between camera and the lasers we make use of a trigger on the frame grabber. The trigger pulse is sent to a printed circuit board that contains a Parallax Basic Stamp module (BS2px24) that then controls which laser will fire and the duration of the laser pulse. The Basic Stamp module is fully programmable and operates at 32 MHz processing up to 19 000 PBASIC instructions/s. This system allows the experimentalist complete freedom to use as few or as many lasers as is necessary. The programmable nature of the firing sequence of the lasers also allows scanning of the flow in any sequence and this can be tailored to the particular experiment, for example, an in depth examination of one or more rapidly evolving areas can be carried out while only taking periodic measurements in areas of where the flow is evolving less rapidly. The camera operates in free-run mode in the sense that while it is responsible for the timing, the frame grabber fires a trigger at the start of each frame. An example of the timing diagram is shown in Fig. 2 and highlights the firing sequence of the camera and three lasers. After post-processing, results recorded by the illumination of the laser sheets provide the raw velocity data that correspond to either a vertical or horizontal level in the velocity grid. There will be time-sweep limitations due to camera and laser repetition rates. In its present modality the system performs without measurable error at up to 62 frames/s (the maximum frame rate of the camera at full resolution), testing at higher frame rates is beyond the scope of this study.

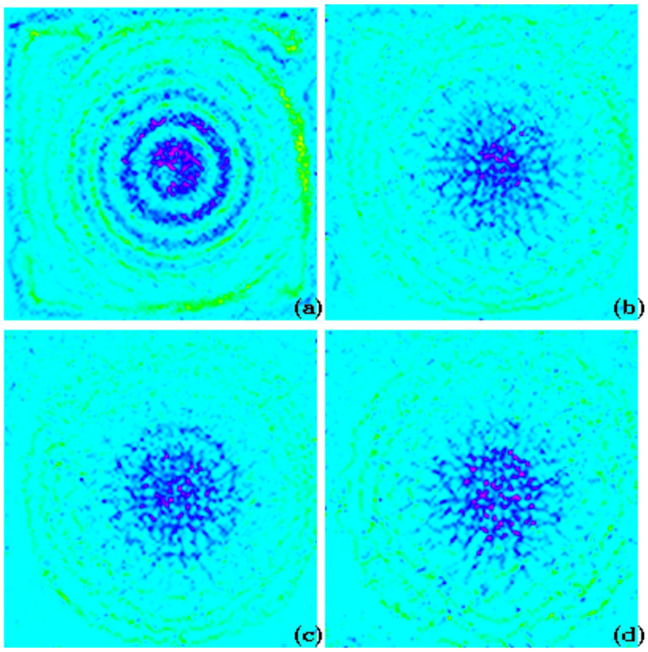

FIG. 3. (Color online) [(a)–(d)] Vorticity maps ($\omega = \nabla \times \mathbf{u}$) highlight the variation in fluid motion throughout the depth of the tank (in the rotating frame of reference). Optimal velocity results were obtained by using image pairs recorded at approximately 1/6 s intervals.

Sample results from a horizontal 2D multilevel study are presented to illustrate the PIV system described here. We observe pattern formation during transient convective spin-up experiments where buoyancy forcing is supplied by evaporative cooling from the top surface of a layer of water. The experiments are carried out on an Australian Scientific Instruments rotating table, with a working surface diameter of 1 m. The workstation, lasers, camera, and fluid filled tank ($0.2 \times 0.2 \times 0.25$ m^3) are arranged on the table. The lasers are located at 25.4 mm vertical spacings throughout the fluid. The camera and laser system are then used to record and illuminate the flow. The rotating table has a camera stage located 1.6 m from the fluid volume. The lens in the system was a Nikon 24–85 mm f/2.8–4.0D IF AF zoom Nikkor, used with a focal length of approximately 50 mm and an aperture of 3.0. The DOF suitable for PIV post-processing was approximately 100 mm which was sufficient to provide a sharply focused image over all the layers throughout the fluid volume.

Using our PIV method, we can extract each term of the momentum equation from the velocity field. In consequence, we demonstrate that a convective ring, or "bulls eye," state arises from the transient balance between Coriolis and viscous forces which dominate inertia. In Figs. 3(a)–3(d) we show horizontal vorticity fields at a given time in the evolution of the flow from only four of the ten possible lasers. This example shows rapidly varying vertical and horizontal structures, with the ring pattern decaying with depth, and demonstrates how the technique described here captures the detailed structure of the velocity field. A complete description of the fluid mechanics of this particular rotating convective system are discussed in a paper dedicated to the topic.[11]

We have developed a low-cost multilevel two-dimensional and grid-based three-dimensional PIV system with design benefits that allow great flexibility to study flows of many configurations and intrinsic time scales. The use of a single camera in conjunction with an arbitrary number of low powered lasers is an inexpensive method of generating a grid of high fidelity PIV data. While the systems design will not allow it to compete with megahertz scan rates obtained by single a laser/oscillatory mirror, the system provides a unique degree of flexibility through the programmable illumination sequences. The utility of the approach has been demonstrated in a study of the structure of evaporatively driven convective spin-up. The structure of such a flow would not have been accessible using a one laser linear stage system, and the fidelity and quality of the results are on par with substantially more costly commercial PIV systems yet with the added benefit of substantially more flexibility.

This research was funded by the NSF under Grant No. OPP0440841 and Yale University. M.D.P. would like to thank Stuart Dalziel and John Milton.

[1] J. M. Coupland and N. A. Halliwell, Appl. Opt. **31**, 1005 (1992).
[2] A. K. Prasad and R. J. Adrian, Exp. Fluids **15**, 49 (1993).
[3] D. H. Barnhart, R. J. Adrian, and G. C. Papen, Appl. Opt. **33**, 7159 (1994).
[4] M. Gharib, M. Raffel, O. Ronneberger, and J. Kompenhans, Exp. Fluids **19**, 69 (1995).
[5] G. M. Harrison, N. J. Lawson, and D. V. Boger, Chem. Eng. Commun. **188**, 143 (2001).
[6] N. J. Lawson and J. Wu, Opt. Lasers Eng. **32**, 1 (1999).
[7] A. K. Prasad, Exp. Fluids **29**, 103 (2000).
[8] C. D. Meinhart, S. T. Wereley, and M. H. B. Gray, Meas. Sci. Technol. **11**, 809 (2000).
[9] Ch. Brücker, Exp. Fluids **19**, 255 (1995).
[10] T. Hori and J. Sakakibara, Meas. Sci. Technol. **15**, 1067 (2004).
[11] J.-Q. Zhong, M. D. Patterson, and J. S. Wettlaufer, Phys. Rev. Lett. **105**, 044504 (2010).