Experiments in Fluids (2005) 39: 159–169
DOI 10.1007/s00348-005-0991-7

R. J. Adrian

Twenty years of particle image velocimetry

Received: 4 October 2004 / Revised: 25 March 2005 / Accepted: 25 March 2005 / Published online: 6 July 2005

Abstract The development of the method of particle image velocimetry (PIV) is traced by describing some of the milestones that have enabled new and/or better measurements to be made. The current status of PIV is summarized, and some goals for future advances are addressed.

1 Historical development

The year 2004 marked the 20th anniversary since the term “particle image velocimetry” (PIV) first appeared in the literature. This article gives a personal view of the development of PIV over those 20 years, followed by a summary of the current state-of-the-art and a prospective view of some of the improvements that are needed and the future possibilities in the field. The presentation reflects the author’s experiences and views of certain developments that seemed particularly important or interesting. No attempt has been made to make the presentation exhaustive, or to credit in any way that is complete the many people who have advanced the field. The reader can achieve a much more complete understanding of the full scope of these developments by referring to the excellent compilation of papers by Grant (1994), to a very good book on PIV by Raffel et al. (1998), and to the bibliography of PIV by Adrian (1996), which is almost exhaustive through 1995 and documents much prior work, including all of the first decade. Three special issues on PIV (Kompenhans and Tropea 1997; Adrian 2000, 2002) contain very useful collections of the more recent work. Lastly, the reader can find many examples of state-of-the-art applications in this Special Issue.

The most rudimentary form of PIV could probably be traced far back in history to the first time a person possessing the concept of velocity watched small debris moving on the surface of a flowing stream. For example, Fig. 1 shows algae floating on the waters of a moat in the backs of Trinity College, Cambridge, UK. It is almost inconceivable that a great intellect like Isaac Newton would not have observed the moving patterns and seen the potential for visualizing and even measuring the surface velocity from the displacements of the particles of algae. From this viewpoint, particle velocimetry is old and very simple. However, in its modern form, PIV means the *accurate, quantitative measurement of fluid velocity vectors at a very large number of points simultaneously*, and we now understand that this is, indeed, a very challenging, complicated, and relatively recent achievement.

The first investigators to achieve such measurements actually used the method of laser speckle, originally developed in solid mechanics, and showed that it could be applied to the measurement of fluid velocity fields. In 1977, three different research groups, Barker and Fourney (1977), Dudderar and Simpkins (1977), and Grousson and Mallick (1977), independently demonstrated the feasibility of applying the laser speckle phenomenon to fluid flow by measuring the parabolic profile in laminar tube flow. The principal elements of their experiments were the use of double-exposure photographs and planar laser light sheet illumination and interrogation by forming Young’s interference fringes from the many pairs of displaced laser speckles in small interrogation spots on the specklegrams. By 1983, a young doctoral student working at the v. Karman Institute, Belgium, Meynart (1979, 1980, 1982a, 1982b, 1983a, 1983b, 1983c), was the leading practitioner of this method, and he had shown that practical measurements

R. J. Adrian
Laboratory for Turbulence and Complex Flow,
Department of Theoretical and Applied Mechanics,
University of Illinois, Urbana, IL 61801, USA

Present address: R. J. Adrian
Department of Mechanical and Aerospace Engineering,
Arizona State University, Tempe, AZ 85287-6106, USA
E-mail: rjadrian@asu.edu

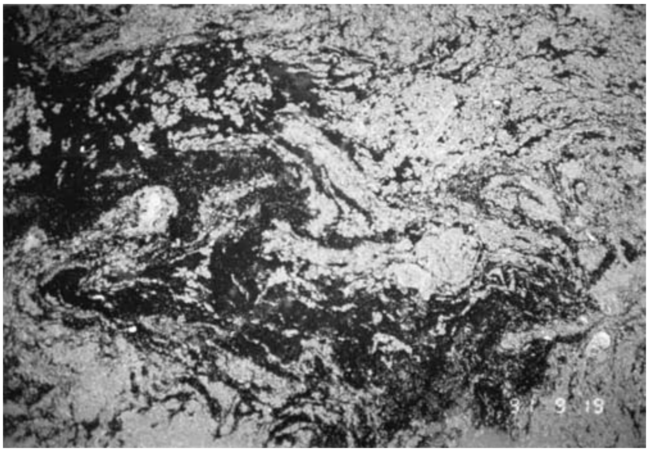

Fig. 1 Algae floating on the surface of water serve as flow markers for elementary particle image velocimetry

could be made in laminar flow and turbulent flow of liquids and gases, thereby stimulating intense interest from the fluid mechanics community.

While Meynart referred to his work as *laser speckle velocimetry* (LSV), the images in his papers often contained images of individual particles instead of speckles. The first explicit recognition of the importance of particle images was made in two short, contemporaneous papers by Pickering and Halliwell (1984) and Adrian (1984). In the latter, it was argued that the illumination of particles in fluid flows by a light sheet would seldom, if ever, create a speckle pattern in the image plane. Instead, the image plane would contain images of individual particles, such as those shown in Fig. 2. The name *particle image velocimetry* (PIV) was proposed to distinguish this mode of operation from the laser speckle mode. A simple criterion was defined by which one could predict the occurrence of one mode or the other using a dimensionless number called the *source density*. The source density equals the mean number of particles in a resolution volume, and the number of overlapping images in the image plane can be expressed in terms of it. For fluids, the allowable concentration of scatterers is normally too small to produce source densities large enough to have speckle patterns formed by overlapping images. Higher particle concentrations are either not achievable or not desirable fluid dynamically (unless one intends to produce two-phase flow effects). Hence, one almost always sees particle images rather than speckles.

Many researchers became interested in PIV because it offered a new and highly promising means of studying the structure of turbulent flow. This goal strongly influenced the choices made in the development of the method. By its nature, turbulence is a phenomenon that occurs over a wide range of physical scales, extending from the largest scales of the flow down to the Kolmogorov scale. Hence, a successful measurement technique must be able to measure over a wide dynamic range of scales in length and velocity. Another salient feature of turbulence is its randomness, which may make it impossible to determine a priori the direction of flow. Hence, the measurement technique must be able to sense flows in all directions. Turbulence also occurs at high Reynolds number, which often means high velocity. Accelerations are large, and, therefore, the particles must be small enough to follow the flow in the presence of large local and randomly fluctuating accelerations. This implies the use of very small particles, a few microns in size, and the small light scattering cross-section of such particles implies the use of high intensity illumination. Coupled with the short time exposures needed to capture images of fine particles without blurring, these requirements lead naturally to the use of high intensity, pulsed lasers.

Fig. 2 Double-pulsed image having low source density and high image density. Flow is from left to right

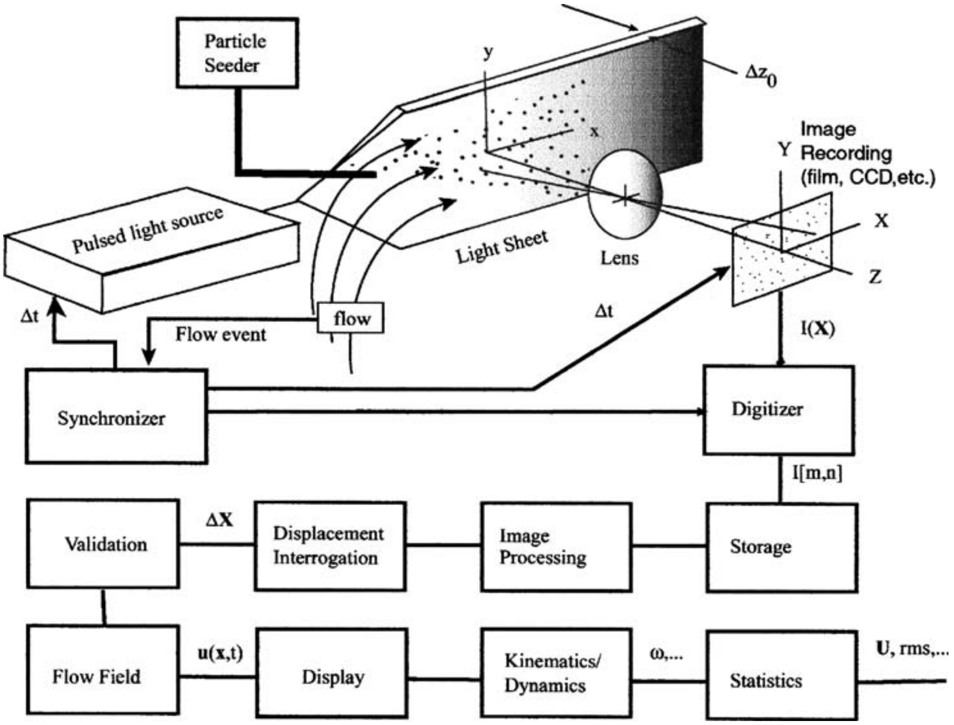

Fig. 3 Typical monoscopic particle image velocimetry system

While these features were necessary for turbulent flow, the capabilities they gave were also useful over a wide range of fluid flow problems. Consequently, the standard basic PIV system now consists of a pulsed laser with a light sheet illuminating particles a few microns in diameter in gases and, perhaps, a few tens of microns in liquids. The main option for recording the images is interline-transfer PIV video cameras, and interrogation by correlation analysis is a de facto standard, at least for the present moment. A typical single-camera system is shown in Fig. 3. These choices seem obvious now, but 20 years ago, one was faced with choosing between chopped continuous wave (CW) lasers, pulsed lasers, CW illumination with a shuttered recording camera, or xenon flash lamps. Then, there was also a variety of illumination coding sequences, including double-pulsed, streak, streak and pulse, multiple-pulsed, and non-uniformly spaced pulses. In a review paper (Adrian 1986a), the author once attempted to encompass systematically all of the various possibilities for optical velocimetry by listing the leading candidates for various types of illumination, coding, particles, image recording, and interrogation. Given about three to five different candidates for each of these categories, there were several hundred combinations that might have produced potentially viable systems. In the mid-1980s, the confusion engendered by this wealth of options was quite evident: one could find dozens of papers describing different types of flow-measuring systems that used optical imaging of particles, each differing from the other by their means illumination, coding, particles, recording, and interrogation.

The energy necessary to illuminate fine particles and produce images of sufficient exposure and clarity was a major issue in PIV. From experience with laser Doppler velocimetry, there existed a good understanding of the particle sizes needed to follow turbulent flows, and of light scattering, so it was possible to compute, using Mie scattering theory, the exposure of images that would result for appropriate particles. In particular, it was possible to show that pulsed lasers would provide enough energy to obtain good photographic images from micron-sized particles in air and 10–30-μm-sized particles in water. Subsequently, a big step in PIV practice was to use double-pulsed solid-state lasers. They produced excellent double exposure photographs of particles without much limit on speed or fluid using high-resolution (300 line/mm) film. The earliest use of Nd:Yag lasers appears to be in 1986 (Kompenhans and Reichmuth 1986). Still later, Nd:Yag lasers became available in compact, dual oscillator packages with self-contained cooling supplies, and they have become the current workhorse of PIV.

The idea of using auto-correlation of double-exposure images of multiple particles in small interrogation spots, instead of measuring the spacing and orientation of Young's fringes that form from illuminating such spots, was first proposed in 1983 (Sutton et al. 1983; Adrian and Yao 1984).[1] Details aside, the two approaches are related by Fourier transform, but the sharp signal peak in the correlation plane is

---

[1] There may be *many* earlier papers from different fields that suggested using correlation in somewhat different contexts. For example, Soo et al. (1959) presented a particularly prescient proposal for the "determination of turbulence characteristics of solid particles in a two-phase stream by optical cross-correlation." Leese et al. (1971) describe "an automated technique for obtaining cloud motion from geosynchronous satellite data using cross-correlation."

obviously the correct signal on which to base measurements. In both methods, the entire image is divided into a grid of (usually overlapping) interrogation spots, and the particle images in each spot are interrogated to obtain the mean displacement of the particles within each interrogation cell, which consists of the intersection of the interrogation spot area, A_I, and the thickness of the light sheet, Δz_0. Analysis of the auto-correlation method (Keane and Adrian 1992) led to the definition of a second dimensionless number, called the *image density*. It is equal to the average number of scatterers in an interrogation cell. This number proved to be very important in describing the characteristics PIV systems and in optimizing their design. The low image density limit corresponds to particle tracking, because, in that limit, it is improbable to find more than one image pair per spot. The high image density limit corresponds to multiple particle correlation PIV (Fig. 4).

In the first decade of PIV, the greatest challenge was the interrogation of the images, simply because computer capabilities were not adequate for the task. In 1985, the DEC PDP 11/23 was a common digital computer in many fluids laboratories. It typically had 128 KB of RAM and a 30 MB hard drive. Imagine holding the operating system, the executable program, and the data in a RAM space that is the same size as the minimum document file size used by current word processors. Practically, it was impossible to perform two-dimensional Fourier transforms or two-dimensional correlation analysis on such machines. Therefore, there was considerable interest in non-statistical methods, such as tracking particles individually. Alternatively, several groups seriously pursued the determination of two-dimensional correlations by analog optical means (Morck et al. 1993; Vogt et al. 1996). Particle tracking implied operating with low image density so that the probability of finding more than one pair of particles per interrogation spot was small. Then, using the principle that nearest-neighbor images corresponded to the same particle (which is only approximate for small, but finite image density), one could make successful measurements. The difficulty with this method was that, at the reduced image density that accompanied reduced particle concentration, the number of vectors per unit area was not large enough to resolve turbulent fields completely.

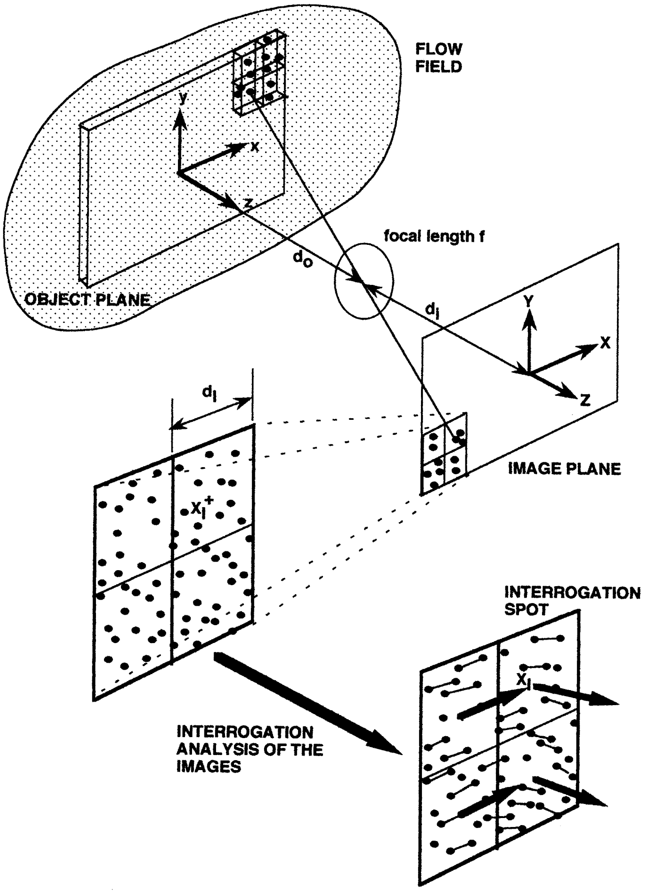

Fig. 4 Analysis of a grid of interrogation spots

To improve the spatial resolution, various investigators sought to optimize the low image density method by using interrogation windows of variable size, shape, and displacement. This led to the implementation of adaptive windowing methods. Currently, adjustable window methods enjoy use as a means of optimizing single-exposed double-frame images obtained with digital cameras.

At the time that Meynart performed his work using Young's fringes, the dynamic velocity range of the technique, defined as the maximum velocity measurable divided by the minimum velocity measurable, was somewhere between 5 and 10. PIV was a velocity-measuring instrument that had a 1-digit display! The dynamic range was clearly far too small for the method to be of value in serious fluid mechanics research. The problem was that the dynamic range corresponds to the maximum displacement of the images divided by the minimum displacement that can be measured. In the double-exposure images used at the time, the lower limit was determined by the images overlapping when the displacement was less than 1 image diameter. Thus, if the maximum displacement was 10 image diameters, the dynamic range was approximately 10:1.

The idea of applying an artificial spatial shift to the second image was developed to improve the dynamic velocity range and to provide a means of determining the direction of the particle displacement from double-exposed images (Adrian 1986b). In this method, the images were recorded in such a way that the second image was shifted precisely in a known direction so that the direction of flow could be determined unambiguously. Further, the probability of two images from the same particle overlapping was zero, and this solved the critical problem of limited dynamic range. By eliminating the overlap of particles images at small displacements, the dynamic range immediately increased to somewhere between 100 and 200, where it remains to this day. Although researchers continue to strive for a larger dynamic range, it is now large enough to permit good measurements, provided the PIV system is optimized.

Various methods of interrogation by correlation, including correlation of separately recorded exposures, have been investigated in theoretical/numerical simulation studies (Keane and Adrian 1992). The main issue is whether or not the signal peak in the correlation plane is larger or smaller than the random noise peaks. If it is smaller, the wrong displacement is identified, and the measurement is *invalid*. The essence of the simulation studies was contained in a simple curve that collapsed the behavior of all the different systems—autocorrelation, cross-correlation, variable window size, and multiple-exposure systems—onto a single plot of the probability of a valid measurement versus a single dimensionless parameter (Fig. 5). This parameter characterizes the effects of out-of-plane loss of images (F_0 is the mean fraction of particles in an interrogation cell that remain within the light sheet after displacing perpendicular to the light sheet), in-plane loss of images (F_I is the mean fraction of particles in an interrogation cell that remain within the interrogation spot after displacing in the plane of the light sheet), measurement volume size and shape, and particle concentration (as contained in N_I). The non-dimensional parameter $N_\mathrm{I}F_\mathrm{I}F_0$ is essentially the mean number of particle image pairs per interrogation volume, taking into account the size of the volume due to windowing—a sort of generalized image density. The curve in Fig. 5 proves to be the single most important curve needed to optimize a PIV system, i.e., to achieve a high probability of valid measurements. If the value of $N_\mathrm{I}F_\mathrm{I}F_0$ is above 7–10, the probability of making valid measurements is very high—approaching 100%. Then, straightforward interrogation by correlation yields excellent results with a very high density of vectors, like the field shown in Fig. 6. If, however, one were to reduce the size of the measurement volume, two things happen: the mean number N_I decreases, and the fractions F_I and F_0 also decrease because fewer particles remain within the smaller volume for both exposures. Decreasing the value of $N_\mathrm{I}F_\mathrm{I}F_0$ by even a factor of two from, say, 10 to 5 drastically reduces the fraction of valid vectors.

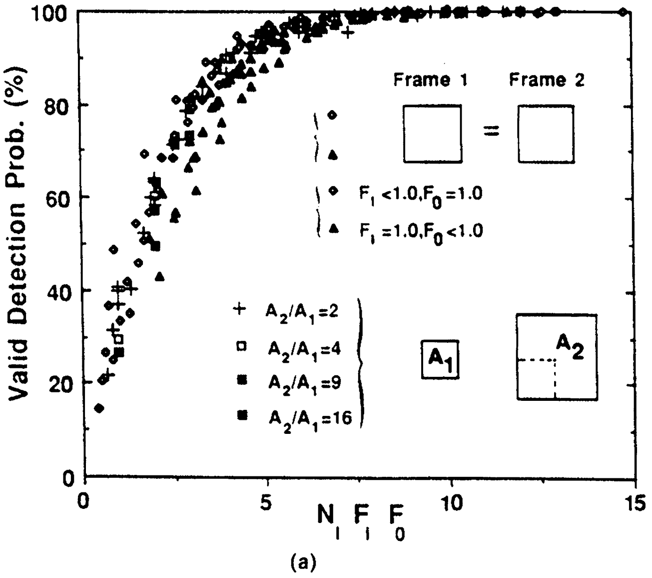

Fig. 5 Probability of successful correlation analysis of an interrogation spot versus the image density, defined as the mean number of particles in the interrogation spot. Correlations between spots of different area are considered (Keane and Adrian 1992)

One of the most important changes in the PIV technique was the move from photographic to videographic recording. This change profoundly influenced the usability and, hence, the popularity of PIV. Of course, many researchers had been using digital cameras in preference to film for years. For example, film recording was seld()om used in Japan. But, in the early 1990s, several investigators, most notably Willert and Gharib (1991) and Westerweel (1993), published results indicating that the low resolution of digital cameras was not as serious an issue as others had supposed, and that digital PIV could be accurate enough to provide useful results. Photographic film possessed very high resolution—100 line/mm for T-Max and 300 line/mm for Technical Pan on 25×35 mm, or even 100×125 mm films. In comparison, digital camera resolution was typically 500×500 pixels. However, digital cameras possessed high regularity in the location of the pixels relative to random locations of grains on a film, and clever methods were developed to enhance the accuracy of the interrogation of digital images. Moreover, the resolution of digital cameras increased rapidly to 1,000×1,000 pixels, and current 11-megapixel cameras are essentially equivalent to 100 line/mm 35 mm film.

In the early 1990s, it was clear that digital imaging would become the standard at some point in the future. What was perhaps not appreciated was the extent to which digital imaging could simplify PIV and make it a process with which everybody was willing to work. The work by Nishino et al. (1989) was extremely influential in this regard. They presented the best turbulence statistics available from PIV at the time. They achieved highly stable averages by taking over 19,200 video images. This was far beyond anything one could do with photographic film. The appeal of digital PIV rested not only on the ease of acquiring images, but it also eliminated the problem of mounting and carefully registering each film frame on an interrogation table. The maximum number of PIV photographs taken by even the most determined investigators seldom, if ever, exceeded 1,000. If one wanted good, accurate turbulence statistics, it was necessary to use digital PIV. Hence, digital PIV enjoyed increasing use in the mid-1990s, and now it is used almost exclusively. The possibility of taking thousands of PIV images made it desirable to speed up the interrogation process and to automate the vector clean-up process. Dantec developed and sold an impressively fast hard-wired PIV correlator, but, ultimately, the incredible advance of PC capability and the flexibility of software drove the development away from specialized, hard-wired devices.

The other outstanding impact of digital PIV came with the advent of interline transfer cameras that could

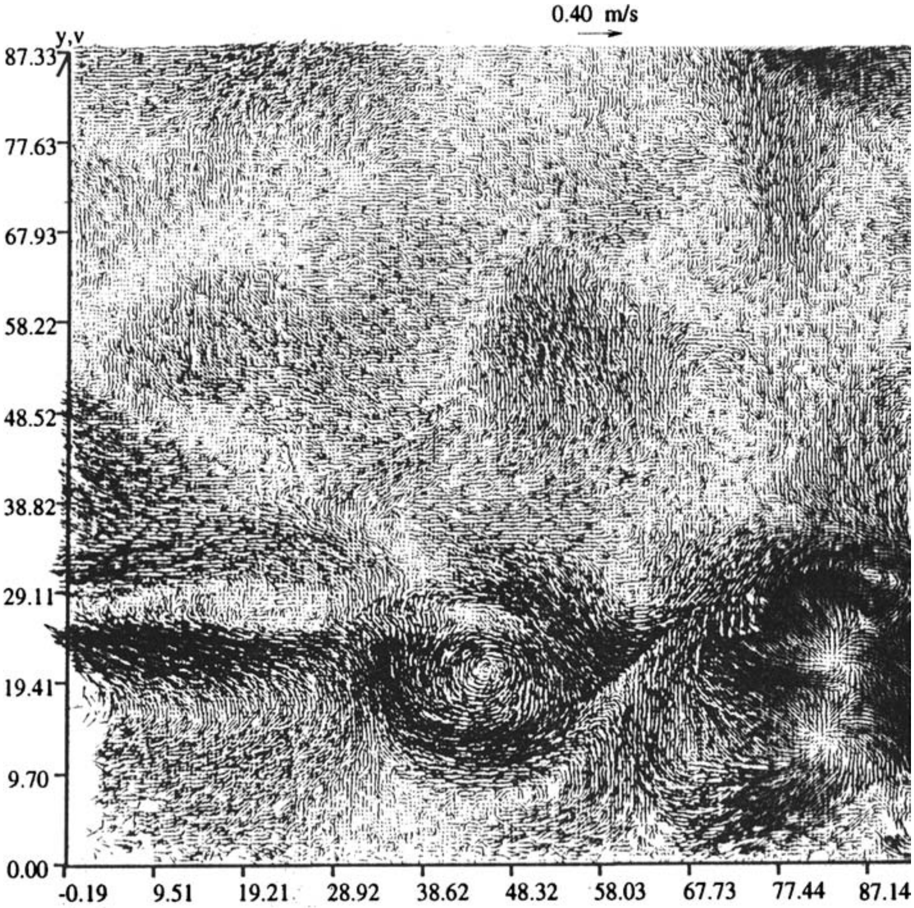

Fig. 6 Vector field of flow downstream of a rearward facing step (expansion) in a pipe flow. Vectors obtained by gridded interrogation spot autocorrelation analysis of a 100×120-mm double-exposed photograph with image shifting and at high image density (Brouillette 1994)

hold two images recorded in rapid succession by transferring the first image recorded by each pixel to an on-chip storage well, and then record a second image. It is the author's understanding that the PIV community is indebted to Lourenco et al. (1994) for convincing Kodak to make such cameras for the PIV market. These cameras enabled three important improvements. First, it was known theoretically that cross-correlation of separately recorded images of the first and second exposures was superior to the auto-correlation of double exposures (Keane and Adrian 1992). But, cross-correlation could not be implemented conveniently until the new cameras became available. Second, the cross-correlation cameras eliminated the need for image shifting: the direction of flow was determined automatically by the order of the exposures. Third, and most importantly, small displacement image overlap was eliminated completely, so that a large dynamic range was possible. The introduction of these cameras was one of the most important developments in the field of PIV.

In PIV, "super-resolution" refers to means of interrogation that improve the spatial resolution beyond that of the basic correlation interrogation spot. As first proposed (Keane et al. 1995), the vectors from a standard correlation analysis were used to enable reliable image pairing in a particle-tracking scheme, thereby obtaining about 5–10 individual particle vectors for each interrogation spot. Many improvements to this method have been proposed (see Proceedings of the International Symposia on PIV 1999, 2001), all with the goal of extending the particle-tracking approach into the realm of high image density. Figure 7 shows a typical result of the super-resolution procedure by Takehara et al. (2001). The research groups of Yamamoto, Kobayashi, and Okamoto have each advanced the interrogation process considerably (see Okamoto et al. 1995; Song et al. 1999; Ishikawa et al. 2000; and the references cited therein). The approach of Yamamoto and coworkers can be put in a class of interrogation methods that might be called "gridless correlation." The idea is to pick each particle and a surrounding group of 5–10 particles as a characteristic pattern. The particle plus group pattern is correlated from one exposure to the next. In principle, this could yield a vector for every particle, but of course, not all correlations yield a valid result. Even so, the method is very attractive. A third line of attack is the hierarchical correlation method, in which correlation results from large interrogation spots are used to guide correlation analysis of smaller spots, and so on, until very small spots are used (Hart 2000). Yet another approach, based on correlation, is to rotate and strain the second window and to perform correlation using six parameters: two translations, two rotations, and two strains (Huang et al. 1993). The approach definitely yields a more accurate evaluation of the derivatives (see Lecordier and Trinite 2004).

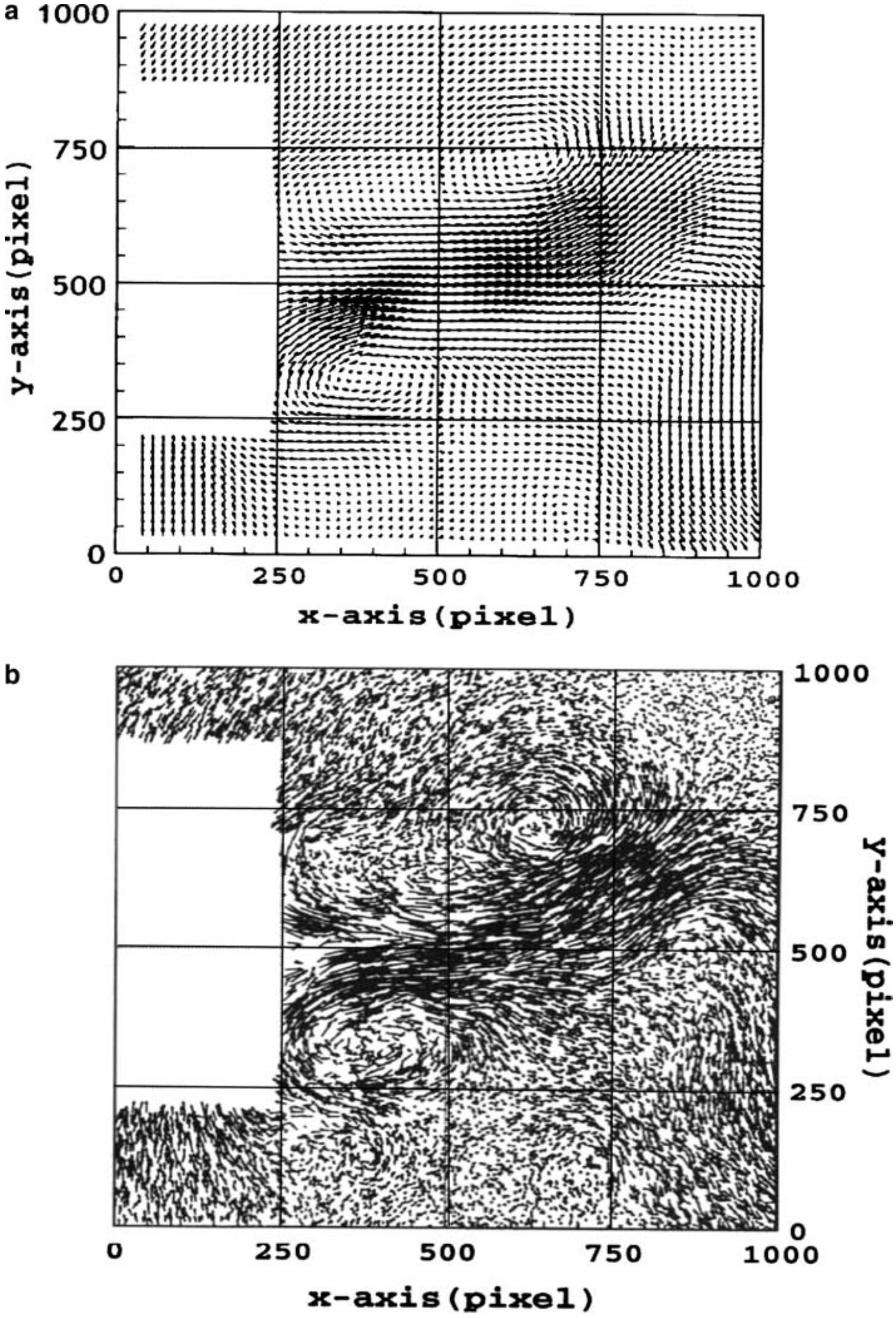

Fig. 7a, b Super-resolution PIV. **a** Vector obtained on a regular grid by correlation analysis. **b** Vectors of individual particles obtained by Kalman filter particle tracking guided by using the vectors in **a** as first estimates (Takehara et al. 2001)

Many developments also occurred on the optical side of the PIV system. Stereographic imaging was used early to make photogrammetric measurements by particle tracking in volumes (Guezennec et al. 1994; Dracos et al. 1993; Maas et al. 1993; Kasagi and Nishino 1993). The consensus experience is that the projection of particles from 3D space onto 2D camera image planes creates particle image overlaps that limit the number of particles that can be imaged to about 3,000. Overlapping images could not be paired unambiguously. Recent work (Pereira and Gharib 2002) using clever, out-of-focus imaging has pushed this number to about 10^4. Stereographic imaging of particles in planar laser sheets does not encounter this limitation because the projected volume of particles is much smaller. In this approach, one can use ray tracing to determine the relationship between image plane locations and particle location (Arroyo and Greated 1991) or generalized calibration with a target in the flow (Soloff et al. 1997). Stereographic PIV solves the problem of perspective error, as well as giving the third velocity component, and it has proven to be a practical generalization of monoscopic PIV.

As noted above, the best performance achieved by 3D photogrammetry yields about 10^4 vectors in a cubic volume, corresponding to a little more than 20 vector sample points per side. After accounting for the randomness of the sample locations by dividing by π, the particle tracking velocimetry measurement is only equivalent to sampling on a regular 7×7×7 grid. This may suffice for studies involving relatively smooth flow fields or two-phase flow, but it is not good enough for turbulence research. These considerations have stimulated several efforts to make volumetric PIV measurements from holographic recordings. Holographic recordings eliminate the particle image overlap problem because they make it possible to isolate one plane at a time. The consensus experience of various research groups (Meng and Hussain 1991; Barnhart et al. 1994; Royer 1997; Trolinger et al. 1997) is that upwards of 10^6 regularly spaced vectors can be obtained using off-axis recording, with rather less using inline recording. This corresponds to a regular grid of about 100×100×100, which is as good as that commonly achieved in planar PIV. The velocity accuracies are also comparable. Figure 8 shows a sample result.

Why then, is holographic PIV not used more widely? First, it is expensive; second, it requires considerable skill; and third, one cannot realistically record enough holograms to give stable turbulence statistics. This situation would change dramatically if electronically readable and writable optical recording media were to become available with adequate resolution and sensitivity. The current multi-mega-pixel cameras are already adequate for this task if one is willing to confine attention to a very small volume. Microscopic inline holography has shown considerable promise (Jian et al. 2003).

The adaptation of PIV to microscale flows (Santiago et al. 1998) reduced the typical PIV measurement volume from 1 mm to 10 microns and less. This remarkable two-orders-of-magnitude increase in spatial resolution is achieved at the cost of reducing the field-of-view by a corresponding amount. Even so, it provides a useful new tool for microfluidics.

2 Current status

Presently, the single-camera, planar light sheet, cross-correlation PIV with a double-pulsed Nd:Yag laser and a 2,000×2,000-pixel cross-correlation PIV camera is the standard system sold by commercial companies. Cooling the cameras to achieve a higher signal-to-noise ratio for the images improves the effectiveness of each pixel, thereby, improving the effective resolution. In turbulence research, just using simple 2D PIV has been enormously rewarding in revealing fundamental aspects of the structure of turbulence. Some of these aspects had been inferred or guessed from earlier flow visualization, but the reliability of PIV visualization has made it possible to eliminate the guessing, to quantify vorticity, and to reveal heretofore-unobservable phenomena that allow completion of the structural pictures of certain canonical flows, such as wall turbulence. More sophisticated forms of PIV will impact efforts to understand turbulence, but one should not rush into complexity before mining the wealth of information that can be had using 2D PIV.

Stereo PIV is now relatively common, and it is working well, except that the out-of-plane component is inherently less accurate than the in-plane components.

Much of the focus over the last 5 years has been on developing accurate, robust means of measuring the image displacement from the image field. It appears that we are closing in on algorithms that are near optimum, and that relatively little can be expected in terms of future improvements in performance. The standard for 2D measurements is now about 300×300 vectors with a velocity dynamic range of no more than 200:1. Because of this small dynamic range, many PIV experiments are still exercises in optimization. Framing rates have increased dramatically with the introduction of new cameras and high-repetition-rate lasers, and this development offers a straightforward path for the expansion

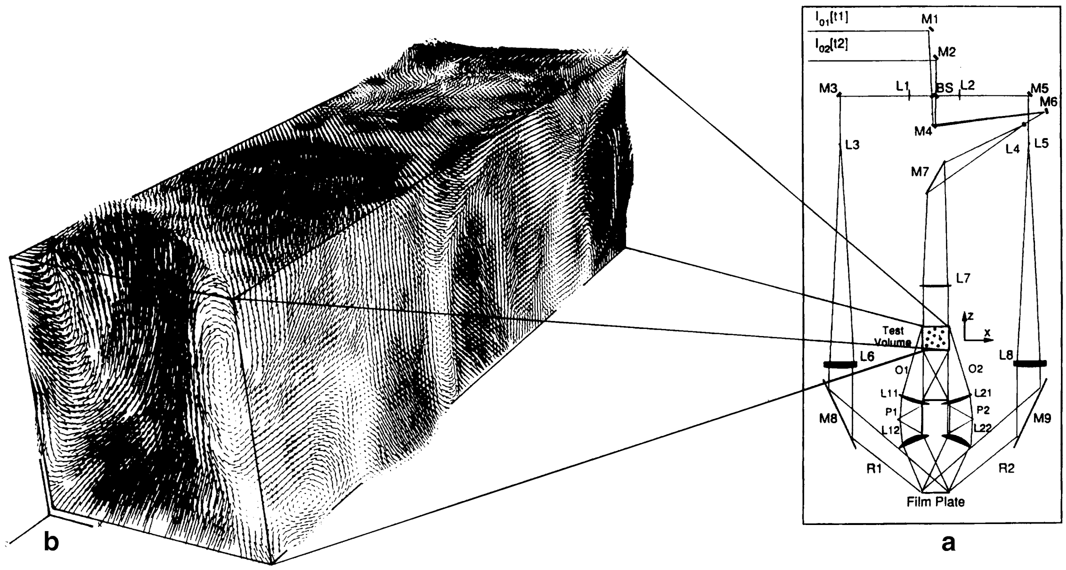

Fig. 8 Three-dimensional vectors measured in a volume by off-axis, double-pulsed holographic PIV (Barnhart et al. 1994)

of PIV capability. Coupling PIV with simultaneous planar laser-induced fluorescence (PLIF) has also enjoyed success and seems relatively straightforward. Making combined measurements of fluid velocity and the velocity of a second phase such as particulate, droplet or vapor phase is a viable and valuable extension of PIV into multi-phase flow. The simultaneous measurements of liquid velocity and bubble phase by Lindken and Merzkirch (2002) in Fig. 9 is an excellent example.

3 Desirable developments

It is risky to predict the future, especially when the advance of PIV depends upon developments in the technology of components that lie outside the field, i.e., computers, lasers, and cameras. However, one can, with some confidence, list developments that would make PIV a more useful and incisive technique:

1. A master theory should be developed that integrates all of the following aspects of PIV:
   - Particle dynamics and the relationship between measured particle displacement, particle velocity, and fluid velocity
   - Imaging, including the accuracy and precision of mapping and distortion compensation
   - Image recording and the effect of pixelization with good noise models for the cameras
   - Optimum algorithms for locating particles with maximum accuracy
   - Optimum algorithms for pairing particle images with maximum reliability
   - Interpolating and smoothing regularly sampled data from correlation interrogation or randomly sampled data from particle tracking velocimetry or super-resolution PIV
2. New, more versatile particle seeding methods are needed to:
   - Enable easy optimization of concentration and higher concentrations in large volumes
   - Produce new particles for flows with severe acceleration—e.g., high-drag particles with large scattering cross-sections, such as spiny spheres

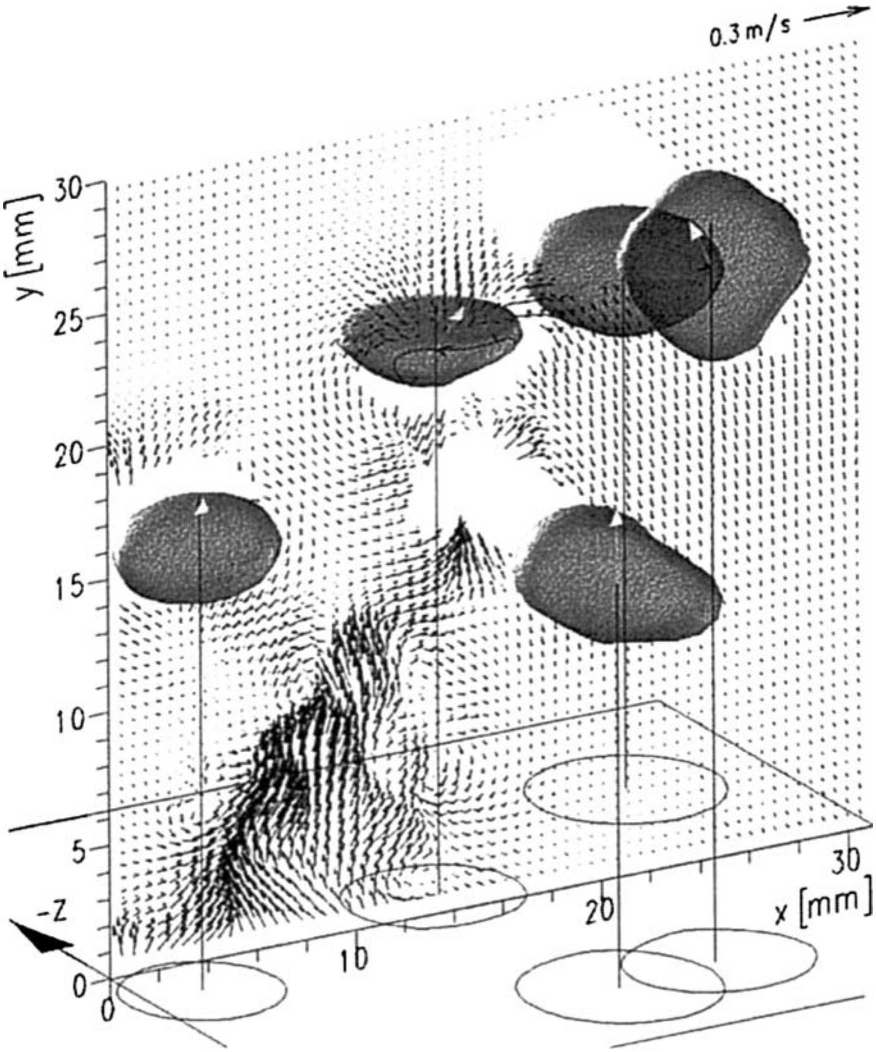

Fig. 9 PIV measurements in a flow containing five bubbles. The bubble velocities are indicated by the *single arrows* (Lindken and Merzkirch 2002)

3. The goal should be set to achieve a velocity dynamic range of 1000:1—this would enormously increase the utility of PIV and render tedious optimization of experimental parameters less important
4. The results of PIV experiments should be held to increasingly rigorous standards. In particular, experimentalists should routinely:
   - Demonstrate the adequacy of the spatial resolution by performing grid resolution tests and/or spatial frequency response tests
   - Demonstrate the accuracy and reproducibility of the velocity measurements
   - Routinely examine the probability density histograms of the velocity data for evidence of experimental artifacts
5. Means should be sought to reduce total system costs by:
   - Reducing the costs of light sources and cameras
   - Developing low-cost, restricted-purpose systems, such as probe-PIV

The reader will undoubtedly have some favorite developments to add to this list.

Acknowledgements This paper was prepared with the support of the U.S. Department of Energy, Los Alamos National Laboratory. The author would like to take this opportunity to acknowledge with gratitude the many contributions of the students, post-doctoral associates, senior visiting scholars, and academic collaborators who, over the past 20 years, have studied particle image velocimetry in the Department of Theoretical and Applied Mechanic's Laboratory for Turbulence and Complex Flow. They are, in rough chronological order: C.-S. Yao, C. Landreth, J. Kompenhans, M. Lee, R. Keane, Z. C. Liu, D. L. Reuss, T. J. Hanratty, P. Offutt, A. Prasad, M. Cui, C. Wark, H. Xu, T. Urushihara, J. Westerweel, C. Westergaard, C. Meinhart, K. Paschal, J. Brouillette, Y. Zhang, D. Barnhart, G. Papen, V. Troy, T. Oakley, E. Loth, C. Tomkins, S. Soloff, U. Ullum, K. Christensen, R. Fernandes, K. Sharp, N. Fujisawa, C. Kaehler, K. Nishino, J. Sakakibara, K.C. Kim, D. Hill, K. Takehara, J. Santiago, M. Olsen, Z. Deng, B. Balasubramanian, E.Yamaguchi, M. Murphy, W. Lai, G. Elliott, and P. Vedula.

References

Adrian RJ (1984) Scattering particle characteristics and their effect on pulsed laser measurements of fluid flow: speckle velocimetry vs. particle image velocimetry. Appl Opt 23:1690–1691

Adrian RJ (1986a) Multi-point optical measurement of simultaneous vectors in unsteady flow—a review. Int J Heat Fluid Flow 5:127–146

Adrian RJ (1986b) An image shifting technique to resolve directional ambiguity in double-pulsed laser velocimetry. Appl Optics 23:3855–3858

Adrian RJ (1996) Bibliography of particle velocimetry using imaging methods: 1917–1995. TSI Inc., St. Paul, Minnesota. Also available as TAM report no. 817, UILU-ENG-96-6004, Department of Theoretical and Applied Mechanics, University of Illinois, Urbana-Champaign, Illinois

Adrian RJ, Yao CS (1984) Development of pulsed laser velocimetry (PLV) for measurement of fluid flow. In: Patterson G, Zakin J (ed) Proceedings of the 8th biennial symposium on turbulence, Rolla, Missouri, September 1984, pp 170–186

Adrian RJ (guest ed) (2000) Proceedings of the 3rd international workshop on particle image velocimetry, Santa Barbara, California, September 1999. Exp Fluids 29:S1–S307

Adrian RJ (guest ed) (2002) Proceedings of the 4th international symposium on particle image velocimetry, Göttingen, Germany, September 2001. Exp Fluids 33:735

Arroyo MP, Greated CA (1991) Stereoscopic particle image velocimetry. Meas Sci Technol 2:1181–1186

Barker DB, Fourney ME (1977) Measuring fluid velocities with speckle patterns. Opt Lett 1:135–137

Barnhart DH, Adrian RJ, Papen GC (1994) Phase conjugate holographic system for high resolution particle image velocimetry. Appl Optics 33:7159–7170

Brouillette JN (1994) Incompressible turbulent flow through a sudden axisymmetric expansion using particle image velocimetry. MS thesis, Department of Mechanical Engineering, University of Illinois, Urbana-Champaign, Illinois

Dracos T, Virant M, Maas HG (1993) Three-dimensional particle tracking velocimetry based on photogrammetric determination of particle coordinates. In: Cha SS, Trollinger JD (eds) Optical diagnostics in fluid and thermal flow. SPIE, Bellingham, Washington, pp 457–466

Dudderar TD, Simpkins PG (1977) Laser speckle photography in a fluid medium. Nature 270:45–47

Grant I (ed) (1994) Selected papers on particle image velocimetry. Milestone Series MS99, SPIE international society of optics engineering, Bellingham, Washington

Grousson R, Mallick S (1977) Study of flow pattern in a fluid by scattered laser light. Appl Opt 16:2334–2336

Guezennec YG, Brodkey RS, Trigui J, Kent JC (1994) Algorithms for fully automated three-dimensional particle tracking velocimetry. Exp Fluids 17:209–219

Hart DP (2000) PIV error correction. Exp Fluids 29:13–22

Huang HT, Fiedler HE, Wang JJ (1993) Limitation and improvement of PIV. Part I. Limitation of conventional techniques due to deformation of particle image patterns. Exp Fluids 15:168–174

Ishikawa M, Murai Y, Wada A, Iguchi M, Okamoto K, Yamamoto F (2000) A novel algorithm for particle tracking velocimetry using the velocity gradient tensor. Exp Fluids 29:519–531

Jian S, Malkiel E, Katz J (2003) Single beam two-views holographic particle image velocimetry. Appl Optics 42:235–250

Kasagi N, Nishino K (1993) Flow field measurement with particle image velocimetry. JSME 96:34–39

Keane RD, Adrian RJ (1992) Theory of cross-correlation analysis of PIV images. Appl Sci Res 49:191–215

Keane RD, Adrian RJ, Zhong Y (1995) Super-resolution particle-imaging velocimetry. Meas Sci Technol 6:754–768

Kompenhans J, Reichmuth J (1986) Particle imaging velocimetry in a low turbulent wind tunnel and other flow facilities. In: Proceedings of the IEEE Montech'86 conference, Montreal, Canada, October 1986. AGARD conference proceedings no. 399, paper 35

Kompenhans J, Tropea C (guest eds) (1997) Special issue: particle image velocimetry. Meas Sci Technol 8:1379–1583

Lecordier B, Trinite M (2004) Advanced PIV algorithms with image distortion—validation and comparison from synthetic images of turbulent flow. In: Stanislas M, Westerweel J, Komenhans J (eds) Particle image velocimetry: recent improvements, proceedings of the EUROPIV 2 workshop, Zaragoza, Spain, March/April 2003. Springer, Berlin Heidelberg New York

Leese JA, Novak CS, Clark BB (1971) An automated technique for obtaining cloud motion from geosynchronous satellite data using cross-correlation. J Appl Meteorol 10:118–132

Lindken R, Merzkirch W (2002) A novel PIV technique for measurements in multiphase flows and its application to two-phase bubbly flows. Exp Fluids 33:814–825

Lourenco LM, Gogineni SP, Lasalle RT (1994) On-line particle image velocimeter: an integrated approach. Appl Opt 33:2465–2470

Maas HG, Gruen A, Papantoniou D (1993) Particle tracking velocimetry in three-dimensional flows. Part 1. Photogrammetric determination of particle coordinates. Exp Fluids 15:133–146

Meng H, Hussain F (1991) Holographic particle velocimetry: a 3D measurement technique for vortex interactions, coherent structures and turbulence. Fluid Dyn Res 8:33–52

Meynart R (1979) Flow velocity measurement by a speckle method. In: Proceedings of the 2nd European congress on optics applied to metrology, Strasbourg, France, November 1979, vol 210, pp 25–28

Meynart R (1980) Equal velocity fringes in a Rayleigh–Benard flow by a speckle method. Appl Opt 19:1385–1386

Meynart R (1982a) Convective flow field measurement by speckle velocimetry. Rev Phys Appl 17:301–305

Meynart R (1982b) Digital image processing for speckle flow velocimetry. Res Sci Instrum 53:110–111

Meynart R (1983a) Instantaneous velocity field measurement in unsteady gas flow by speckle velocimetry. Appl Opt 22:535–540

Meynart R (1983b) Speckle velocimetry study of vortex pairing in a low-*Re* unexcited jet. Phys Fluids 26:2074–2079

Meynart R (1983c) Speckle velocimetry: an application of image analysis techniques to the measurement of instantaneous velocity fields in unsteady flow. In: Proceedings of the international congress on instrumentation in aerospace simulation facilities (ICIASF'83), Haut-Rhin, France, September 1983. IEEE record, pp 30–36

Morck T, Andersen PE, Westergaard CH (1993) Processing speed of photorefractive optical correlators in PIV-processing. In: Adrian RJ, Durao DFG, Durst F, Heitor MV (eds) Laser techniques and applications in fluid mechanics. Springer, Berlin Heidelberg New York, pp 227–242

Nishino K, Kasagi K, Hirata M (1989) Three-dimensional particle tracking velocimetry based on automated digital image processing. ASME J 111:384–391

Okamoto K, Hassan YA, Schmidl WD (1995) New tracking algorithm for particle image velocimetry. Exp Fluids 19:342–347

Pereira F, Gharib M (2002) Defocusing digital particle image velocimetry and the three-dimensional characterization of two-phase flows. Meas Sci Technol 13:683–694

Pickering CJD, Halliwell N (1984) LSP and PIV: photographic film noise. Appl Opt 23:2961–2969

Raffel M, Willert C, Kompenhans J (1998) Particle image velocimetry, a practical guide. Springer, Berlin Heidelberg New York

Royer H (1997) Holography and particle image velocimetry. Meas Sci Technol 8:1562–1573

Santiago JC, Meinhart CD, Wereley ST, Beebe DJ, Adrian RJ (1998) A particle image velocimetry system for microfluidics. Exp Fluids 25:316–319

Soloff S, Adrian RJ, Liu ZC (1997) Distortion compensation for generalized stereoscopic particle image velocimetry. Meas Sci Technol 8:1441–1454

Song X, Yamamoto F, Iguchi M, Murai Y (1999) New tracking algorithm of PIV and removal of spurious vectors using Delaunay tessellation. Exp Fluids 26:371–380

Soo SL, Tien CL, Kadambi V (1959) Determination of turbulence characteristics of solid particles in a two-phase stream by optical autocorrelation. Rev Sci Instrum 30:821–824

Sutton MM, Wolters WJ, Peters WH, Ranson WH, Macneill SR (1983) Determination of displacements using an improved digital correlation method. Opt Eng 1:113–139

Takehara K, Adrian RJ, Etoh GT, Christensen KT (2001) A Kalman tracker for super-resolution PIV. Exp Fluids 29:S34–S41

Trolinger JD, Rottenkolber M, Elandaloussi F (1997) Development and application of particle image velocimetry techniques for microgravity applications. Meas Sci Technol 8:1573–1580

Vogt A, Reichel F, Kompenhans J (1996) A compact and simple all optical evaluation method for PIV recordings. In: Adrian RJ, Durao DFG, Durst F, Heitor MV, Maeda M, Whitelaw JH (eds) Developments in laser techniques and applications to fluid mechanics. Springer, Berlin Heidelberg New York, pp 423–437

Westerweel J (1993) Analysis of PIV interrogation with low pixel resolution. In: Cha SS, Trolinger JD (eds) Optical diagnostics in fluid and thermal flow. SPIE, Bellingham, Washington, pp 624–635

Willert CE, Gharib M (1991) Digital particle image velocimetry. Exp Fluids 10:181–193