TWENTY YEARS OF PARTICLE IMAGE VELOCIMETRY

R. J. Adrian
Department of Theoretical and Applied Mechanics
University of Illinois, Urbana, Illinois 61801

Abstract. In the first part of this talk some of the milestones in the development of PIV will be described. In the second part the current status of PIV will be summarized and some goals for the future will be addressed.

1. Historical Development

The year 2004 marks the 20th anniversary since the term "particle image velocimetry ' first appeared in the literature. This article will give a highly personal view of the development of particle image velocimetry over those twenty 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. The presentation will reflect my own experiences and views of certain developments that seemed particularly important or interesting. It will not be possible to make an exhaustive presentation, nor to credit the many people who have advanced the field, in any way that is complete. For that I apologize. For more details, the reader is referred to the excellent book on PIV by M. Raffel, C. Willert and J. Kompenhans (1998), or to the bibliography of PIV by R. J. Adrian (1996) which is almost exhaustive through 1995 and documents much prior work, including all of the first decade.

The most rudimentary form of particle image velocimetry could probably be traced back to the first time someone watched a hand full of leaves moving on the surface of a flowing stream However, in its modern form PIV means the *quantitative measurement of fluid velocity at a large number of points*. 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. Specifically, in 1977 three different research groups, D. B. Barker and M. E. Fourney (1977), T. D. Dudderar and P. G. Simpkins (1977), and R. Grousson and S. Mallick (1977), each demonstrated the feasibility of LSV for fluid flow by measuring the parabolic profile in laminar tube flow. The principal elements of laser speckle velocimetry were the use of double-exposure photographs, planar laser light sheet illumination, and interrogation by forming Young's interference fringes from the many pairs of displaced laser speckles. By 1983 a young doctoral student from the Free University of Brussels, Roland Meynart (1979, 1980, 1982a,b, 1983a, b, c) was the leading practitioner of this method, and he had shown that practical measurements could be made in laminar flow and turbulent flow of liquids and gases, thereby establishing the grounds for intense interest from the fluid mechanics community.

My first contribution to the field was a short paper (R. J. Adrian 1984) in which 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. The name "particle image velocimetry" was proposed to distinguish this mode of operation from the laser speckle mode. In that paper 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 scatters was normally too small to produce source densities large enough to have speckle patterns formed by overlapping images. Higher particle concentrations were either not achievable or not desirable fluid dynamically. Hence, one would almost always see particle images rather than speckles. Contemporaneously and independently, C. J D. Pickering and N. H. Halliwell (1984) also published a paper in which they also used the term " particle image velocimetry ".

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). Other salient features of turbulence are 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 led naturally to the use of high intensity, pulsed lasers.

While these features were necessary for turbulent flow, the capabilities they gave were also useful over a wide range of fluid flow problems. Hence 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. This seems so simple, now, but 20 years ago one was faced with choosing between chopped C W Lasers, pulsed lasers, C W 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.

The energy necessary to illuminate fine particles and produce images of sufficient exposure and clarity is also 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 size particles in air and 10-30 micron size 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. Still later, Nd:Yag lasers became available in compact, dual oscillator packages with self-contained cooling supplies. and they became the work-horse of PIV.

I once wrote a review paper (R. J. Adrian, 1986) that tried to encompass systematically all of various possibilities for optical velocimetry by listing the leading candidates for various types of illumination, types of coding, types of particles, types of image recording and types of interrogation. Given about 3-5 different candidates for each of these categories, there were several hundred combinations that might have produced potentially viable systems. In the mid 1980's the confusion engendered by this wealth of options was quite evident: one could find dozens of papers describing different types of flow of measuring systems that used optical imaging of particles, each differing from the other by their means illumination, coding, particles, recording, and interrogation. Often, when the correct answer is finally determined, it looks so simple that one wonders why so much effort was needed to arrive at it. But, this is not unusual. It is common in technological development to start with many options and confusion before finishing with a few good options that are well understood. In the case of PIV the main option has resolved to double-pulsed solid-state lasers, interline-transfer PIV video cameras, and interrogation by correlation analysis, at least in the first pass.

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 (M. M.Sutton, W J. Wolters, W. H. Peters and S. R. Macneill, 1983; R. J. Adrian and C. S. Yao, 1983)[1]. The two approaches are related by Fourier transform, roughly speaking, but the sharp signal peak in the correlation plane is obviously the correct signal on which to base measurements. Analysis of the auto-correlation method 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 whose volume is defined by the area of the interrogation spot and the thickness of the light sheet. 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,

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[1] There may be *many* earlier papers from different fields that suggested using correlation in somewhat different contexts. For example, S. L. Soo, C. L. Tien and V. Kadambi, 1959 presented a particularly prescient proposal for "Determination of turbulence characteristics of solid particles in a two-phase stream by optical cross-correlation". J. A. Leese, C. S. Novak and B. B. Clark, (1971) describe " An automated technique for obtaining cloud motion from geosynchronous satellite data using cross-correlation".

because, in that limit, it is improbable to find more than one image pair per spot, while the limit of high image density corresponds to multiple particle correlation PIV.

In the first decade of PIV the greatest challenge was the interrogation of the images, simply because computer capabilities were not adequate to the task. In 1985 the DEC PDP 11/23 was a common digital computer in a fluids laboratory. It typically had 128 Kbytes 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 a modern version of MS Word. Practically, it was impossible to perform two-dimensional Fourier transforms or correlation analysis on such machines. Therefore, there was considerable interest in non-statistical methods such as tacking particles individually. Alternatively, several groups seriously pursued the determination of two-dimensional correlations by analog optical means (T. Morck, P. E. Andersen and C. H. Westergaard, 1992; A. Vogt, M. Raffel and J. Kompenhans, 1992). 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 the turbulent fields completely.

To improve the spatial resolution, various investigators sought to optimize the low image density method by using interrogation windows of variable size and shape and displacement. This led to the implementation of adaptive widowing methods. Currently, adjustable window methods have enjoyed 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. Imagine-a velocity measuring instrument that has 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 could be measured. The lower limit is determined by the images overlapping. 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 to provide a means of determining the direction of the particle displacement from double exposed images (R. J. Adrian, 1986). In this method, the images were recorded in such a way that the second image was always shifted in the known direction precisely so that the direction of flow could be determined unambiguously. Further, the probability of two images from the same article overlapping was zero, and this solved a 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 larger dynamic range, it is now large enough to permit very good measurements, provided the system the PIV system is optimized.

Various methods of interrogation by correlation, including correlation of separately recorded images, have been investigated in theoretical/numerical simulation studies (R. D. Keane and R. J. Adrian, 1992). The essence of these studies is contained in a simple curve collapses 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. This parameter characterizes the effects of multiple exposure, out-of-plane loss of images, in-plane loss of images, measurement volume size and shape, particle concentration and interrogation window size, shape and displacement. The non-dimensional parameter is essentially the effective number particles images per interrogation volume, taking account of the size of the volume due to windowing- sort of generalized image density. This proves to be the single most important curve needed to optimize a PIV system, i.e. to achieve a high probability of valid measurements.

One of the most important changes in PIV was the move from photographic to video graphic recording. This change profoundly influenced the popularity of PIV. Of course, many researchers had been using digital cameras in preference to film for years. For example, almost everyone in Japan used video. But, in the early 90's several investigators, most notably C. E. Willert and M. Gharib (1991) and J. Westerweel (Ph.D. thesis, 1993) published results indicating that the low resolution of the digital cameras was not as serious an issue as others had supposed, and that digital PIV could be as accurate as film PIV. Photographic film possessed very high resolution- 100 lines per mm for T-Max and 300 lines per mm for Technical Pan on 25mm by 35mm, or even 100 x125mm, film. In comparison, digital camera resolution was typically 500 by 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 being developed to enhance the accuracy of the interrogation of digital images. Moreover, the resolution of digital cameras increased rapidly to 1000 x 1000 pixels, and it is currently approaching the 2500 by 3500 pixels that would be essentially equivalent to 35 mm film.

The writing was on the wall, and it was clear that digital imaging would become the standard at some point in the future. What was perhaps not appreciated in the early 1990's was the extent to which digital imaging could simplify PIV and make it a process that everybody was willing to deal with. The work by K.Nishino, N Kasagi and M. Hirata (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 19,000 video images. This of was far beyond anything one could do with photographic film. The maximum number of PIV photographs taken by even the most determined investigators seldom, if ever, exceeded 1000. If one wanted good, accurate turbulence statistics, it was necessary to use digital PIV. Hence, digital PIV enjoyed increasing use in the mid-90's, 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 special, hard-wired devices.

The other outstanding impact of digital PIV came with the advent of interline transfer cameras that could hold two images recorded in rapid succession by transferring the first image recorded by each pixel to an on-chip storage well, and then recording a second image. It is my understanding that we are indebted to Louis Lourenco (L. M. Lourenco, et al. 1993) 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 auto- correlation of double exposures. But, cross-correlation could not be implemented 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 certainly one of the most important developments in 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 (R. D. Keane, R. J. Adrian and Y, Zhang, 1995) the vectors from a standard correlation analysis were used to enable reliable image pairing in a particle-tracking scheme, thereby obtaining about 5-7 individual particle vectors for each interrogation spot. Many improvements have been proposed to this method (c.f. Proceedings of the International Symposia on Particle Image Velocimetry, 1999, 2001, 2003) all with the goal of extending the particle tracking approach into the realm of high image density. The research groups of Prof. F. Yamamoto and T. Kobayashi and K. Okamoto have advanced the interrogation process considerably. A second 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 (D. Hart 1999). 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 (H. T. Huang, H. E Fiedler and J. J. Wang, 1993). The approach is time-consuming, but is definitely yields more accurate evaluation of the derivatives.

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. (Y. G. Guezennec, R. S. Brodkey, N. Trigui and J. C. Kent, 1994; T. Dracos, M. Virant and H. G. Maas, 1993; H. G. Maas, A. Gruen and D. Papantonoiu, 1993; N. Kasagi and K, Nishino, 1993). The consensus experience was that the projection of particles from 3-D space onto 2-D camera image planes created particle image overlaps that limited the number of particles that could be imaged to about 3,000. Overlapping images could be paired unambiguously. Recent work by Gharib and co-workers using clever out of focus imaging has pushed this number to about 10^4. Stereo 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 (I. Grant, Y, Zhao, J. N. Stewart and Y. Tan, 1991), or generalized calibration with a target in the flow (S. M. Soloff, R. J. Adrian and Z. C. Liu, 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 mono-scopic PIV.

As noted above, the best performance achieved by 3-D photogrammetry yield 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 PTV measurement is only equivalent to sampling on a regular 7x7x7 grid. This may suffice for studies involving relatively smooth flow fields, 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 it is possible to isolate one plane at a time. The consensus experience of various research groups (H. Meng and F. Hussain 1991; D. H. Barnhart, R. J. Adrian and G. C. Papen 1994, H. Royer, 1997; J. D. Trolinger, M. Rottenkolber and F. Elandaloussi, 1997]. Is that upwards of 10^6 vectors can be obtained using off-axis recording, with rather less using in-line recording. This corresponds to a regular grid of about 100x100x100, which is as good as that commonly achieved in planar PIV. The velocity accuracies are also comparable.

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 one Mpixel cameras are already adequate to this task if one is willing to confine attention to a very small volume. This microscopic in-line holography has shown considerable promise (J. Katz, 2003).

The adaptation of PIV to micro-scale flows (J. G. Santiago, C. D. Meinhart, S. T. Wereley, D. J. Beebe, D. J. and R. J. Adrian, 1998) reduced the typical PIV measurement volume from one millimeter to 10 microns and less. This remarkable two order of magnitude increase in spatial resolution is only achieved at the cost of reducing the field of view by a corresponding amount. Even so, it provided a useful new tool for micro fluidics.

2. Current status

Presently, the single camera, planar light sheet cross-correlation PIV with a double-pulsed Nd:Yag laser and a 2k x 2k cross-correlation PIV camera is the standard system sold by commercial companies. We have found that just using simple 2-D 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 guessing, to quantify vorticity, and to reveal here-to-fore 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 2-D PIV.

Stereo PIV is now relatively common, and seems to be 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 2-D measurements is now about 300 x 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 this seems to offer a straightforward path for expansion of PIV capability, provided laser pulse rates can keep up. Coupling PIV with simultaneous PLIF has also enjoyed success and seems relatively straightforward.

3. Desirable developments

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

a. A master theory should be developed that integrates all of the following aspects of PIV:
- Particle dynamics and the relationship between measured 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 PTV or super-resolution PIV

b. New, more versatile particle seeding methods are needed to
- Enable easy optimization of concentration and high 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.

c. The goal should be set to achieve velocity dynamic range of 1000:1. This would enormously increase the utility of PIV and render tedious optimization of experimental parameters less important

d. Means should be sought to reduce total system costs by reducing the costs of light sources and cameras

e. Low cost systems should be developed for restricted purpose applications such as probe-PIV.

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

References

References in this article can be found by entering the author names and date into bibliographic search engines such as INSPEC or COMPENDEX. For readers who prefer paper, see:

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