DEVELOPMENT OF PIV AT THE UNIVERSITY OF ILLINOIS: 1983-1993

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Introduction

The research group headed by Dr. Jeurgen Kompenhans at the DLR, Göttingen has played a key role in the general development of particle image velocimetry. It ultimate objectives have always been the advancement of aerospace measurement science through advancement of the techniques and practice of PIV. By their efforts, this group leads the world as practitioners of the science and art of PIV in the aerospace context. Their measurements are at once accurate, reliable and beautiful, and they can be trusted openly state the limits of the measurements as well as their strengths. Further, the community if PIV users is indebted to the DLR group for providing pivotal leadership by writing an important and very useful book on the theory and practice of PIV, organizing numerous workshops and meetings, and offering short courses that enabled many new researchers to employ the PIV method. Such efforts characterize the generosity with which the DLR has shared its knowledge.

LSV and PIV

Following the seminal work of Barker and Fourney (1977), Grousson and Mallick (1977) and Dudderar and Simpkins (1977) and the pioneering accomplishments of R. Meynart (1979, 1980, 1982a,b, 1983a,b,c)[*] on laser speckle velocimetry (LSV), I began working on laser speckle velocimetry at the University of Illinois in 1982 with support from the US National Science Foundation. My first paper, in a 1992 NASA workshop, discussed some rather silly analog ways for performing interrogation by two-dimensional correlation by reflecting an image of the interrogation spot back on itself, shifting the reflection with a scanning mirror and searching for a maximum of the transmitted light. In1993, C.-S. Yao and I presented our first real paper on "*Development of Pulsed Light Velocimetry (PLV) for Measurement of Fluid Flow*" at one of the Rolla Turbulence Symposia. It appeared in 1984 in a book that had very little distribution, so the paper had almost no impact, even though it drew the distinction between LSV and PIV, and it laid out the system that would become the 'standard' PIV of today: operation in the low source density, high image density limit using a double-pulsed solid-state laser and two-dimensional spatial autocorrelation for interrogation.[**] In a short note to *Applied Optics* in 1984, I argued that the low source density (i.e. non-speckle) limit would be the most

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* References can be found in the *Bibliography of Particle Velocimetry Using Imaging Methods: 1917-1995*, R. J. Adrian, DLR Göttingen Anniversary Edition, (2009).
** Sutton, et al. (1983) proposed a *digital* correlation method for interrogation of displacements in solid mechanics.

common situation in fluid mechanics and that the more proper name for the technique, when applied to fluids, would be particle image velocimetry (PIV). Contemporaneously, Pickering and Halliwell (1984) also used the term PIV in a Letter to *Applied Optics* about film noise.

PIV development at UIUC

Early work in my laboratory at Illinois concentrated on getting good, high image density particle images. On the basis of Mie scattering computations (Adrian and Yao 1985), we acquired a double-pulsed single-oscillator ruby laser, which is being used to this day. But, after learning about the DLR, Göttingen work with a twin oscillator Nd:Yag, we adopted their approach as soon as we could afford it, primarily the twin oscillators allowed for flexible time delay between pulses.

Prior to 1986 we could not interrogate by 2-D correlation because our DEC 11/23 lab computer only had 128kByte RAM to hold the OS, the programs and the data! Our first interrogations used crossed cylindrical lens to compress the 2-D spots onto orthogonal 1-D CCD arrays, followed by 1-D FFT based correlations. With this method we could only interrogate low image density photographs, and we had to use adaptive windowing to optimize the reliability. In 1986 we got funding to purchase a DEC MicroVAX II with a 30mflops Numerix 432 attached array processor. Finally, we could interrogate with *2-D FFT-based digital correlations using high image density*, but the dynamic velocity range was still less than 10:1, because of overlapping double exposures at small velocities. The break-through came when we developed *image shifting* (Adrian 1986) which allowed us to determine direction and to eliminate image overlap, thereby increasing the *dynamic range to about 100:1*. The results were much improved (Landreth, Adrian and Yao 1988), and with 2-D digital correlation and image shifting we were able to make the first ever PIV measurements of turbulent vorticity and strain-rate in laminar flames, turbulent flames and IC engines.

Throughout this period we watched the optical correlation at the DLR, Göttingen carefully, because we could not be sure that digital correlation would be superior to optical correlation in the long run. We also followed particle tracking velocimetry (PTV) and 3-D photogrammetric PTV carefully, for the same reasons.

A theory relating the results of 2-D correlation analysis was presented at the 1988 Lisbon Symposium and appeared in the proceedings book. Later, R. Keane and I extended and explored the theory in a series of three papers (c.f. Keane and Adrian 1992), leading to the *one-quarter rule* for out-of-plane displacement, the rule that the mean number of pairs should exceed 7-10 per interrogation spot, and the idea that *cross-correlation* was inherently superior to auto-correlation.

Willert and Gharib (1991) opened the door to DPIV, and I must admit we were very skeptical since we used 512 x 512 camera resolution *per interrogation spot*, and they proposed using it for an entire flow field. To see if this could be possible we looked at the accuracy and resolution constraints due to coarsely sampling the particle images with relatively few pixels (Prasad, Adrian, Landreth and Offutt 1992), and this led to the identification of the *pixel locking effect* and the rule that one needs *at least 2-3 pixels per particle image diameter*. With the publication of J. Westerweel's Ph.D. thesis on DPIV in 1993, the innovation of PIV cameras stimulated by L. Lourenco, and the advent of 1-2 mpixel CCD cameras, we reluctantly gave up using film *circa* 1994.

Our first serious study of turbulent flow was a water channel flow at low Reynolds number (Liu, Landreth, Adrian and Hanratty 1991). The color contour map of vorticity in the figure taken from that paper may be the first ever measurement of the vorticity field of a turbulent wall flow.

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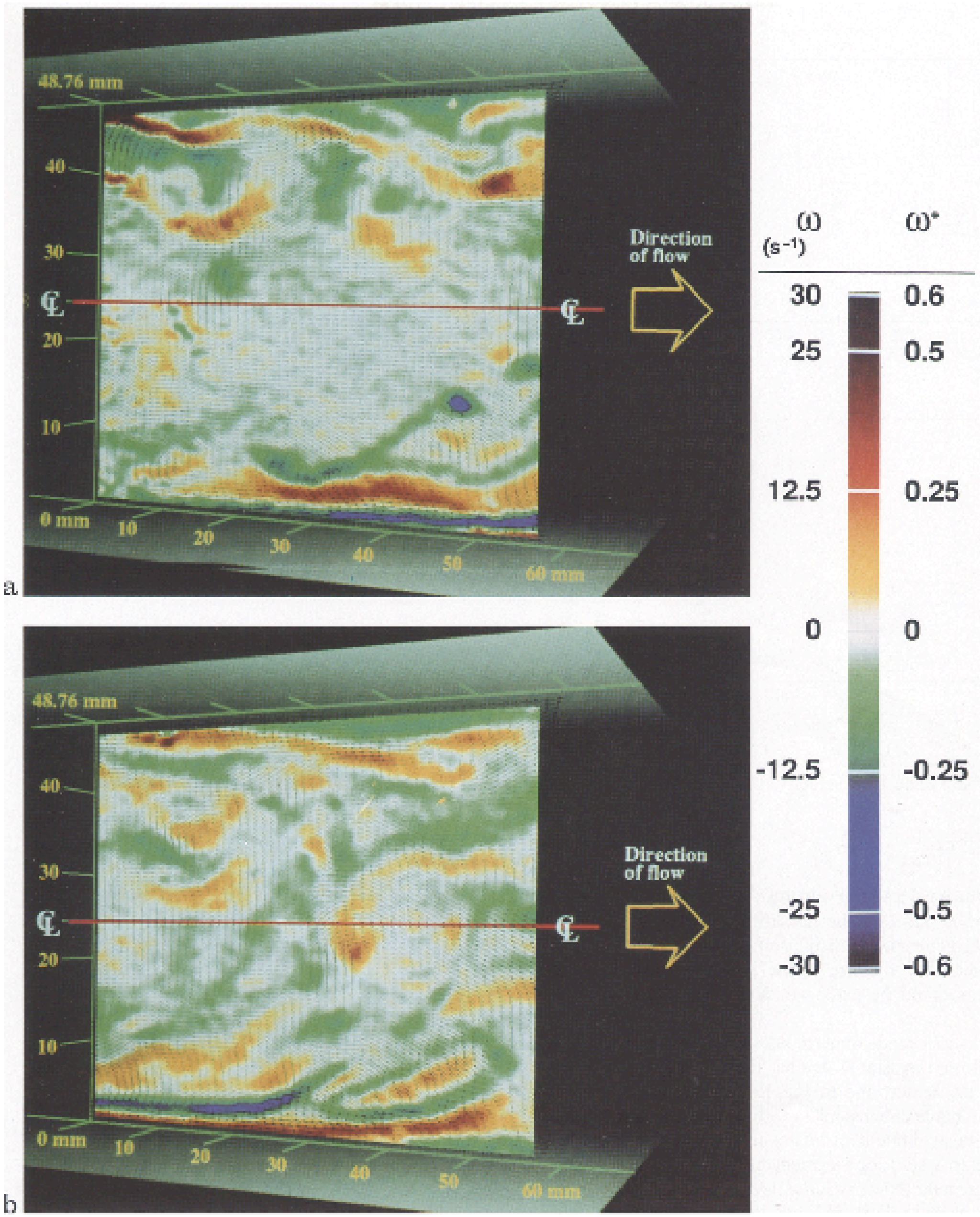

Fig. 9 a and b. Color maps of instantaneous vorticity fields corresponding to the velocity fields of Figs. 6a and b. Velocity vectors are superposed on color fields

(*from* Liu, Landreth, Adrian and Hanratty Exp Fluids (1991) **10**, 301-312.)

The Ph.D. study of turbulent boundary layer by C. Meinhart was well under way in 1993, and we were able, with T. Urushihara, Nissan Motors and C. Wark, Illinois Institute of Tech., to observe structure in the logarithmic layer of turbulent pipe flow with 80 micron interrogation spot size over 100 x 125 mm (Urushihara, Meinhart and Adrian 1993).

Dr. Kompenhans asked me to make observations about the contributions PIV has made to science. By far, the most important one in my mind is the understanding of turbulent structure that we have gained by being able to 'see' the entire flow field, even if it is only on a plane. Before PIV, one had to infer the 3-D structure from single-point time series, or, in some elaborate experiments collections of time series from 8-32 hot-wire probes in an array. This was much like understanding human anatomy by taking needle-point biopsy samples, instead of performing a full dissection. With the advent of PIV we have been able to play the 2-D PIV data at higher Reynolds numbers against the 3-D DNS data of lower Reynolds number flows to achieve a new level of understanding of the structure of wall turbulence.

In conclusion, I would like to thank the colleagues with whom I had the pleasure to work during my first decade of PIV. Chung-Sheng Yao is a Senior Scientist at NASA Langley; Chris Landreth is an independent film producer whose computer animations have won numerous distinctions, including an Oscar; Ajay Prasad is a professor at the Univ. Delaware; Richard Keane teaches engineering at Univ. of Illinois; and Zichao Liu retired in 2002 after working more than a decade with Prof. Thomas Hanratty (also retired) and myself.