PivNet 2

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Thematic Network – A European collaboration
on development, quality assessment, and standardization of
Particle Image Velocimetry for industrial applications

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The main objective of PivNet 2 is the establishment of direct information exchange between end users in industry and PIV developers in universities and research institutes in order that the end users will obtain a clear picture of the state-of-the-art of the PIV technique and the developer will receive knowledge about problems in industry to be solved with PIV. Therefore, recent activities of PivNet 2 were addresse to the dissemineation of know-how on the recording of high quality PIV images, PIV evaluation algorithms and data vaidation procedures. The exchange of knowledge and the discussion of the demands of potential end users have been undertaken in a variety of hands-on workshops and presentations in different fields of application.

Image quality assessment

The quality of the PIV recordings is of crucial importance for the quality and reliability of the PIV technique as such. No evaluation algorithm regardless of its sophistication is capable of recovering data which was lost due to poorly acquired images. The number of causes for low-quality PIV recordings is highly varied and includes:

- laser light sheet irregularity (non-uniform beam intensity distribution)
- non-parallel laser light sheet (missing co-planarity)
- laser flare from surfaces (reflections)
- inadequate seeding
- poor imaging optics (blurred particle images)
- background luminosity (also flame luminosity for combustion)
- camera noise, cross-talk between frames and other camera artifacts
- improper choice of pulse delay (too long → loss of correlation, too short → noisy data)
- optical distortions due to thick windows

Certainly each of these must be addressed individually in the course of setting up a PIV experiment and unfortunately generalized recipes do not exist for many of them. Previous experience plays a vital role here.

Instrumental for guaranteeing a successful PIV measurement series is a means of quickly assessing the quality of recordings immediately prior to acquiring large amounts of data, better even, a continual monitoring (e.g. by randomly checking images). Image quality (contrast, focus) as well as seeding density is easily controlled by displaying images on a monitor. Additional numerical tools such as estimators for seeding density, particle image diameter, signal-to-noise ratio could be very helpful for automation but need further investigation.

However, these control mechanisms are insufficient to guarantee successful PIV measurements as they are incapable of characterizing the recordings with regard to PIV interrogation. Therefore some sort of rapid (on-line) PIV analysis is always required.

Algorithms

Over the past decade PIV analysis algorithms have evolved quite remarkably and, due to dramatic increases in off-the-shelf computing power, can provide high quality data within a reasonably short time frame (e.g. within a few seconds). At the core of essentially all PIV interrogation algorithms is some sort of correlation scheme which statistically analyzes the inter-frame correspondence of the PIV image pair. In general both a high correlation value and a high number of particle images per sampling area are desired. Low correlation values is caused by a combination of

- loss of particle image match (large in-plane or out-of-plane flow)
- high gradients within the local sampling area
- light sheet non-uniformity (holes in profile)
- intensity variations between the two frames

The primary aim of the more modern evaluation algorithms is to increase the degree of correlation (e.g. matching) by offsetting the sampling areas locally with respect to each other. Thereby both the precision of the displacement measurement and also the spatial resolution are increased (given sufficient particle image density). More advanced algorithms also perform a local (or global) image deformation to account for the gradient present in the sampling areas. In general it can be stated that if a PIV recording can be evaluated reliably at a coarse resolution using a single pass (0th order) algorithm, it will most likely be suited to be evaluated at least twice the spatial resolution with more advanced multiple pass schemes. Therefore optimization is always necessary during the recording phase of the PIV measurement campaign and should be possible using rather straightforward algorithms.

An overview of some of the more important algorithms is given in table 1 in the order of increased complexity. The primary advantage of the pyramid grid refinement algorithm is that it can handle a higher range of displacements with smaller interrogation windows and thereby can increase the spatial resolution. In conjunction with image deformation techniques the grid refinement approach can even tackle high gradient flow areas which are common to many industrial flows.

Validation schemes and validation rates

Validation of PIV data is an essential step in the PIV processing chain and state-of-the-art commercial software generally offers a wide choice of validation filters. Common to all these filters is that some sort of threshold (cut-off value) separates questionable data (spurious vectors) from valid data. In general this threshold is a user-given value, although it also could be possible to automatically calculate these thresholds, for instance by analysis of the probability density functions of the data. The parameter adjustment is equivalent to a cost optimization process, that is, disabling as many obviously questionable data while at the same time keeping the number of falsely disabled 'valid' data as low as possible. The best possible validation can be achieved by combination of several different filters.
Given adequately set validation parameters, the validation rate is also a good measure of the PIV data quality. Low validation rates usually point to any of the problems earlier in the processing chain on the imaging or recording side. As a consequence on-line PIV processing coupled with validation schemes during or prior to a measurement campaign is very helpful in optimizing the PIV recording chain. In following a few validation schemes are briefly described:

- *Magnitude filter:* This is one of the simplest forms of validation and considers valid a displacement/velocity to fall below a given maximum magnitude. It is effective for the detection of rather obvious outliers, but frequently omits outliers buried in the data.
- *Range filter (Global histogram filter):* This is an extension of the magnitude filter as it considers valid data to fall within a given range. Its efficiency is slightly better than the magnitude filter but it requires more user-defined parameters (i.e. min./max. for each component). In principle, its parameters could be estimated automatically using the PDF of the data.
- *Displacement difference filter (gradient filter):* Compared to the previous validation filters, this filter performs a comparison of the data point with its neighborhood, in this case by computing the magnitude of the vector difference to each of the eight surrounding neighbors. A data point is considered questionable if the vector difference threshold is exceeded at least 4 times (one could also check if the difference is only to one side). Efficiency-wise this operator can be considered to be one the more robust validation filters as it can detect spurious data left untouched by the previous filters. However it can also falsely remove valid data in high gradient areas of the flow field.
- *Median filter:* This filter is also a neighborhood operator and compares the data in question with the median of the 8 surrounding vectors. In practice, the medians of each displacement component as well as the magnitude is calculated. A given vector is considered questionable if the difference to the neighborhood medians exceed a given threshold at least twice. On the efficiency side it performs similar to the gradient filter but may detect spurious data not found by it, and vice versa. However, the required sorting process in the median calculation can influence the overall processing speed.
- *Minimum correlation filter:* As mentioned earlier, a low correlation coefficient is indicative of a strong loss of particle match and may have a variety of causes. Thus, a validation filter may be very helpful in detecting problematic areas in the

field of view. However it is of lesser importance for the actual validation of PIV data, as low correlation values do not necessarily point to invalid displacement readings (the measurement uncertainty increases, though).

- *Peak-height ratio filter:* In this case the correlation peak representative of the displacement reading is compared to the first noise peak in the correlation map. A low ratio of the peak heights may point to an inadequately seeded area and a higher likelihood that the measured displacement is questionable. In terms of validation it is less effective because mismatched areas may have a high correlation coefficients especially when seeding levels are low.

An overview of these filters with regard to their efficiency and possible parametric optimization is summarized in Table 2. In summary it should be stated that the filters relying on a neighborhood comparison are considered to be the most effective and reliable. The other filters may be useful in pointing out deficiencies in the recording chain

Algorithm	Processing strategy	Complexity	Speed	Advantages	Drawbacks
Single pass	none	low	highest	simple implementation	no iterative match optimization
Multiple pass	integer-based window matching	medium-low	high	better matching	low tolerance to gradients
Multiple grid	pyramid based grid refinement (inherent integer-based window matching)	medium	high	increased spatial resolution and dynamic range	convergence requires intermediate validation
Localized window deformation	iterative, window matching on sub-pixel level	high	lowest	high precision, tolerates strong gradients	requires image interpolation
Multiple pass with global image deformation	predictor-corrector scheme using interpolated displacement field	high	low	high precision	requires image interpolation, intermediate validation
Multiple grid with global image deformation	predictor-corrector scheme using interpolated displacement field	highest	medium	high precision, increased dynamic range & spatial resolution, tolerates strong gradients	requires image interpolation, intermediate validation

Table 1: Overview of PIV processing algorithms – complexity vs. speed

Filter (see text for details)	Number of req'd. parameters	Outlier detection efficiency	Automatic parameter optimization	Other use
Magnitude	1	low	simple	
Range	2 – 4	medium	simple	
Gradient	1	high	possible	
Median	1	high	possible	
Dynamic mean	2	medium	difficult	can deal with flow discontinuities (shocks)
Minimum correlation	1	low	possible	detects low seeding, poor recording configuration
Peak ratio	1	low	difficult	detects low seeding, poor recording configuration

Table 2: Validation filters – efficiency and use

Workshop and Presentation PIV application for household appliances

Location: Ancona, Italy, 25.-26..06.03
Task Manger: University of Ancona

The industrial sector identified for the purpose is the appliance industry, with particular emphasis on home appliances and appliances which are used inside buildings, offices, commercial etc.
Typical products of the appliance industry have a relatively low industrial cost and the appliance market shows a strong competition, in which appliance technical performance plays a role together with aesthetics and cost. Many of such appliances have fluid-dynamic problems that need accurate studies for an effective improvement; for such purpose it is important that any experimental technique proposed to tackle the problems bears inherent characteristics of simplicity, provides a rapid mean to collect experimental data, provides information that engineers can readily exploit for product enhancement, and mostly for Computational Fluid- Dynamic (CFD) code validation, due to the fact that most of the design is performed through numerical computation of fluid-dynamics. During the workshop and presentation the utilization of Particel Image Velocimetry for household appliances has been demonstrated on a variety of employments:

- PIV applied to kitchen evacuation hoods
- Mixed flows near inlet air conditioner
- PIV applied to the internal fluid dynamics of close control air-conditioning systems
- Comparison between PIV measurements and CFD Modelling on a domestic gas oven
- Natural gas burners for domestic appliances: application of the Particle Image Velocimetry Technique
- Study of lamp cooling by 3D PIV
- PIV application to fluid dynamics of bass reflex ports
- Optical techniques applied to the study of internal fluid dynamics of ice-cream refrigerators

The participation to the event has been larger than expected, with a large percentage of participants that had no previous experience in PIV; this demonstrates the success of a dissemination activity, fully in agreement with the PIVNET-2 workprogramme.

55 delegates attended the Presentation and Workshop, coming from Universities, Enterprises and Research Institutes from all around Europe (Belgium, Denmark, Germany, Italy, Portugal, Spain, Turkey, United Kingdom), from Mexico and from South Korea.

Of all the participants only 18% were PIVNet 2 partners. It is very important to note that the workshop was attended by delegates from the leading European manufacturers of PIV instrumentation (Dantec Dynamics A/S, Intelligent Laser Applications GmbH, LaVision GmbH), engineers from the R&D divisions of appliances producers (Whirlpool Europe Srl, Electrolux, Faber Spa, Liebert Hiross, Bauknecht Hausgerate GmbH, Clabo Group, iGuzzini, Merloni Termosanitari, B&C Speakers, Arcelik Co, Candy Elettrodomestici), and experts and researchers in the fluid dynamics field.

Particle Image Velocimetry in Biomedical Flows

Location: Aachen, Köln, Jülich, Germany, 06.-07.11.2003
Task Manager: Intelligent Laser Applications GmbH

The objective of this PivNet 2 workshop was to show the potential of Particle Image Velocimetry techniques for Biomedical Flows. The region around Aachen and Jülich is well known for biomedical research. During the PivNet workshop an overview of PIV in biomedical flow applications has been given by users related to industry or research facilities. A reputed research facility, a manufacturer of PIV equipment and several other experienced contributors provided the participants with information about the possibilities that today's PIV technique offers for the study of biomedical flows. This workshop has given the opportunity for the participants to exchange their experience with other leading scientists in the field of PIV in different biomedical applications:

- Time resolved PIV of the flow behind different artificial heart valves
- Stereo-PIV inside axial blood pump (LVAD) using self-calibration on particle images
- PIV in a micro axial blood pump
- High Speed PIV in an arterial junction
- In vivo micro-PIV measurements in the embryonic avian heart
- PIV measurements in lung bifurcation models
- In vitro stereoscopic PIV of mechanical heart valves in unsteady pulsatile flow
- Measurement of forces on blood cells downstream an artificial aortic valve
- Experimental study of the diastolic flow within the left ventricle
- Micro PIV for blood flow measurement in microcirculation

Investigations of the fluid flow in lung bifurcations can enhance the understanding of pulmonary diseases. The delivery of drugs to certain parts of the lung and the basic research on transport phenomena inside the lung is of special interest for the group from VKI (Bruxelles). Here the unsteady behaviour of the oscillating flow and the resulting different particle tracks are investigated. Furthermore the modelling of different flow profiles allows the enhancement of the model. Conclusions of the project are:

- Particle Image Velocimetry is very useful in lung investigations
- Powerful techniques exist for the construction of transparent models
- Chronological measurements are essential
- Particle Tracing Velocimetry (PTV) is used for steady Streaming
- PTV will be used for the investigation of aerosol behaviour
- The spatial cyclic behaviour of flow is put in evidence

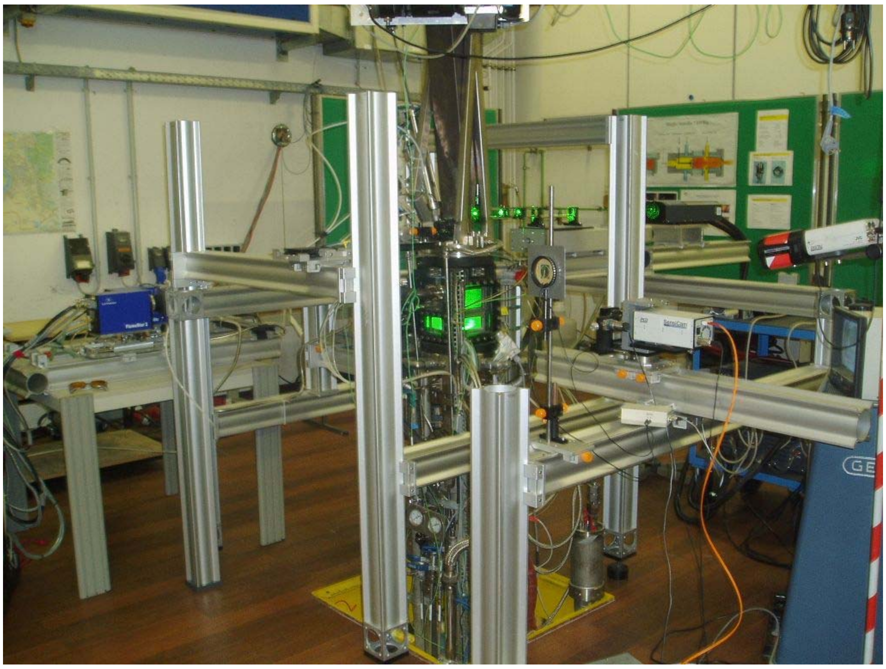
In-Vivo PIV can be used to measure blood flow velocity in living animals. The research group from TU Delft (Netherlands) showed the possibility to do PIV in an embryonic avian heart and in a mouse by using fluorescent particles. The particles are covered with stealth liposomes, in order to prevent the immune system of the animal from destroying the particles. Enhanced algorithms allow the evaluation of the images which are of different quality compared to common PIV particle images.

Particle Image Velocimetry for Applications in Turbomachinery

Location: Köln, Germany, 11.-12.-02.2004
Task Manager: Deutsches Zentrum für Luft- und Raumfahrt e.V.

Similar as for a transonic wind tunnel, special problems arise when PIV is applied in confined flows (optical access, light scattering from the surfaces, oblique viewing etc.). The workshop organized by DLR's Institute of Propulsion Technology in Cologne showed that high quality PIV results can be obtained in the area of turbomachinery as well, even in pressurized combustion facilities. The combination of PIV and DGV (Doppler Global Velocimetry) seems to be able to overcome some of the drawbacks associated with each of these techniques, mainly that of reduced optical access in complex test facilities. The following topics have been addresssed during this exchange workshop:

- PIV application in atmospheric and pressurized combustion chambers
- Overview Doppler Global Velocimetry principles and applications
- Application of DGV in an industrial-sized atmospheric combustor
- Combustion facilities at the Institute of Propulsion Technology
- Introduction to laser diagnostic activities at the Institute of Propulsion Technology
- Application of planar laser induced fluorescence at combustion rigs
- Investigation of unsteady effects in turbomachinery using PIV
- PIV investigation of internal cooling channels for gas turbines, with 45° inclined ribs
- PIV application in internal cooling passages of turbine blade models
- A novel approach to highspeed PIV at kHz-range for turbulent gas flow visualization
- First steps in the development of Doppler Global Velocimetry



Single sector combustion test facility illuminated by a PIV laser light sheet.The PIV camera system is visible to the right of the combustion chamber.

Application of Particle Image Velocimetry in Small and Medium Enterprises

Location: Bruxelles, Belgium, 18.02.2004
Task Manager: Von Karman Institute for Fluid Dynamics

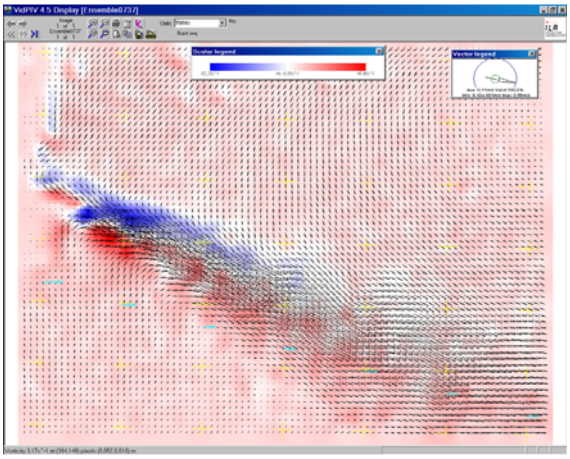
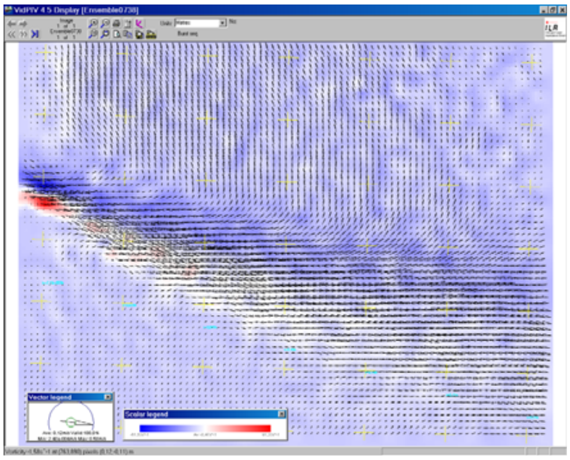
The workshop was organized by a well known research institute in Fluid Dynamics (VKI) and a manufacturer of PIV equipment (ILA GmbH). The location of VKI was chosen, in order to show the possibilities of a research institute and to be able to perform practical demonstrations of PIV measurements in a real test facility. The test case was chosen to be the test rig of VKI for PIV investigations of continuous steel casting. An additional reason was the experience of VKI in organizing more than ten lecture series per year concerning fluid dynamic related themes. For supplying the necessary fundamentals to the participants, a PIV expert was available - Prof. Riethmuller from VKI.

11 participants from 2 different European countries attended the workshop. Most of the participants came from Germany and some from Belgium.

The workshop was free of charge for SME members which have been introduced into the following main topics:.

- Fundamentals of PIV I
- Fundamentals of PIV II
- Applications of PIV in SME
- PIV in continuous casting of steel
- Discussion of possible applications
- Visit of VKI Facilities and PIV demonstration

The lecture of Prof. Riethmuller gave a good introduction of all fundamental aspects of PIV and also of present developments in this area. Mr. Kallweit from ILA gave an overview of PIV applications that were done as consultancy work for SMEs. Mr. Gouriet presented a detailed view into the use of PIV in investigations of steel manufacturing. Ms. Corieri presented all the research facilities available at VKI and explained the current research projects. The participants could participate in measurements performed in a water model built to investigate continuous casting of steel. This demonstration had been prepared by engineers of ILA and VKI.

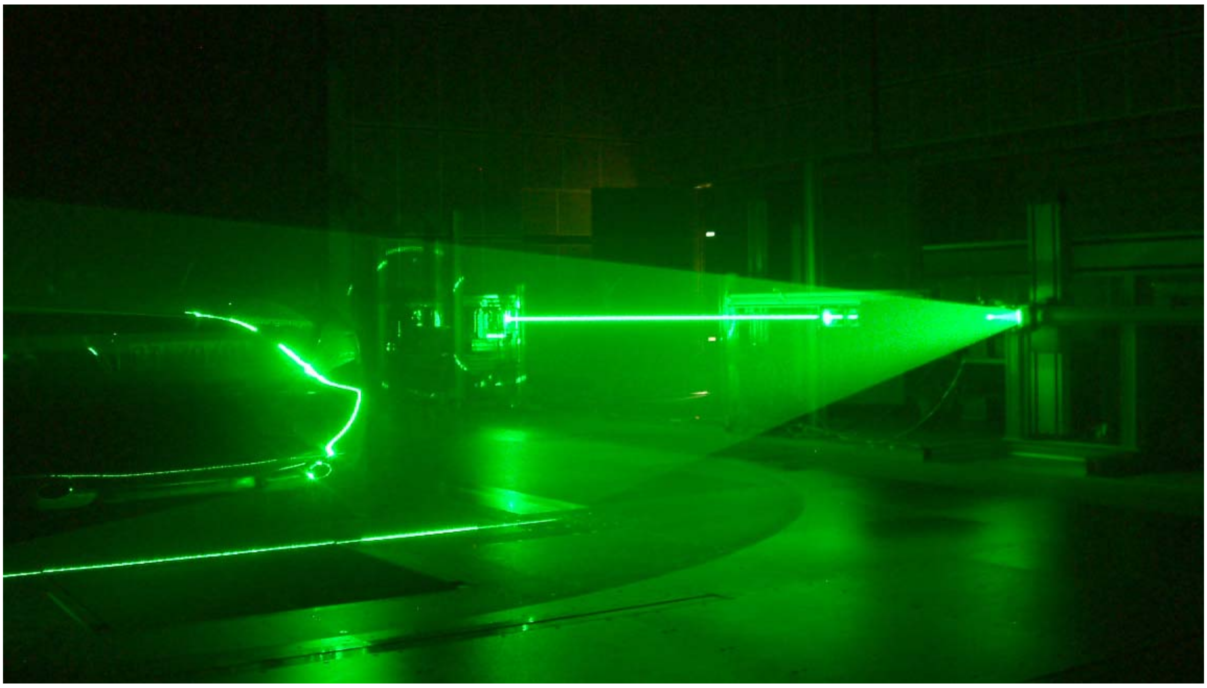



Evaluated PIV images of a steel casting process without bubbles (left) and with bubbles (right). The mean mean shaer strain in the flow is shown above which has been derived from the velocity field.

Application of Particle Image Velocimetry for Problems of Transportation

Location: Stuttgart, Germany, 24.03.2004
Task Manager: Deutsches Zentrum für Luft- und Raumfahrt e.V.

On occasion of the EuroMotor Short Course 'Progress in Vehicle Aerodynamics III - Unsteady Flow Effects' at the Forschungsinstitut für Kraftfahrzeugwesen und Fahrzeugmotoren (FKFS) in Stuttgart the DLR PIV team has been asked to prepare a PIV presentation in the large wind tunnel of FKFS. The two PivNet2 partners Pininfarina and DLR gave presentations during this workshop. The objective to inform industrials being participants of the EuroMotor Short Course about the potential of the PIV technique has been achieved by this joint activity which took place on March 24, 2004. In addition, the participants of the EuroMotor Short Course have been informed about PivNet's activities and the major workshop and presentation of PIV in car industry planned for 2005.
The presentation clearly showed the potential of PIV in the transportation and vehicle field, but nevertheless improvements in field scales, measurement and wind tunnel time and time resolution for e.g. aero-acoustic problems were demanded. On the other hand the affluence of information which can be derived out of a high number of instantaneous velocity vector maps like aspects of flow topologies and development, turbulence statistics etc. could be used to follow more advanced optimisation strategies in vehicle design. To show the potentials of PIV for these purposes was a main goal of the presentation.
The demonstration of a Stereo PIV system, a live measurement of the flow around a sports car in the full scale 1:1 wind tunnel of the FKFS and an immediate evaluation of instantaneous 3C velocity vector fields produced big interest amongst the participants of the workshop. A lot of discussions mainly in respect to the applicability of PIV to vehicle aerodynamics arose and were discussed. The feedback of the participants was very positive.



Laser light sheet pulse with high energy for a Stereo PIV measurement during the presentation visible for the participants via video projection inside the control room.