25 Years of Particle Image Velocimetry in Aerodynamics

DLR Göttingen, Germany, September 23 – 25, 2009

Program
&
Abstracts

Deutsches Zentrum für Luft- und Raumfahrt e.V.

Carl von Ossietzky Universität Oldenburg

25 Years of Particle Image Velocimetry in Aerodynamics

http://25-years-PIV.dlr.de

Jürgen Kompenhans and Klaus Hinsch
Chairmen Symposium '25 Years of Particle Image Velocimetry in Aerodynamics'

Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

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Symposium '25 Years of Particle Image Velocimetry in Aerodynamics'

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Contents

Preface

Welcome to the Symposium „25 years of Particle Image Velocimetry in Aerodynamics"! It all started in September 1984 when a group of researchers from Oldenburg shipped their high-energy ruby laser across a bumpy highway to Göttingen. Our aim was to test how the novel technique of PIV would perform when applied to a wind tunnel flow at the DLR facility. No one could then anticipate the impressive development of this method into a powerful routine tool in experimental fluid dynamics. Now, after a quarter of a century there is a perfect occasion to commemorate this event. It is time to document the various ways research and development took, identify highlights and failures and study the factors that influenced the development of this technical tool.

We are thankful that so many colleagues who were involved in PIV in the past quarter of a century responded to our call for participation. Thus we can provide a substantial program of ambitious presentations. We will review the historic development, will hear about the state-of-the-art of various PIV versions and their applications and participate in an analysis of the parameters that influenced the development of our technique. This retrospective will also give us a chance to better appreciate our own role in history. And last not least will the recollection of former mutual experiences deepen personal friendships that grew during the many collaborations and meetings.

We would like to take this opportunity to thank all, who helped to make this symposium possible, the lecturers coming from all continents, the local organizing committee, the financial support of the vendors of PIV equipment, and, in particular, the generous support of the German Research Foundation (DFG), State of Lower Saxony and the German Aerospace Center (DLR).

We hope that the congress will provide stimulations and challenges for your future work as well as valuable personal interactions and conversations. Enjoy your time in Göttingen!

Jürgen Kompenhans

Klaus Hinsch

Welcome Addresses

Prof. Dr.-Ing. Joachim Szodruch

On behalf of the German Aerospace Center DLR I am pleased to welcome you to the Symposium

25 Years of PIV in Aerodynamics

in Göttingen.

One of the prime objectives of the aeronautical research of the German Aerospace Center DLR is to further develop its virtual design capabilities in order to be able to assess aeronautical systems and technologies. A prerequisite for this is the development of advanced numerical methods and the capability of their experimental validation. In a unique manner DLR has available large industrial and research wind tunnels as well as research aircraft for the improved understanding of complex unsteady flow phenomena, the validation of numerical simulation methods and the demonstration of technologies.

In parallel image based and acoustical experimental methods have become standard tools for DLR's research in aeronautics. This is mainly due to focused development work during the past two and a half decades associated with remarkable technological progress in optics, electronics, video technique and computer hardware. Today, these experimental methods allow capturing data for nearly all physical quantities of interest in a plane or volume of the flow within a very short time interval. Thus, such methods are highly appropriate to improve the understanding of physical phenomena in complex unsteady flows (planar or volumetric data, time-resolved data), to provide high quality data for validation of numerical codes, and to obtain experimental data at high (flight) Reynolds numbers. One of the most important of such experimental methods is Particle Image Velocimetry (PIV). Since its first application for aerodynamics in a wind tunnel of DLR Göttingen twenty five years ago this technique has matured and became a proven tool for research in industrial wind tunnels. As mobile system the PIV technique has been successfully used by DLR in many internal, national, EC funded and industrial projects.

The symposium '25 Years of PIV in Aerodynamics', Göttingen, September 23 - 25, 2009, is a good opportunity to remember the success story of PIV, its progressive development from the laboratory to industrial test facilities and to discuss its future possibilities.

I welcome the delegates of the symposium at the DLR center Göttingen and wish a successful meeting.

Prof. Dr.-Ing. Joachim Szodruch
German Aerospace Center
Member of the Executive Board

Dear Colleagues:

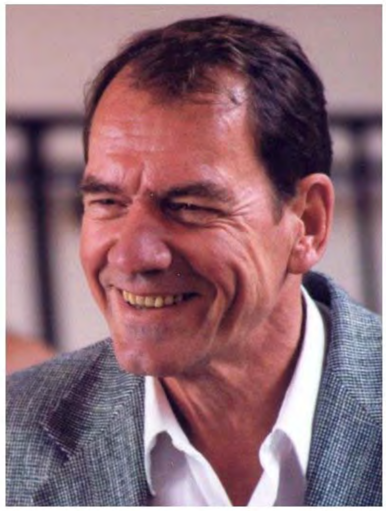
It is my pleasure to join the DLR, Dr. Jeurgen Kompenhans and all of the DLR staff who work on PIV in welcoming you to this celebration of *25 years of Particle Image Velocimetry in Aerodynamics*. The development of PIV theory and practice that has been conducted here in the German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, has been critical to the success PIV in aerodynamics and in the broad field of fluid flow science and engineering. It is both appropriate and enjoyable to pause at this juncture to look back on the history of the subject in order to appreciate the steps that make progress in our subject, which relies partly on our own innovations and partly on developments in other technologies.

I hope that, in addition to the history that is recorded on the record in our papers, we will also hear some oral history about personalities and anecdotes that never find their way into a journal article. I expect that such stories in combination with our various viewpoints will give us a new view of the subject and a better appreciation of our accomplishments.

Please join me in thanking Jeurgen Kompenhans and his colleagues for conceiving of this celebration and for their many efforts in organizing it.

Sincerely,

Ronald J. Adrian
Ira A. Fulton Professor of Mechanical and Aerospace Engineering
Arizon State University
Tempe, Arizona 85213
rjadrian@asu.edu



In 1984 Jürgen Kompenhans came to me to suggest that we try to learn techniques already being used by Klaus Hinsch in Oldenburg, by which velocity fields could be measured by scattering light off particles illuminated by a laser sheet. Two exposures separated by a known time interval permitted determination of the velocity component of each particle in the plane of the sheet. This seemed a promising idea, so we invested a small amount of money with which Kompenhans would do a demonstration. At the time, the recording was done with wet film, of course. When he was able to produce the flow field of a sonic jet in this way I was very impressed, and I think we put some more funding into it. In the intervening 25 years the development of PIV techniques have blossomed into capabilities that have far exceeded at least my wildest dreams at that time.

After I moved to GALCIT in 1987, and we hired Mory Gharib to the GALCIT faculty, it was then particularly gratifying for me to see that Mory and Jürgen started a collaboration which became very successful through the exchange of young researchers between DLR and GALCIT. I have myself only been an indirect beneficiary of PIV and not a contributor, so my only excuse for being here is my early recognition that it was worth buying into it. In this case the bet paid enormous dividends as is evident from the DLR group’s place in the field.

If the pace of progress of the first 25 years, as documented by the impressive contributions to this meeting, is an indication of things to come, we can look forward to an exciting future.

Hans G. Hornung
Kelly Johnson Professor of Aeronautics, Emeritus
GALCIT Director, Emeritus
Graduate Aeronautical Laboratories
California Institute of Technology

Striving for the best airplanes for its customers world wide AIRBUS is continuously improving its products. During the design process of new airplanes the most advanced tools need to be employed to achieve our demanding goals. In the domain of flight physics these are – among others - numerical and experimental simulation. Experimental simulation in particular is needed for improved understanding of the complex unsteady flow field around airplanes at off-design conditions and for validation of numerical simulation.

In this context Particle Image Velocimetry (PIV), being able to capture the instantaneous flow field, is one of the experimental methods of high importance for our work at AIRBUS.

Our interest in PIV goes back as far as to the year 1993. The PIV method still being in its infancy, AIRBUS decided to participate at the newly established GARTEUR action group on PIV. In the following years AIRBUS was a quite active partner in the two very successful EC funded research projects: EUROPIV 1 and 2. One of the first applications of PIV in an industrial wind tunnel has been successfully performed in the AIRBUS Bremen Low Speed Wind Tunnel early in 1997.

Once the potential of the PIV technique for the needs of an airplane manufacturer in an industrial environment had been demonstrated, the interest from inside our company increased to use PIV for applications such as high lift configurations, wake vortex interactions, propeller flows etc. in many projects and facilities, funded by national or European sources or by in-house contracts.

AIRBUS is proud having actively supported the development of the PIV technique towards its use in aeronautical test facilities and looks forward to future innovative developments of this technique.

We wish the participants of the Symposium 25 Years of PIV in aerodynamics a successful meeting and fruitful discussions.

Gérard Icart

Head of Airbus Wind Tunnel Testing

Objectives

The twenty fifth return of the day when the first PIV measurements in a wind tunnel have been performed in Göttingen is considered to be a good opportunity to commemorate the early developments of the PIV technique and to contrast the technical possibilities of those days to the state-of-the-art of PIV today. Decisive inventions will be acknowledged at this occasion as well as many small but significant contributions to the development of the PIV technique, - made in the past two and a half decades by many researchers world wide. New users of the PIV technique, in most cases employing off-the-shelf commercial PIV systems, shall be familiarized with problems that had to be faced in the past due to inadequate technology of those days. In addition, as there are still documents (photos, PIV recordings, lab notes, etc.) available describing the research work from the early development of the PIV technique, it shall be discussed with experts in the field of the history of science whether an annotated compilation and archiving of such documents would be feasible.

General Information

Oral presentations

Authors should contact the chairman of their session at least 30 min before the start of the session and should check the equipment available for presentation prior to the session with the technical assistant.

The time allocated for each oral presentation will be 18 min plus 1 min for one question and 1 min for change of speaker (= 20 min in total). Session chairmen will indicate the time remaining for each presentation (5 min (i.e. after 13 min talk), 3 min (i.e. after 15 min talk), STOP (i.e. after 18 min talk)). Further questions can be asked and supporting material can be presented during the afternoon discussion.

In the lecture room a video beamer and a Windows PC (with switch for laptops) will be available with the following software installed:

- Office 2003 (including PowerPoint)
- Acrobat Reader 9
- Tecplot 10 (including Framer)
- WinZip 9

The same PC infrastructure will be available in the afternoon discussion sessions.

Poster presentations

Please mount and remove your poster according to the time schedule given to you. Posters related to *PIV yesterday* will be on display on Wednesday, September 23, 2009. Posters related to *PIV today* will be on display on Thursday, September 24, 2009.

Lunch

Lunches will be served in the DLR canteen. Lunch tickets for each day (Wednesday, Thursday, Friday) have been given to participants at registration.
Please, return tickets which you will not use during the symposium to the registration desk.

Technical Excursion

Technical excursions to DLR and LaVision or Guided City Tour of Göttingen will take place on the afternoon of September 24, 2009 at 15:30. Tickets for two different tours (alternatives) have been selected by participants during registration:

- **Tour A**: DLR and LaVision GmbH
    - *Research areas: application oriented research in aviation and traffic engineering. Visit of wind tunnels for industrial and fundamental research. http://www.dlr.de*
    - Bus transfer to LaVision
    - *CCD-based camera systems and integrated optical diagnostics systems in the field of fluid dynamics (PIV), spray, combustion, deformation analysis and material sciences. http://www.lavision.de*
    - Bus transfer to Symposium Dinner

- **Tour B:** DLR and Guided City Tour
    - *Research areas: application oriented research in aviation and traffic engineering. Visit of wind tunnels for industrial and fundamental research. http://www.dlr.de*
    - *The cultural heritage of the university town Göttingen has been formed by many personalities, scientists, scholars, Nobel-prize winners, artists and creative artists who have left their visible marks in the town. Numerous memorial plaques at their living and working quarters give evidence of this fact. Georg Christoph Lichtenberg, Carl Friedrich Gauss, Gottfried August Bürger, the Göttinger Hainbund, the Göttinger Seven, the Göttingen Appeal of Leading Nuclear Scientists, the former Göttingen film studios, the theatre and music institutions rich in tradition, the renowned scene of the Göttingen publishing houses are just some examples which express the unique cultural tradition of Göttingen and indicate the vibrant intellectual life which is still here today. http://www.goettingen.de*
    - Bus transfer to Symposium Dinner

Please, return tickets for the technical excursion, which you will not use, to the registration desk.

Symposium Dinner
The symposium dinner will take place on Thursday, September 24, 2009 at 19:00 at Hotel-Restaurant ‘Biewald’, Weghausstrasse 20, 37133 Friedland. Tickets for the Symposium Dinner have been given to the participants during registration. Please, do not forget to bring your ticket with you for the dinner.

Bus transfer to the restaurant is included in Technical Tour A. Participants of Technical Tour B and remaining participants will leave by bus at 18:30 from DLR center Göttingen.

After the end of the dinner (approx. 23:00) busses will bring participants back to Göttingen. Please check for bus which will take the route closest to your hotel.

Please, return tickets for the symposium dinner, which you will not use, to the registration desk.

Vendors’ Party
The vendors’ party will take place on Wednesday, September 23, 2009 at 19:00 in the canteen of DLR Göttingen. Tickets for the Vendors’ Party have been given to the participants during registration. Please, do not forget to bring your ticket with you for the party.

This event shall provide the frame for informal discussion between the participants, not only on technical and scientific aspects of PIV, but also about less serious events of the past 25 years.

Please, return tickets for the vendors’ party, which you will not use, to the registration desk.

Wireless LAN
It is planned to provide WLAN access in the lecture hall. Some internet features may not work to due security issues.

Your comments/suggestions
Near the end of this booklet you will find a form for you to let us know, what you thought of the Symposium '25 Years of Particle Image Velocimetry in Aerodynamics'.

As this symposium has a somewhat different format as scientific conferences in general, we would be very grateful if you would take a few minutes to complete it and return it, either to the registration desk, or after the symposium by fax or e-mail to *25-years-PIV@dlr.de*.

Symposium '25 Years of Particle Image Velocimetry in Aerodynamics'
Göttingen, September 23 -25, 2009

Organizing Institutions, Sponsors and Exhibitors

Different organizations, public bodies and companies contribute to the organization of the Symposium '25 Years of Particle Image Velocimetry in Aerodynamics'.

The organizers and participants of the symposium greatly appreciate this support.

Supporting organizations, public bodies, and companies are:

Organizing Institutions

DLR	**Deutsches Zentrum für Luft- und Raumfahrt e.V.**	http://www.dlr.de
CARL VON OSSIETZKY universität OLDENBURG	**Carl von Ossietzky Universität Oldenburg**	http://www.uni-oldenburg.de

Sponsors

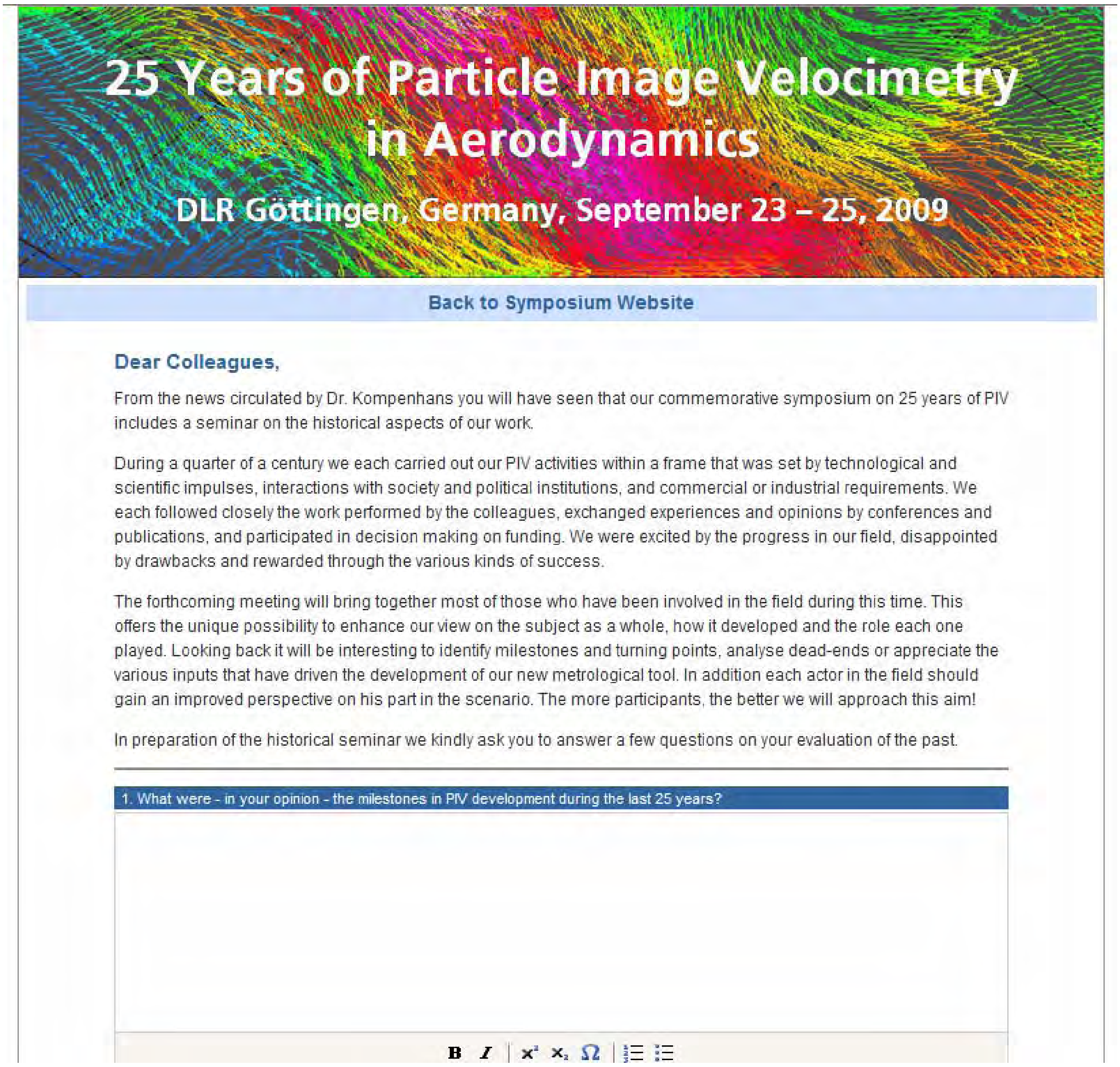
Deutsche Forschungsgemeinschaft DFG	**Deutsche Forschungsgemeinschaft**	http://www.dfg.de
DLR	**Deutsches Zentrum für Luft- und Raumfahrt e.V.**	http://www.dlr.de
Lower Saxony	**State of Lower Saxony**	http://www.niedersachsen.de

Exhibitors

DANTEC DYNAMICS	**Dantec Dynamics GmbH**	http://www.dantedynamics.com
INNOLAS LASER	**InnoLas GmbH**	http://www.innolas.com
ILA Intelligent Laser Applications GmbH	**Intelligent Laser Applications GmbH**	http://www.ila.de
LAVISION We count on Photons	**LaVision GmbH**	http://www.lavision.de
pco. imaging	**PCO AG**	http://www.pco.de
Quantel	**Quantel**	http://www.quantel.fr
Springer	**Springer Verlag**	http://www.springer.com
TSI	**TSI GmbH**	http://www.tsi.com

On-line Questionnaire 'Your evaluation of the past'

The symposium website *http://25-years-piv.dlr.de* provides a link to an on-line questionnaire, where we kindly ask you to answer a few questions on your evaluation of the past of Particle Image Velocimetry.



25 Years of Particle Image Velocimetry in Aerodynamics

DLR Göttingen, Germany, September 23 – 25, 2009

Back to Symposium Website

Dear Colleagues,

From the news circulated by Dr. Kompenhans you will have seen that our commemorative symposium on 25 years of PIV includes a seminar on the historical aspects of our work.

During a quarter of a century we each carried out our PIV activities within a frame that was set by technological and scientific impulses, interactions with society and political institutions, and commercial or industrial requirements. We each followed closely the work performed by the colleagues, exchanged experiences and opinions by conferences and publications, and participated in decision making on funding. We were excited by the progress in our field, disappointed by drawbacks and rewarded through the various kinds of success.

The forthcoming meeting will bring together most of those who have been involved in the field during this time. This offers the unique possibility to enhance our view on the subject as a whole, how it developed and the role each one played. Looking back it will be interesting to identify milestones and turning points, analyse dead-ends or appreciate the various inputs that have driven the development of our new metrological tool. In addition each actor in the field should gain an improved perspective on his part in the scenario. The more participants, the better we will approach this aim!

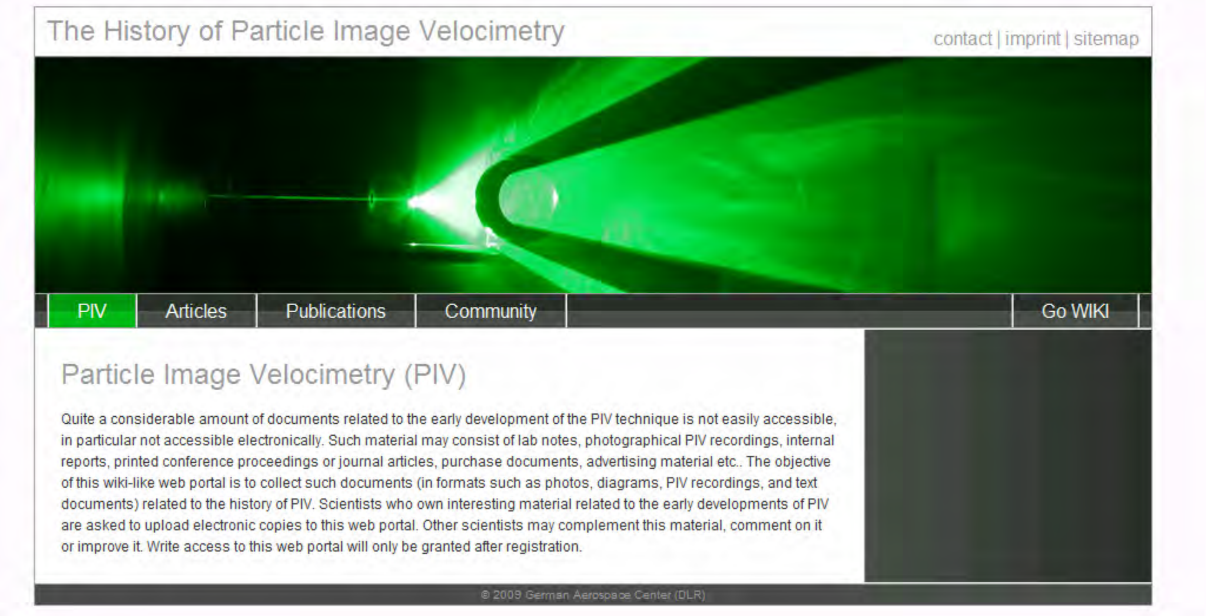
In preparation of the historical seminar we kindly ask you to answer a few questions on your evaluation of the past.

1. What were - in your opinion - the milestones in PIV development during the last 25 years?

Wiki-like web portal 'The History of PIV'

Quite a considerable amount of documents related to the early development of the PIV technique is not easily accessible, in particular not accessible electronically. Such material may consist of lab notes, photographical PIV recordings, internal reports, printed conference proceedings or journal articles, purchase documents, advertising material etc.. The objective of this wiki-like web portal is to collect such documents (in formats such as photos, diagrams, PIV recordings, and text documents) related to the history of PIV. Scientists who own interesting material related to the early developments of PIV are asked to upload electronic copies to this web portal. Other scientists may complement this material, comment on it or improve it. Write access to this web portal will only be granted after registration.

The symposium website *http://25-years-piv.dlr.de* provides a link to this web portal.



General Schedule

Wednesday, September 23, 2009

PIV yesterday

- Lectures on the early development of PIV
- Wiki: The History of PIV, free contributions, posters,
- Discussion of aspects of the early development of PIV
- Vendors' party

Chairman: Prof. Klaus Hinsch, University of Oldenburg

08:00 – 09:00	Registration
09:00 – 10:40	Five lectures by J. Kompenhans, R. Adrian, R. Meynart, M. Riethmuller, K. Hinsch
10:40 – 11:00	Coffee break
11:00 – 12:40	Five lectures by R. Kelnberger, B. Lecordier, M. Raffel, C. Willert, A. Boutier
12:40 – 13:40	Lunch
13:40 – 15:20	Five lectures by M. Gharib, C. Kähler, K. Okamoto, K. C. Kim, H. Frahnert
15:20 – 16:00	Coffee break
16:00 – 18:00	Open session, discussion
19:00	Vendors' party, DLR canteen

Thursday, September 24, 2009

PIV today

- Lectures on state-of-the art PIV developments and applications, and future prospects of PIV
- Free contributions, posters
- Discussion of future prospects of PIV
- Visit of DLR center Göttingen, LaVision or Guided City Tour in Göttingen
- Dinner

Chairman: Dr. Jürgen Kompenhans, DLR, Göttingen

08:30 – 09:00	Registration
09:00 – 10:40	Five lectures by J. Westerweel, S. Wereley, F. Scarano, J. Soria, M. Oshima
10:40 – 11:00	Coffee break
11:00 – 12:40	Five lectures by M. Stanislas, A. Schröder, K. Pengel, W. Kühn, E. Roosenboom
12:40 – 13:30	Lunch
13:30 – 15:00	Open session
15:00 – 15:30	Coffee break
15:30 – 18:30	Visit of DLR center Göttingen and LaVision company / guided city tour
19:00 – 23:00	Symposium Dinner, Hotel-Restaurant Biewald, Friedland

Friday, September 25, 2009

History in the Making – You are part of the History!
Five sessions of about one hour of discussion, each with a short introductory statement

Chairman: Dr. Falk Rieß, Center of Didactics and History of Physics, University of Oldenburg

09:00 – 10:00	Prehistory of PIV (Chair: M. Riethmuller, Brussels, tbc.)
10:00 – 11:00	Is there more than one history of PIV? (Chair: J. Kompenhans, Göttingen)
11:00 – 11:30	Coffee break
11:30 – 12:30	Success! What Success? (Chair: Andreas Junk, Oldenburg)
12:30 – 13:30	Lunch
13:30 – 14:30	Milestones and Turning Points (Chair: Klaus Hinsch, Oldenburg)
14:30 – 15:30	Is there a *Social History* of PIV? (Chair: Falk Rieß, Oldenburg)

Wednesday, September 23, 2009, 13:00 – Thursday, September 24, 2009, 13:00

Exhibition of vendors of PIV equipment

List of Oral Presentations

First day PIV yesterday
Chairman: Prof. Klaus Hinsch, University of Oldenburg

Wednesday, 23.9.2009

8:00	Registration		
	Author	**Affiliation**	**Title**
9:00	Jürgen Kompenhans	DLR, Göttingen, Germany	25 years of PIV development for application in aeronautical test facilities
9:20	Ron Adrian	Arizona State University, Tempe, USA	Development of PIV at the University of Illinois: 1983 -1993
9:40	Roland Meynart	European Space Agency, The Netherlands	The prehistory of PIV
10:00	Michel Riethmuller	VKI, Brussels, Belgium	Early PIV developments at the von Karman Institute
10:20	Klaus Hinsch	University of Oldenburg, Oldenburg, Germany	The role of optical processing in PIV
10:40	**Coffee break**		
11:00	Reinhard Kelnberger	Innolas, Munich, Germany	First commercial double oscillator Nd:YAG laser for PIV
11:20	Bertrand Lecordier, and Michel Trinité	CORIA, Rouen, France	PIV cameras and time resolved PIV measurement
11:40	Markus Raffel	DLR, Göttingen, Germany	PIV from lab to large wind tunnel
12:00	Christian Willert	DLR, Cologne, Germany	On the transition of PIV into the digital age - Recounting 20 years of digital PIV
12:20	Alain Boutier	ONERA, Paris, France	From prehistory of PIV to recent DGV, through 40 years of LDV
12:40	**Lunch**		
13:40	Mory Gharib	Caltech, Pasadena, USA	From art to science: The revolution of quantitative visualization
14:00	Christian Kähler	Universität der Bundeswehr, Munich, Germany	Achievements in sheet and volumetric PIV techniques with micron resolution
14:20	Koji Okamoto	University of Tokyo, Tokyo, Japan	History of PIV development in Japan
14:40	KC Kim, SJ Lee, DH Doh	Korea	Development of PIV in Korea
15:00	Holger Frahnert	Frahnert Forschung & Beratung, Göttingen, Germany	Introduction to the Community Platform on the History of Particle Image Velocimetry
15:20	**Coffee break**		

Second day PIV today
Chairman: Dr. Jürgen Kompenhans, DLR, Göttingen, Germany

Thursday, 24.9.2009

8:30	Registration		
	Author	**Affiliation**	**Title**
9:00	Jerry Westerweel	TU Delft, Delft, The Netherlands	PIV applied to strongly inhomogeneous turbulence
9:20	Steve Wereley	Purdue University, West Lafayette, USA	Micrometer and nanometer spatial resolution with μPIV
9:40	Fulvio Scarano	TU Delft, Delft, The Netherlands	4D-PIV advances to visualize sound generation by airflows
10:00	Julio Soria	Monash University, Melbourne, Australia	Investigating flow stability, turbulence and flow control using PIV
10:20	Marie Oshima	University of Tokyo, Tokyo, Japan	PIV applications in bio-engineering
10:40	**Coffee break**		
11:00	Michel Stanislas & all participants to GARTEUR AG 19, EUROPIV 1 & 2, PIVNET 1 &2 and PIV Challenge.	LML, Lille, France	The benefit of European networks and international cooperation for the development of PIV
11:20	Andreas Schröder	DLR, Göttingen, Germany	Developments for industrial PIV
11:40	Kurt Pengel	DNW, Emmeloord, The Netherlands	Use of PIV in DNW wind tunnels
12:00	Winfried Kühn, Klaus-Peter Neitzke, Andreas Schröder, Jürgen Kompenhans	AIRBUS, Bremen, DLR, Göttingen, Germany	Use of PIV in aeronautical industry
12:20	Eric Roosenboom	DLR, Göttingen, Germany	High quality PIV data for numerical validation
12:40	**Lunch**		

Third day History in the Making – You are part of the History! *Chairman: Dr. Falk Rieß, Center of Didactics and History of Physics, University of Oldenburg* Five sessions of about one hour of discussion, each with a short introductory statement **Friday, 25.9.2009**			
8:30	Registration		
	Chair	**Affiliation**	**Topic of discussion**
9:00	Michel Riethmuller tbc.	VKI, Brussels, Belgium	Prehistory of PIV
10:00	Jürgen Kompenhans	DLR, Göttingen, Germany	Is there more than one history of PIV?
11:00	**Coffee break**		
11:30	Andreas Junk	University of Oldenburg, Oldenburg, Germany	Success! What Success? Scientific: New Findings? Technological: Does it Work? Economical: Can You Buy It, Can You Sell It? Personal: Help for Individual Careers?
12:30	**Lunch**		
13:30	Klaus Hinsch	University of Oldenburg, Oldenburg, Germany	Milestones and Turning Points
14:30	Falk Rieß	University of Oldenburg, Oldenburg, Germany	Is there a *Social History* of PIV?
15:30	**End of symposium**		

List of Posters

Wednesday, September 23, 2009: PIV yesterday			
Author(s)	**Organization**	**Country**	**Title**
DAVID, Laurent; TEXIER, Alain	University of Poitiers	France	Measurements by Particle Streak Velocimetry: first step to the PIV ?
Markovich, D.M, Fomin, N.A.	Institute of Thermophysics, Novosibirsk Heat & Mass Transfer Institute, Minsk	Russia, Belarus	Flow velocimetry in Former Soviet Union States
SHEN, Gong-Xin	BUAA, Beijing	China	From WBPIV to 3Dt-3c PIV in China
Burgmann, Sebastian	RWTH Aachen	Germany	More than a decade of PIV at the Institute of Aerodynamics – Development and Application
Thursday, September 24, 2009: PIV today			
Author(s)	**Organization**	**Country**	**Title**
DAVID. Laurent; CALLUAUD, Damien; CHATELLIER, Ludovic; THOMAS, Lionel; TREMBLAIS, Benoit	University of Poitiers	France	Post-processing tools from PIV measurements
Scholz, Peter; Ortmanns, Jens; Casper, Markus	TU Braunschweig	Germany	Stereo-PIV as a tool for optimization of flow control devices
DOH, Deog Hee; CHO, Gyeong Rae; JO Hyo Jae; TAKEI, Masa	Korea Maritime University, Busan; Nihon Univ., Tokyo	Korea Japan	A Volume PTV
Atkinson, C. J.; Soria, J.	Monash University, Melbourne Ecole Centrale de Lille	Australia France	Accelerated Tomographic Particle Image Velocimetry for 3C-3D Velocity Measurements
M. Bartelt, A. Mohseni, V. Opilat, J.R. Seume	Leibniz University, Hannover	Germany	Endoscopic Stereoscopic PIV Measurements in Turbomachines
S. Große, J. Westerweel	TU Delft	The Netherlands	Large-scale coherent motion in turbulent pipe flow
R. Badreddine, M. Lawerenz	University of Kassel	Germany	PIV-Messung selbsterregter periodischer Str¨omungen
A. Henning, L. Koop, K. Ehrenfried, A. Heider	TU Berlin DLR Göttingen	Germany	Application of PIV in acoustic and aeroacoustic experiments
D. M. Markovich	Institute of Thermophysics, Novosibirsk	Russia	PIV-LIF techniques for multiphase flows diagnostics. Recent results of Institute of Thermophysics

Abstracts *PIV yesterday*

25 years of PIV development for application in aeronautical test facilities

Jürgen Kompenhans

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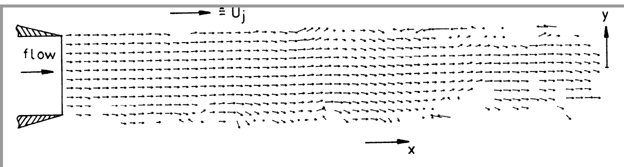
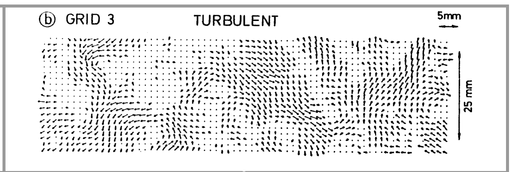
In summer 1984 teams of the University of Oldenburg and DLR carried out measurements of instantaneous flow field by means of Particle Image Velocimetry for the first time in a wind tunnel of DLR Göttingen. In those days the recording of the PIV images had to be done photographically. Also, the evaluation of the recordings to obtain the displacement of the images of the tracer particles, added to the flow, had to be performed optically. A few months later DLR had the first double oscillator Nd:YAG laser at its disposal and started the development of a PIV system applicable for aerodynamic research in large industrial wind tunnels. Around 1995 a major breakthrough in the development of PIV, which has been a prerequisite to bring this technique out of the laboratory and into use at research organizations for applications of relevance to industry, has been made. Then, digital video cameras, allowing capturing the two frames of a PIV recording within a short time interval and with full spatial resolution and the necessary cross correlation evaluation algorithms became available. In the following decade the PIV technique has been widely spread and differentiated into many distinct applications ranging from micro flows to combustion and supersonic flows, both for research and industrial needs. This was made possible mainly due to further technological progress in video techniques, lasers and the development of sophisticated evaluation algorithms.

The most important developments and achievements required to perform successful application of PIV in aeronautical test facilities of industrial interest have been: powerful seeding devices, robust double oscillator Nd:YAG lasers, hard- and software for PIV allowing to utilize cross correlation for evaluation, Gaussian peak fit, sensitive (cooled) CCD cameras, and continuous improvement of spatial and temporal resolution of light sources and cameras. The acceptance of the PIV technique by industry has been facilitated through the support of European projects such as EUROPIV, EUROWAKE, EUROLIFT, AWIATOR etc. where it has been possible to demonstrate the additional and new knowledge about the behavior of flow structures in complex unsteady flow fields (separated flows, tip vortices, wake vortices, boundary layers, gap flows etc.) as obtainable by application of PIV.

Nowadays the PIV technique is considered a 'validated tool' by the aeronautical industry and used in large industrial wind tunnels to support the design of new aircraft. Within this context PIV flow field data are increasingly used for validation of results of numerical calculations.

1986 - 1989





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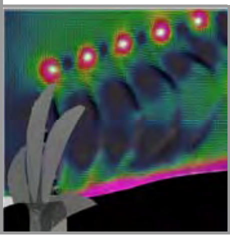

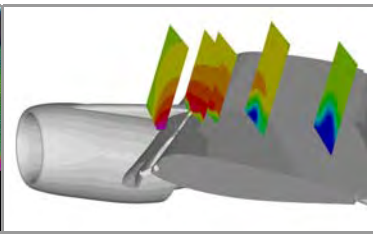

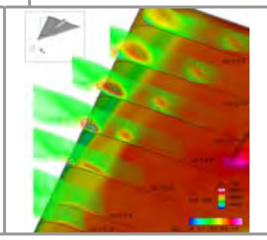

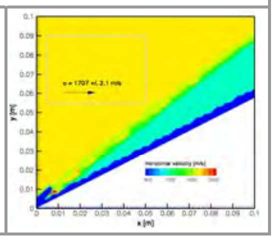

For further details see of results of PIV team of the Department of Experimental Methods: http://www.dlr.de/as/en/desktopdefault.aspx/tabid-183

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

* 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.

Z.-C. Liu et al.: High resolution measurements of turbulent structure 309

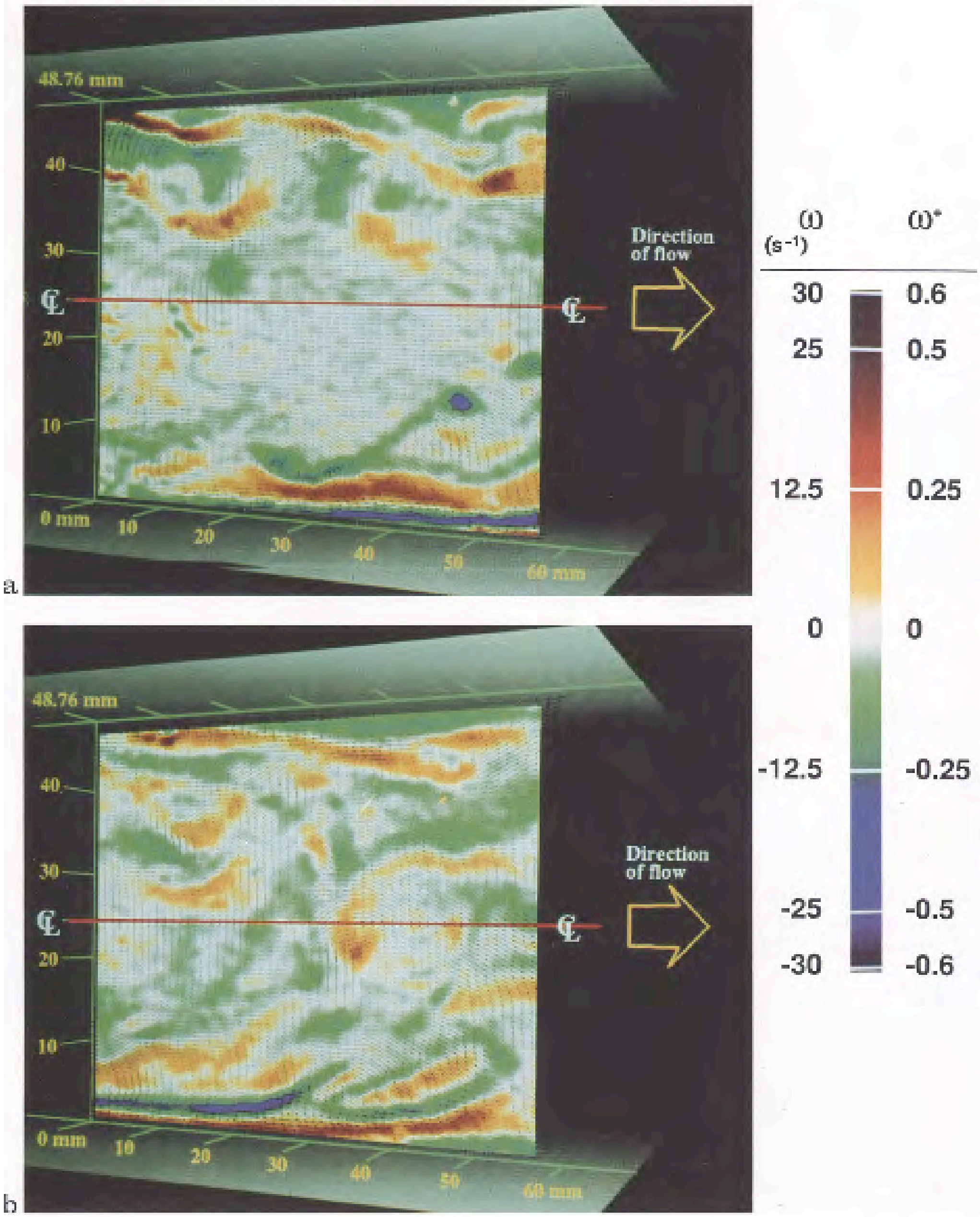

Fig. 9a and b. Color maps of instantaneous vorticity fields corresponding to the velocity fields of Figs. 6a and b. Velocity vectors are superposed on color fields

(*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.

The prehistory of PIV

Roland Meynart

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During the seventies, the availability of powerful, stable and single-mode lasers made possible the development of a new range of metrology techniques based on the use of coherent laser beams. These experimental methods were used to measure deformations and stresses of solid surfaces by exploiting the displacement or correlation of wavefronts or speckle patterns scattered by the surface (holographic interferometry, speckle photography, speckle interferometry).

The techniques were adapted to also probe transparent 3-D objects. In particular, some optical experimenters tried, sometimes just for fun, to estimate the displacement of particles carried by fluid flows. A simple double-exposure of a flow illuminated by a laser light sheet would show pairs of particle images whose displacement could be measured by optical techniques. Although the recording of the images was pretty conventional, the breakthrough was the use of analysis methods inherited from speckle photography.

At a time when efficient digitisation of the photographic image– not to say direct digital recording of the particle field -was not credible, laser illumination of the photographic negative produced systems of optical fringes that could be processed in a much easier way. Young's fringe production –in fact analog Fourier transformation-proved to provide a simple displacement measurement method, that could be used to explore the performance of the technique for various types of fluid flows.

During the years 1980-1985, the technique, initially called speckle velocimetry because of the similarity of its image processing with that of speckle photography, was further developed: different types of pulsed or chopped lasers were used for various types of liquid and gas flows, particle insemination techniques were refined and, even, some primitive form of fringe digitisation and automatic processing were introduced. Quite a few fluid mechanics metrologists started getting interested in a technique that could provide instantaneous velocity fields. What was initially an optical laboratory curiosity became part of the palette of established measurement techniques available to "serious" experimenters and, a bit to the surprise of the author, the subject of commercial product developments.

EARLY PIV DEVELOPMENTS AT THE VON KARMAN INSTITUTE

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INTRODUCTION

Roland Meynart introduced Particle Image Velocimetry at the von Karman Institute where he started in 1981 to perform part of his pioneering work within his PhD research. After the end of his thesis, the VKI continued the development and applied this technique to most domains of fluid dynamics.

SILVER PROCESS: 1981 – 1989

This paper describes the work done at the VKI between 1984 and 1997. It first presents work done with silver processes and development of Young's fringe processing, then the implementation of a moving mirror by V. Gauthier, a post-graduate student, in 1986 to resolve directional ambiguity and increase velocity dynamics. Also, in 1986, another student, J.F. de Almeida Dias Delgado performed the world first stereoscopic PIV measurements using photo cameras. The same year, C.S. Moraitis performed measurements in a small supersonic nozzle and started to develop holographic processing of young's fringes. In 1987, N. Paone performed the world first PIV measurements in a transparent pump using a CW laser pulsed by a combination of rotating shutter and moving blade. In 1988, the VKI organized the first meeting devoted to PIV in the form of a Lecture Series with courses given by the few experts of the time and a series of paper presentations given by the researchers who were active in the early developments of PIV at this time. In 1989, R. Obertacke and P. Corieri performed PIV measurements in a model of a lung bifurcation using the early silver technique.

DIGITAL PIV: 1990 - 1997

The first cross-correlations of digital images were made at the same time by N. Selfslagh and tested on the lung test in 1990 by P. Corieri. Since the computers were still far too slow, correlations were made on binarized images issued from video framing camera recordings using Logical Functions and moving windows were already applied. PC based array processors were also applied to improve processing time. In 1993, the silver technique was applied to measurements in a compressor facility by D. Tisserant. After several developments, in 1995 the first full cross-correlation using FFT and sub-pixel interpolation was developed by J-B Moens who also converted a video camera into a dual frame recording tool. The era of digital PIV was started at the VKI and numerous applications were immediately performed: natural convection on a heated wire, surface velocity of wavy liquid films and micro-PIV to measure the velocity field in the nip between two roll coating cylinders, using a microscope. At the same time, some people were still convinced of the power of holography and E. Fabry developed a stereoscopic technique based on holographic recording to perform measurements in turbomachines. Time resolved measurements were started in 1996 by H. Richard in a water tunnel using a CW laser with a camcorder and by A.H. Rike in a wind tunnel using a CW laser with a High Speed Video camera. 1997 was the end of the early developments with the work of F. Scarano who developed an advanced algorithm for processing PIV images that used window displacement and distortion with an iterative multigrid technique. This type of algorithm soon became the standard of most processing tools.

CONCLUSION

In conclusion, we can say that an important work has been performed at the VKI in the early days of PIV. A good dissemination of knowledge has been ensured through the multiple Post-graduate students who worked in the field and also by the successive Lecture Series, the first one being organized in 1988. The VKI also applied very early the PIV in a wide range of applications.

The role of optical processing in PIV

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This symposium is commemorating the 1984 PIV records from the low-turbulence wind tunnel at DLR in Göttingen. The double-exposure photographic images from this campaign had to be processed by inspecting the Young's fringes produced by diffraction of a laser beam interrogating small areas in the photo. At that time, there was no reasonable alternative to this kind of optical processing. The implementation of an optical device was essential for the success of the method. Gradually, with the progress of electronic image acquisition and digital data processing the optical methods offered for the evaluation of PIV records became less significant. Looking back, they can be considered auxiliary or even just optional tools. The present paper explores the historical development of the role optics played in the interrogation of PIV images by briefly recalling the most important approaches proposed, placing them in the technological scene of the time and identifying essential influences that governed the development.

The first decade is characterized by efforts to economize the fringe method by more effective extraction of fringe orientation and spacing. While most techniques aim at a digital output of the final displacement values, quite a few make use of auxiliary optical components. These serve to avoid some cumbersome computations like in spatial integration or image rotation. The initiating 1984 measurements at the Göttingen wind tunnel were mainly carried out to explore the suitability of the new technique under wind tunnel conditions. In addition a novel optical processing scheme called large-area-interrogation was tested. In this study, the degree of turbulence was determined from the space-dependent visibility of the overall fringe pattern thus bypassing the accumulation of point-wise interrogation data. Other optional proposals were to reduce the large portion of interrogation time spent in scanning the interrogating laser over the PIV transparency. Simultaneous interrogation of many spots by a light field from a 2-D array of many small lenses served this purpose. Finally, spatial-frequency filtering was applied for generating velocity contour lines to provide a kind of flow field visualization of the complete observation area. This was achieved purely by optical means.

This latter method points towards even more challenging solutions that were pursued to obtain the displacement of a particle cluster by applying optical spatial correlation. The spacing of the side peaks in the autocorrelation of the light intensity in the interrogation area yields the wanted displacement vector. Autocorrelation requires a sequence of operations: a first Fourier transformation, modulus-square operation and another Fourier transformation. All Fourier transformations can be performed easily by optics. The procedure in between, however, requires transcribing the fringes pattern onto a spatial light modulator. The availability of various types of modern optical components promoted as well as limited the performance of these correlators. Efforts in the field finally led to sophisticated three-dimensional correlation architectures.

Optical procedures that were originally essential for the performance of PIV faded when the digital techniques expanded. It is interesting to analyze when and how researchers reacted to the competing methods that were fueled by technological needs beyond PIV requirements. Many an ingenious optical invention became obsolete and the attention turned from physics more to technology and computing. A similar development is presently seen in particle holography.

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First commercial Double Oscillator Nd:YAG Laser for PIV

Introduction

Back in 1984 teams of the University of Oldenburg (Prof. Klaus Hinsch) and DLR performed the first PIV tests in a wind tunnel at DLR in Göttingen.
The Laser, which was used at this time, was a JK 10 Joule Ruby Holographic Laser System (Model HLS 4)

In October 1984, we at JK Lasers Deutschland GmbH received an enquiry from Dr. Kompenhans of DFVLR in Göttingen, for a Laser system, capable of similar pulse separations as the HLS 10 but with a much faster repetition rate. The pulse energy could be less.

The only way to achieve a repetition rate in the range of 10 Hz was to use a frequency doubled Nd:YAG Laser system instead of a Ruby system.

At this time, this requirement was quite difficult to achieve with a single oscillator. The storage time of YAG is much shorter (230µs) than on a Ruby (1,2 ms). At interpulse separations of less than 230 µs, a very careful Q-switch control would be necessary to achieve balance of the pulse amplitudes. JK Lasers in England refused to build such a system since the technical risk was to high.

After some deep discussions, between Hans Schürer and myself (both from JK Lasers in Germany) and Clive Irland from JK Lasers in England, it was agreed that the best proposal would be to use two separate standard HyperYAG 200 Laser systems with orthogonal polarizations. The two beams could be combined via a polarizer prior to entering a KD*P-Type II doubling crystal.

PIV Cameras and time resolved PIV measurement.

B. Lecordier[1] and M. Trinité
UMR CNRS 6614 CORIA, Université & INSA de Rouen, France

In the late 1980s, the video cameras progressively replaced the double exposed photographic records used for auto-correlation PIV technique. The optical auto-correlation map or directly the double exposed particle fields were recorded in digital format using video camera. The transition towards a fully digital PIV system has been more and more pronounced in the beginning of nineties, when the developments of CCD sensor had made possible separated images recording in short time delay (< 10 µs) using the frame-straddling synchronisation[2,3]. Even if at that time, the CCD resolutions were very low (720x580 in CCIR Standard), and that the two separated images were distributed on the even and odd fields of interlined CCD device, the advantages of the cross-correlation approach (non directional ambiguity, high particle density, large range of velocity measurement,.no self correlation-peak..) compared to difficulties and limitations of auto-correlation technique, have strongly contributed to the definitive transition of the photographic film towards the video cameras. That transition has been enforced by the sub-pixel technique, which compensated the lost of measurement accuracy induced by the low resolution of images and by the significant increasing of computer power permitting to consider fully-digital image processing approaches. From that time, the camera improvements have never stopped and nowadays, devices able to record up to 4kx4k double images with inter-frame delay smaller than one microsecond become more or less standard cameras for PIV applications.

For time resolved PIV measurement in high speed flows (> 1 m/s), namely when the video frame rate has to reach more than 1000 frames/s, the transition to digital acquisition devices has been done around ten years later than for the low framing-rate systems (< 100 Hz). During the 90s, more or less the only way to access to time resolved PIV measurements was to combine high-speed photographic camera with a coper vapour laser[4]. The photographic films were then digitized with many precautions thanks to high resolution film scanner to allow the correlation between images recorded at different positions on the photographic film. The first high speed video cameras able to record more than 1000 frames/s had very low resolution (< 256x256 pixels) and could not be synchronised in frame-straddling mode for short inter-frame delay. Nevertheless, these cameras have quickly replaced photographic film recording due to more flexible and simpler operating conditions. During the last ten years, performances of high speed video cameras have been extensively developed and improved in term of resolution, sensitivity and frame rate. Nowadays, time resolve PIV measurement reaches accuracies close to those obtained from classical PIV system.

In this lecture, the different historical evolution and transition of recording systems for PIV measurement will be presented and discussed.

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1 Email:Bertrand.Lecordier@coria.fr

2 Lecordier, B.; Mouqallid, M.; Vottier, S.; Rouland, E.; Allano, D. & Trinité, M. (1994), 'CCD Recording Method For Cross-Correlation Piv Development In Unstationary High-Speed Flow', *Experiments In Fluids* **17**(3), 205—208

3 Huang, H.T. & Fieldler H.E. (1994) Reducing time interval between successive exposures in video PIV. Eperiments in Fluids – 17, 356-363

4 Lecordier, B.; Mouquallid, M. & Trinité, M. (1999), 'Simultaneous 2D measurements of flame front propagation by high speed tomography and velocimetry field by cross-correlation"7th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon Portugal'.

PIV from lab to large wind tunnel

by Markus Raffel

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In the early 1990's, the relevant literature was written by Adrian, Riethmuller, and Lourenco (to name just a few). At DLR in Göttingen Jürgen Kompenhans and his former PhD students succeeded measuring in a transonic flow in a wind tunnel, but for three reasons PIV was not ready to be used as a matter of routine:

- It was hard to get enough particles of the right size homogeneously distributed in the laser light sheet, especially in blow-down facilities, at high flow velocities.
- The dynamic range of the velocity one could successfully measure was very limited and measuring reverse flows was impossible, as the particle images would have overlapped on the doubly exposed photographic film.
- Adjusting the set up for best focus meant photographing at different distances between camera and light sheet and analysing the result on the developed film under a microscope Than, going back to the position that seemed to be best and starting the measurement (mostly on the next day).

These three problems had to be solved and were solved by the methods described below.

The system worked pretty well even in the larges wind tunnels until the first cross-correlation video cameras came onto the market in 1996.

The author would like to state that - despite of the tonnes of paper that have been published on the improvement of digital PIV evaluation - the accuracy received with photographic PIV was not far from today's digital PIV. However, the recording of one good PIV image required typically a week of preparation in the wind tunnel, one day for developing and drying the negative, one day for preparing and drying the contact copy and about two days for an optical/digital evaluation.

On the transition of particle image velocimetry into the digital age – Recounting 20 years of digital PIV

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Early 1989 the first image sequences of single exposed particle images were acquired for a low speed thermal plume in water and for the first time demonstrated the double-frame, single-exposure PIV recording and processing concept, that was to become the most common implementation of PIV up until today. The presentation provides a historical perspective of the development of digital PIV in the presence of the then already well established photographic PIV methods. Initially the implementation of the two techniques seemed to cater to different areas of application, but a steady improvement of the theoretical background during the 1990's clarified that the two techniques are merely different implementations of the same measurement principle.

In the early 1990’s digital PIV was limited to the study of low speed water flows below 1 m/s at rather low spatial resolutions but nonetheless allowed time-resolved measurements through the analysis of continuous video image sequences [1]. The access to the time-evolving vorticity field and other quantities derived from the velocity maps gave researchers a powerful tool, for example, in the visualization and understanding of vortex dynamics and also has helped in the validation of numerical results obtained with direct numerical simulation (DNS).

Technological advances in subsequent years, both on the imaging as well as computational side, were key in bringing digital PIV to a much wider range of applications. In a first step digital processing of photographic PIV recordings became possible with the emergence of slide scanners which eventually replaced the optical interrogation methods. Soon thereafter new camera technology based on interline-transfer CCD sensors allowed the capture of two separate images on the microsecond scale and for the first time provided reliable digital PIV measurements of high speed flows in aerodynamics. From 1996 onward a wide variety of projects conducted by DLR made extensive use of digital PIV, turning the technique into one of the most important flow diagnostics tools in aerodynamics. At the same time these projects, oftentimes funded by the EU, were instrumental in promoting the acceptance of the technique for industrial research.

A steady increase in sensor resolution nowadays provides a spatial resolution that rivals that of high-resolution 35 mm photographic film. Extensions of the technique led to the development of stereo PIV, multiple plane PIV and tomoscopic PIV yielding three-component as well as volume resolved velocity data. The recent availability of high frame-rate cameras now also allows for time-resolved PIV measurements of aerodynamic flows. In parallel the increase of computational capabilities by several orders of magnitude over the past two decades can now provide high-resolution PIV velocity maps exceeding video frame rates.

[1] Willert C, Gharib M (1991) *Digitial particle image velocimetry*. Exp. Fluids **10**:181-193

Symposium 25 Years of PIV in Aerodynamics
Göttingen, September 23 - 25, 2009

From Prehistory of PIV to Recent DGV, through 40 Years of LDV

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History of my laser velocimetry activities started in 1970 with a series of tests in the R4 facility of Modane-Avrieux centre of ONERA, i.e nearly 40 years ago.

The objective was to measure velocities in a propulsion device simulator. It's the first time that a kind of PTV system has been employed. The flow was illuminated by a laser sheet issued from two different lasers: a Q-Switched laser delivered two or three pulses in order to mark the positions of the particles (recorded by a camera) and a free running laser was used to create on the film a straight line allowing to find upstream the dots due to the pulses (we should call that now image encoding). All the processing was done manually, with an original and human synchronisation system.

Then there has been the long development of LDV, going from 1D to 2D and finally operational 3D systems. With the flexible apparatus developed at ONERA, it has been also possible to perform spatial correlations on hot jets, with large movement displacements. The most outstanding application of 3D laser velocimetry took place in 1994 at DNW, where two 3D set-ups were simultaneously installed on platforms 10 m high, in order to characterize the vortex interaction with rotor blades of a helicopter: DLR device was investigating advancing blade and ONERA device the retreating blade. Seeding problems and other synchronization systems left very deep souvenirs to all the scientists who contributed to this one month campaign.

In laser velocimetry history, the development of time of flight instruments dedicated to turbine investigation has been also very important: it was necessary to improve the signal to noise ratio in order to get velocity information in narrow channels where the presence of walls very close to the probe volume created a lot of stray light. One family of instruments is very famous: the L2F developed by DLR. At ONERA we have also developed a mosaic laser velocimeter for large facilities and air intakes.

Finally DGV appeared in the 1990's for application in large facilities and for high velocities. In spite of many efforts of a few expert teams through the world, the commercial development did not occur, so that it remains a very useful technique providing real time velocity maps for people who have kept expertise of DGV.

In conclusion, we may outline the main characteristics of the various techniques which must be considered as providing complementary information:
- LDV performs local measurements with very high data acquisition rates, allowing assessing fluctuation spectra of turbulence;
- PIV provides snapshots of instantaneous velocity maps, allowing pointing out instabilities or intermittence effects;
- DGV is able to provide real time mean velocity maps, and is more appropriate for large facilities and high velocity flows;
- L2F is the quasi unique instrument able to perform velocity measurements in turbines.

From art to science: The revolution of Quantitative Visualization

Mory Gharib

California institute of Technology

The progress in science has greatly depended on the experimentalists' capabilities to question nature by means of observation and experimentation, and by way of measuring magnitudes that could be analyzed and interrelated through mathematical formulation. It is a historical fact that every time experimental techniques have taken a leap forward, the "experimentalist" has made totally unexpected and unimagined discoveries. In the field of fluid mechanics, for more than a century, the progress in understanding some of the grand challenges of the field such as turbulence, unsteady separated flows and many others depended on techniques that could only reveal a partial view of the real physics of these important problems. In recent decades, advances in computer science and Computational fluid dynamics (CFD) have opened the attractive prospect of accurately simulating the experimentally hard to realize fluid mechanical problems. However, many fluid mechanical problems of scientific and engineering importance exhibit complex, unsteady and multi-dimensional dynamics that makes it difficult if not impossible to resolve them through current state-of-the-art in CFD. The Invention of Particle Image Velocimetry (PIV) and its amazing development into a method of choice in the field of fluid mechanics have helped us to acquire new capabilities in the whole-field flow mapping techniques. In fact these capabilities have enabled us to efficiently interface with CFD. This new horizon is promising in its capabilities to guide, validate and actively interact in conducting reliable simulation of complex flows. In this lecture we present some of the key challenges and technological advantages that the revolution of PIV has accomplished in making quantitative visualization an important research tool in the field of fluid dynamics.

Achievements in sheet and volumetric PIV techniques with micron resolution

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My first contact with PIV happened on a demonstration performed by Chris Willert, Markus Raffel and Jürgen Kompenhans at the Technical University of Clausthal, in the spring-time of 1995. Coincidentally, I had a deep interest in coherent near wall flow structures in turbulent boundary layers at the time and the demonstration made a strong impression on me. I became excited about using this method and fortunately I had the opportunity to join the PIV group of Jürgen Kompenhans at DLR Göttingen to work on my diploma project. In August of 1995 I started my first measurements using photographic PIV with the rotating mirror system, developed by Markus. For the illumination, a heavy 70 mJ Lumonics HY 200 SPECIAL Nd:YAG laser was available. Instead of optically evaluating the contact copies of the 36mm film after the experiment, which was the state-of-the-art at that time, I digitized the recordings with a brand-new scanner in order to evaluate them digitally. I was deeply impressed by the large-scale coherent flow structures I could resolve with the system (figure 1), but the spatial resolution was far too low to resolve the velocity profile down to the viscous sub-layer.

In February of 1996 Chris had integrated a 1k×1k digital camera (Pulnix) in the DLR PIV system. Apart from the low spatial resolution compared to photographic PIV, digital PIV was a fantastic improvement, particularly due to the multi-pass cross-correlation analysis with window-shifting (already of second order at that time). I was able to much better resolve the velocity profiles (up to the buffer layer, see figure 2) but when I plotted the histogram, I saw what today we refer to as peak-locking (figure 3). This effect was not known from photographic PIV (probably due to the noise) and none of my famous colleagues or visitors at the DLR at that time (Jerry Westerweel and others) had observed it before. As the implication of this effect on velocity measurements was obvious, Jürgen Kompenhans recommended that we do not publish the graph in my diploma thesis, though I did nevertheless [1].

Enthusiastic by the technical improvements and my first findings, in March 1996 Jürgen Kompenhans sent me to Ron Adrian at Urbana Champaign to get familiar with digital stereo PIV. Learning from Ron was a great honor for me. Additionally, Jerry spent some weeks visiting Ron during the same period to work on “The Book”. So I was able to discuss all my findings at lunch with Jerry and, at least once a week, with Ron. Back in Germany, I evaluated the 2k×2k stereo PIV recordings made during my stay at Urbana Champaign, with the stereo software that Chris developed in my absence. Surprisingly the out-of-plane motion was always on the same side of the low-speed streaks. I realized that this effect was caused by slight differences between the calibration and the measurement configuration. So I worked on a way to compensate for this effect, which is known today as disparity correction [2], and I learned that even when you are doing everything right there might still be something wrong!

After finishing my Diploma thesis, I continued the work at DLR during my Ph.D. with the development of the multi-plane stereo-PIV technique, to estimate unsteady and 3D flow characteristics in air, and I was able to analyze turbulent boundary layers in much more detail [3]. Thanks to Michel Stanislas and Jürgen Kompenhans I could perform the experiments in Lille, which is greatly appreciated. Besides my work on boundary layers, I was also involved in many international test campaigns where I learned to apply PIV with a team in large scale catapult- and wind- tunnels and in 1998 I had the privilege, together with my colleague Andreas Schröder, to work in Mory Gharib’s group at Caltech. California was just wonderful and I learned that life is not just work. In September of 2001 I left the DLR PIV group after six exciting and extremely fruitful years which have influenced me greatly.

From October, 2001 until April, 2008 I focused my attention on intrusive and non-intrusive flow control concepts and the development, improvement and application of all kinds of PIV variants at the TU

Braunschweig. I worked, particularly, on a long-range micro-PIV system with single pixel resolution in order to resolve the viscous sub-layer. In 2005 I was able to measure the boundary layer velocity profile with a resolution of 0.028 viscous units in a wind-tunnel, at a free stream velocity of 10 m/s. The resolution of one thousand measurement points within a millimeter over a distance of 0.5 m was far beyond my highest expectations when I began my research in 1995 at DLR Göttingen. So I tend to believe that there is always a solution, we just have to explore it!

Today, I still like the Particle Image Velocimetry, mainly because

1. the technique still puzzles and inspires me to come up with improvements,
2. as a physicist, I like the components involved (laser, CCD camera, optics, image analysis),
3. I met many good people in this community and it is always a pleasure to meet them at conferences or events such as the 25 years of PIV at DLR Göttingen in 2009.

[1] Kähler CJ: Ortsaufgelöste Geschwindigkeitsmessungen in einer turbulenten Grenzschicht. Forschungsbericht der Deutschen Forschungsanstalt für Luft- und Raumfahrt, DLR–FB–97–32, 1997

[2] Kähler CJ, Adrian RJ, Willert CE: Turbulent boundary layer investigations with conventional and stereoscopic PIV. 9^{th} Int. Symp. on Appl. of Laser Techn. to Fluid Mech., Lisbon, Portugal, June 13–16 1998, paper 11-1

[3] Kähler CJ: The significance of coherent flow structures for the turbulent mixing in wall-bounded flows. Forschungsbericht des Deutschen Zentrums für Luft- und Raumfahrt, DLR-FB-2004-24, 2004 (http://webdoc.sub.gwdg.de/diss/2004/kaehler/kaehler.pdf)

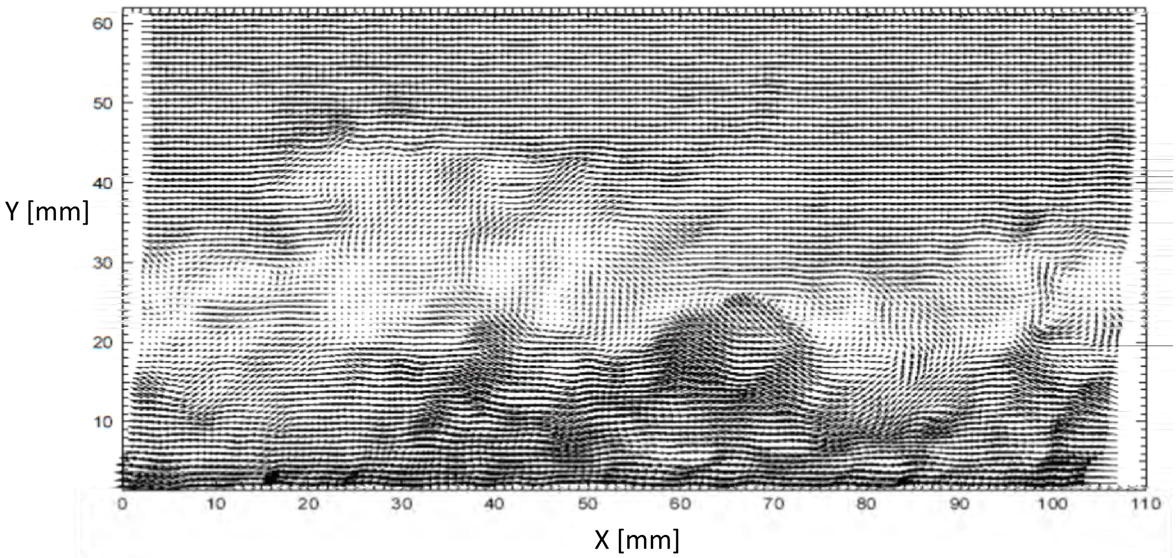

Figure 1. Photographic PIV measurements of a turbulent boundary layer [1].

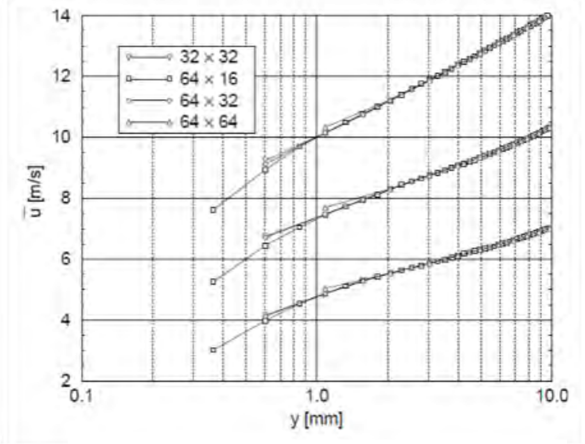

Figure 2. Near-wall velocity profile measured with digital PIV [1].

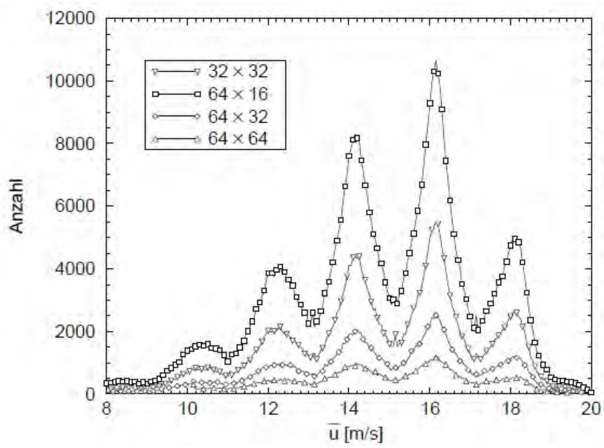

Figure 3. Histogram of the velocities measured with digital PIV [1].

History of PIV development in JAPAN

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The Flow Visualization Society of Japan had been established in 1978. The PIV research and development had been carried out in the Society and its successive society, Visualization Society of Japan (VSJ). In early 1980s, the digital image processing technique had been applied to flow visualization researches. Prof. Yano (1983), Kobe University, proposed the cross-correlation PIV technique as shown in Fig.1. From then, many PIV algorithms had been proposed in Japan, including color-coded PTV, 3D PTV and so on. The fluid engineering researchers were working on the PIV development. In this report, three major epoch making researches of Japanese PIV development history in every decade will be reviewed.

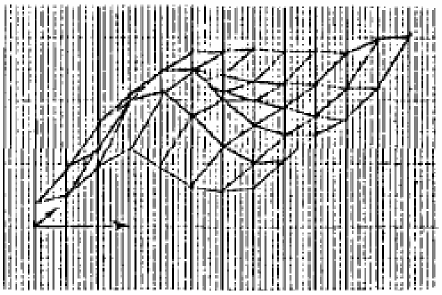

Fig.1 Cross-correlation of binary images (Yano, 1983)

1980s: Near Wall Turbulent Measurement (3D-PTV)

Nishino et al. (1989a, 1989b) developed the 3D-PTV technique to validate the Direct Simulation results of near wall turbulence. They used three cameras and laser disk image recorder. Then, they reconstructed the 3D-3C velocity field with 3D-PTV technique. The velocity data had been statistically averaged to discuss the three-dimensional near wall turbulence. The accuracy of the data was high enough to compare the simulation results. After 20 years, their data are still referred.

1990s: Standard PIV Images

Okamoto, et al. (2000a, 2000b) proposed the Standard PIV Images in 2D/3D. The objective of the Standard Image was to quantitatively compare the PIV algorithms. The correct velocity information was known as the numerical simulation results. Then, the artificial particle images were generated and distributed through internet. (www.piv.jp). The images are extended to measure the 3D+T/3C flow field, i.e., three camera images with time sequence. The Standard PIV images followed the PIV Challenge projects in Goettingen (2001), Busan (2003) and Pasadena (2005).

2000s: Dynamic PIV (Time-resolved PIV, High-speed PIV)

In 2002, the high-speed high-resolution C-MOS camera and high-reputation Nd:YAG laser had been applied to measure the transient flow field (1k x 1k pixel under 2000fps). The PIV now can have the potential to capture the transient without sacrificing the image resolution. The high-speed camera is widely used in many PIV applications, e.g., micro PIV, bio PIV, Digital Holographic PIV, Hybrid PSP/PIV and so on (Okamoto, 2002, 2005). The time-resolved two-dimensional flow fields measurement is now the standard PIV system.

References

Yano, M., 1983, Velocity Measurement using Correlation concerning with Digital Tracer Image, *Trans. Flow Visualization*, **3**, 189-192 (in Japanese)
[http://www.journalarchive.jst.go.jp/jnlpdf.php?cdjournal=jvs1981&cdvol=3&noissue=10&startpage=189]

Nishino, K., Kasagi, N. and Hirata M., 1989a, Three-dimensional Particle Tracking Velocimetry Based on Automated Digital Image Processing, *Trans. ASME, J. Fluid Engineering*, **111**, 384-390.

Nishino, K and Kasagi, N., 1989b, Turbulence Statistics Measurement in a two-dimensional channel flow using a three-dimensional particle tracking veclocimeter, *7th Symp. Turbulent Shear Flows*, **2** pp.22.1.1-6.

Okamoto, K., Nishio, S., Saga, T. and Kobayashi, T., 2000a, "Standard images for particle-image velocimetry," *Meas. Sci. Technol.*, **11**, 685-691.

Okamoto, K., Nishio, S., Kobayashi, T., Saga, T., Takehara, K., 2000b, "Evaluation of the 3D-PIV Standard Images (PIV-STD Project)," *J. Visualization*, **3**, 115-124.

Okamoto K, 2002, High speed PIV, *Proc. Seiken Symp.*, Tokyo, Aug.23, 2002, 167-194.

Okamoto K, 2005, Time and Space Resolved PIV, *6th PIV Symp.*, Pasadena

Development of PIV in Korea

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Abstract

History of PIV development in Korea can be divided in three stages. During the past 25 years, the first 10 years (1984-1994) can be called the initial stage. Korean scholars have learned PIV technique from advanced countries. They conducted PIV or PTV experiments individually. The second stage, 1995-2001, was an expending period of PIV works in Korea. The number of researcher has been rapidly increased. Especially in this period, Japan and Korea shared ideas in PIV. In 1999, the first Japan-Korea Joint PIV Seminar has launched. This special seminar has held every two years until now. Korea hosted the 6th Asian Visualization Symposium in 2000 at Busan, Korea. This event and the activity of the Visualization Society of Japan stimulated to create a society based on PIV researches in Korea. At last, the Korean Society of Visualization has been established in 2001. The third stage, 2002-present, can be thought as a matured period in Korea. New ideas such as a miniature PIV, X-ray PIV, 3D3C defocusing Micro-PTV, Digital Holographic Micro-PIV has been contributed to the worldwide PIV communities. Thanks to the active contributions of Korean scholars, we hosted the 5th International Symposium on PIV successfully in Busan, 2003. The KSV received a grant from Korean Government for the standardization of PIV. We have suggested International Association for PIV Standardization (IAPS) and organized meetings at Gottingen in 2006 and at Rome in 2007 with representative experts in PIV. Although the idea of IAPS has not continued now, we have to recognize that PIV is the most widely used technique in most of experiments in fluid physics and engineering. The number of members of KSV is continuously increasing in these days. Among them, many of young scholars are challenging to development original and novel ideas for the future PIV technique. In 2010, Korea is hosting the 14th International Symposium on Flow Visualization in Daegu, Korea. After this event, KSV is going ahead to the next decade.

In the presentation, we will present early works related in PIV first then show some pictures taken during international conferences held in Korea. Several key player's works of PIV developed in Korea will be introduced from past to present. Prof. SJ Lee measured velocity field of Red Blood Cell using MRI method in 1984. His in-vivo experiment was not a usual PIV, but another kind of PIV experiment. His laboratory developed 2-frame PTV technique in early 90's and present the result at the 1st International Symposium on PIV. Prof. Lee's group developed X-ray PIV method in late 90's successfully, and measured velocity field in opaque pipe and xylem of leaf. Prof. YH Lee was one of early starter of PIV research in Korea. He has organized the 1st Japan-Korea joint symposium on PIV. Prof. DH Doh developed simultaneous measurement of Temperature and Velocity using LIF/PIV combined method during his Ph.D work at the University of Tokyo in early 90's. After return back to Korea, he developed 3D3C PTV algorithm based on genetic approach. Prof. KC Kim started PIV experiments after working with Prof. RJ Adrian in the middle of 90's. He developed a miniature PIV using super LEDs and CMOS camera with volume illumination in 1999. The system can be used as a velocity measurement probe based on PIV method. Prof. Kim suggested a novel 3D3C Micro-PTV adopting a de-focusing concept using a three-hole aperture and successfully measured time-resolved velocity field and 3D particle positions in a micro-channel in 2005. Despite of simple optical configuration, the accuracy of spatial resolution is excellent than any other 3D3C Micro-PIV method. Prof. JY Yoo developed Nano-PIV based on evanescent wave field using a total internal reflection microscopy. His research group tried to measure Brownian motion of nano-particles very near the solid surface. Prof. SK Kim applied PIV technique to measure nasal flow intensively and the results are used by medical people. In these days, Korean scholars expend the application of PIV technique to Micro/Nano/Bio-Fluid Mechanics. Prof. SJ Lee's group developed digital micro-holographic PIV to measure 3D3C velocity field in micro-channel. The accuracy seems superior compared with other research groups working for holographic –PIV. Prof. HB Kim developed an echo-PIV using ultra-sound technique to measure velocity field in opaque conduit or in-vivo experiment. Prof. HJ Sung conducted PIV experiments to verify the reduction of viscous friction in turbulent boundary layer with micro-bubbles. Some more interesting applications and results obtained by Korean researches will be introduced.

Abstract for contribution to the symposium
25 Years of Particle Image Velocimetry in Aerodynamics
DLR Göttingen, Gemany, September 23-25 2009

Introduction to the Community Platform on the History of Particle Image Velocimetry

http://25-years-piv.dlr.de/wiki

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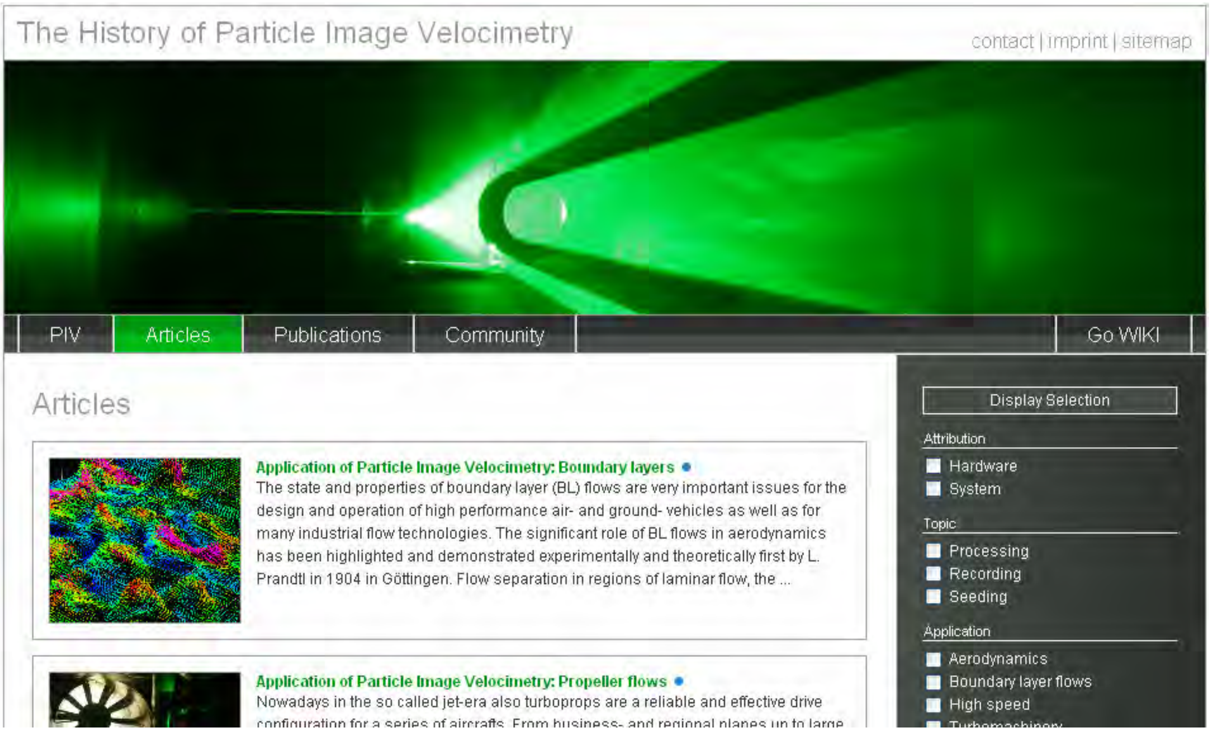
The community platform is made of a wiki that supports collection and presentation of articles, images, sample data, publications, and the introduction of people involved in the development of Particle Image Velocimetry in the course of the past 25 years. After registration and approval of membership colleagues from the PIV-Community are invited to draw attention to their own very special findings on the track of making PIV to what it is in our days. Especially the widespread applications of PIV in Aerodynamics, Biology, Micro Flows, Turbulence and Boundary Layers, and many other fields of interest may be presented on the community platform.

This talk gives an introduction to the handling of the wiki and discovers the ideas behind the functions for content modification and the retrieval of information. It is to make for a quick start in taking advantage of the systems capabilities. Like the user instructions on how to operate the wiki start with the sentence "It's easy", the talk is intended to convey this credo.



The central means of finding information inside the wiki is by searching on categories. To get there each record can be tagged with a variety of attributes. They are called "Classification Options" in the content editor. First of all, each article as a whole carries a set of attributes to cover its general scope. But also paragraphs, images, sample data sets or what ever content element inside an article can be tagged with an individual set of attributes. That makes possible a precise description of parts of content and hence enables for a well focused set of search results.

Measurements by Particle Streak Velocimetry: first step to the PIV ?

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In France, the first chronophotographic studies are published by EJ. Marey in 1893 who was interested in the visualization of flows around obstacle. Full-field velocity measurements began more tardily with Ch. Camichel during the 1930s, Ch. Chartier (1937) carried out stereoscopic quantitative flow measurements around obstacles and marine propellers. Installed at Poitiers in the IMAP, which will become the ENSMA, he carried out aerodynamic and hydrodynamic measurements in flows at various velocities. J.M. Bourot (1949) worked on the ability of particles to follow gas flows, especially at high speeds (200, 300 m/s). The studies started from photography have been continuously improved during many years, under the impulse of M. Coutanceau. At the end of the 1980s, the technique of particle streak velocimetry was automated on microcomputer by MF Collin and A. Texier. Digitized images at high-resolution allowed the extraction of instantaneous velocity fields for flows in channels or starting wakes. With the emergence of digital cameras at the laboratory in the 1990s, other flow measurement techniques were developed (PIV, PTV, Polychromatic PSV 3D) and in 1996 the comparative results between PSV, PTV and PIV signed the end of the PSV.

EJ. Marey, 1893 : Le mouvement des liquides étudié par la chronophotographie. Comptes rendus hebdomadaires des séances de l'Académie des Sciences, 1893, 116 : 913-924

Ch. Chartier, 1937: Chronophotogrammétrie plane et stéréoscopique. Publications scientifiques et techniques du ministère de l'air.

J.M. Bourot, 1949 : Chronophotographie des champs aérodynamiques. Publications scientifiques et techniques du ministère de l'air.

M.F. Collin, A. Texier, M. Coutanceau, 1989: Velocity field determination based upon flow image analysis. 5th International Symposium on Flow Visualization - Prague 1989.

A. Texier, L. David, 1996: A kinematic study of hydrodynamic flow using particle streak velocimetry. *Journal of Flow Visualization and Image Processing* Vol 3, n°3, 479-498.

L. David, A. Texier, J. Fayolle, J. Jay, 1996: Three PIV technique comparisons in hydrodynamic flows. *4th Asian Symposium on Visualization*, ed. QD.Wei, pp 273-276.

Flow velocimetry in former Soviet Union States

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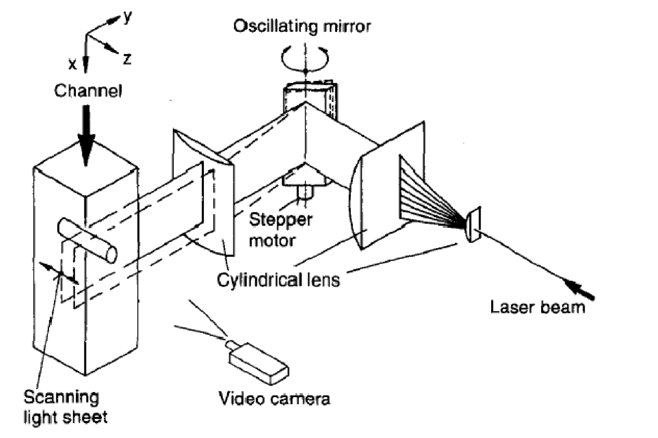
Abstract

The present work gives an introduction to historic aspects of planar optical techniques for flow velocity measurement development in republics of former USSR. In general, the work can be divided into two parts. The first one describes the origins of development of stroboscopic instruments in the Institute of Thermophysics (Siberian Branch of Russian Academy of Sciences, Novosibirsk) in collaboration with other institutions. In particular, instantaneous velocity fields were measured in channel turbulent flows (water as working fluid was used) with special emphasis to the near-wall region. For three-component velocity field measurements near the wall the mirror wall was used. As the light source the pulsed mercury lamp was used and photo film was utilized for image storage. By processing digital data via an electronic computer, statistical characteristics of the flow (mean velocity fields and distributions of Reynolds stresses) were calculated for wall-bounded turbulent flows. Also, the prototype of "micro-PTV" was elaborated for the measurements of the instantaneous velocity profiles in the liquid film wavy flows by using semi-automatic image processing.

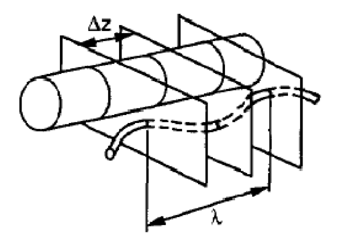
The second part of the work describes history of speckle anemometry development in former Soviet Union. This technique was elaborated mainly in the Heat and Mass Transfer Institute (Minsk, Belarus) by group of Nikita Fomin. Speckle velocimetry was applied in turbulent flow studies, combustion and detonation diagnostics and number of another applications.

More than a Decade of PIV at the Institute of Aerodynamics
Development and Application

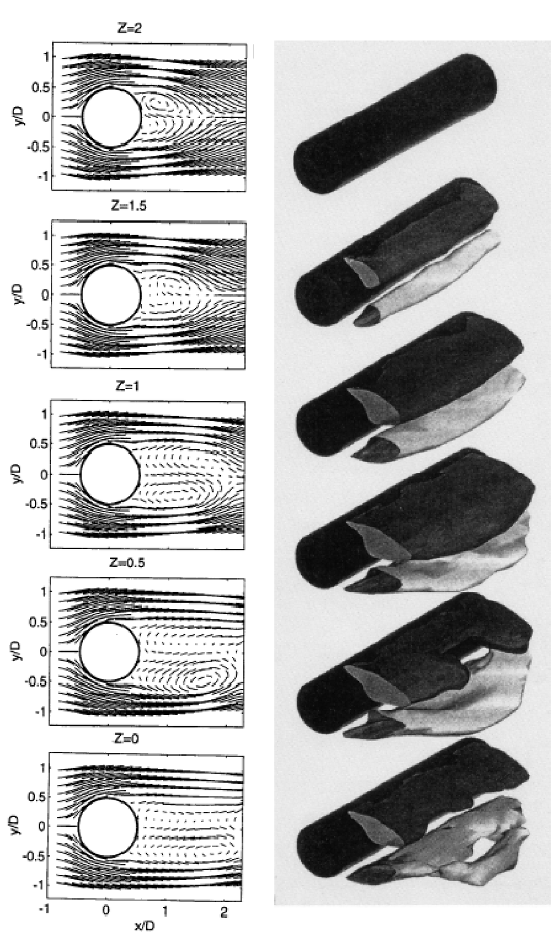
Digital-Particle-Image-Velocimetry (DPIV)in a scanning light-sheet: 3D starting flow around a short cylinder



➢ *top:* flow channel and optical set-up for the light-sheet scanning method
➢ *bottom*: spacing of the light-sheets in comparison to the depth scale of the flow



out-of-plane velocity: $w(z_k) = w(z_0) - \int_{z_0}^{z_k} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)(z)\, dz$



➢ *left:* instantaneous flow structure around a circular cylinder at $T^* = 6.6$ ($T = 8.8$s) after abrupt increase from rest to $Re = 300$ in five different cross-sections ranging from $z/D = 2$ (near endwall) to $z/D = 0$ (middle cross section); short sectional streamlines

➢ *right:* evolution of the 3D spanwise vorticity downstream of a cylinder after abrupt increase from rest to $Re = 300$ ($T_0^* = 0.6 \leftrightarrow T_0 = 0.8$s, $\Delta T^* = 1.5 \leftrightarrow \Delta T = 2$s, level $= \pm 2.3$)

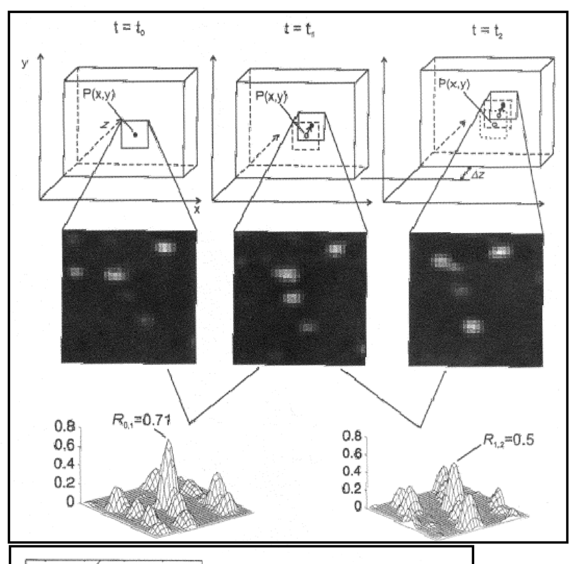
1995

Ch. Brücker: *Digital-Particle-Image-Velocimetry (DPIV)in a scanning light-sheet: 3D starting flow around a short cylinder*, Exp. Fluids, vol. 19, pp. 255-263, 1995

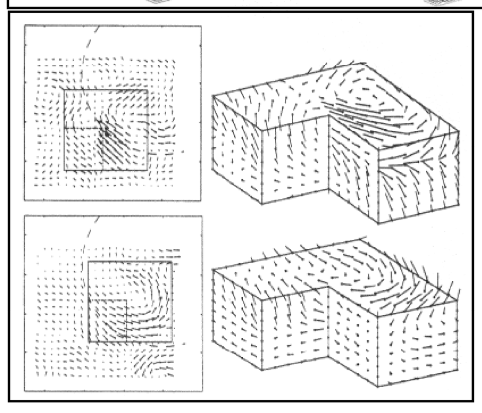
3D scanning PIV applied to an air flow in a motored engine using digital high-speed video

out-of plane velocity:

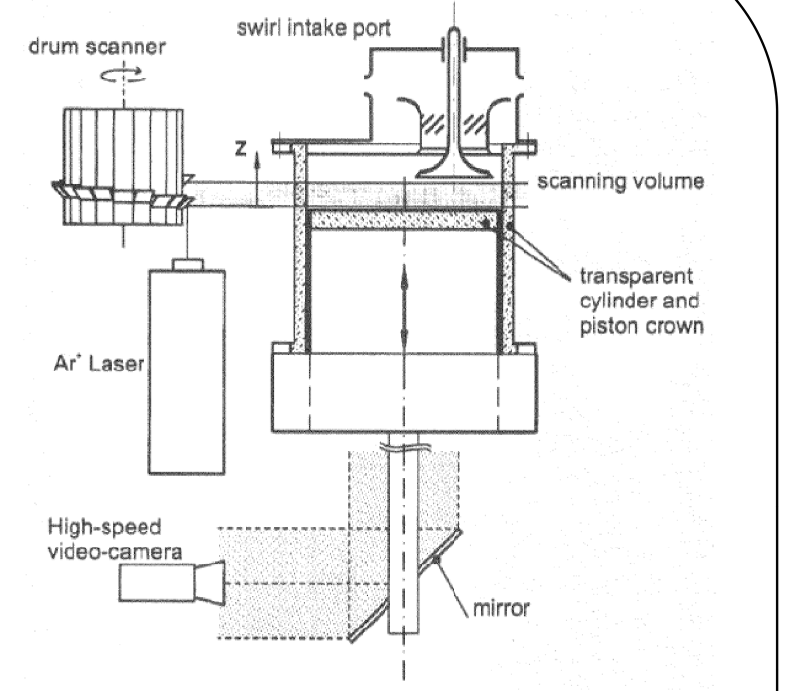
$$w = \frac{\Delta z}{2\Delta t} + \frac{D^2}{8\Delta t \Delta z} \ln\left(\frac{R_{1,2}}{R_{0,1}}\right)$$



➢ *top right:* ensemble tracking over three images in two overlapping light-sheet planes and corresponding normalized cross-correlation data



➢ *bottom right:* 3D vector reconstruction within a cube to illustrate the three-dimensional vortical pattern of the selected area

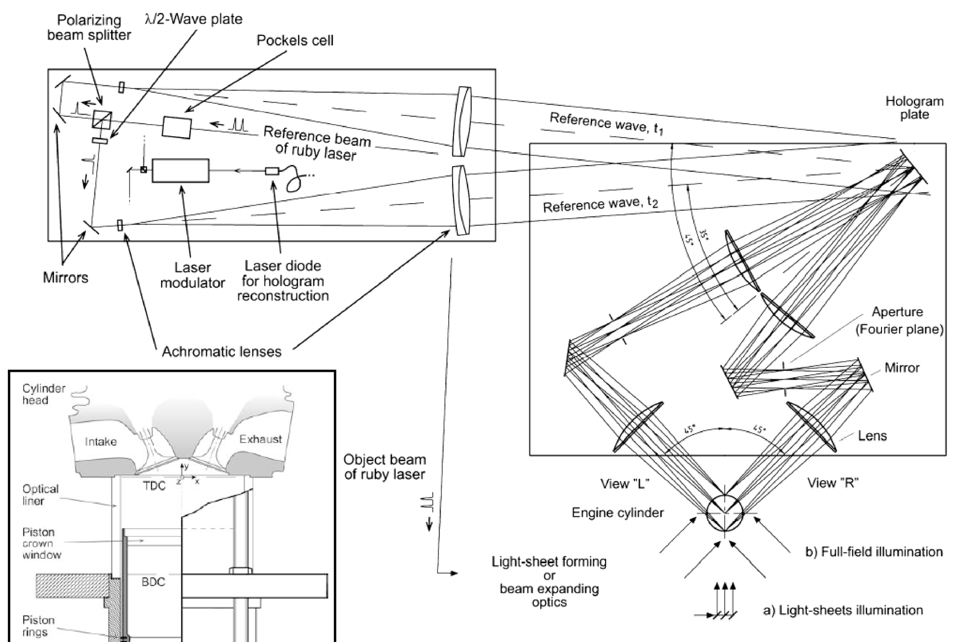


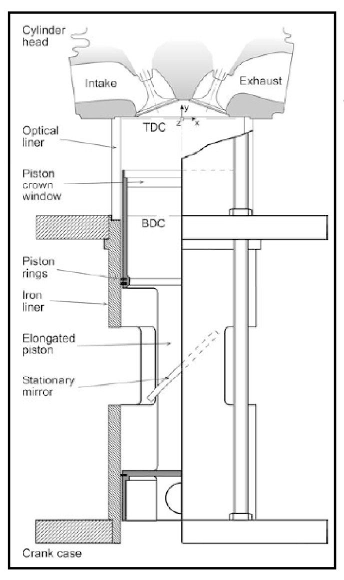
➢ *top:* sketch of the optical research engine and optical set-up showing the 3D beam scanning device and the viewing configuration for radial planes of measurements

1997

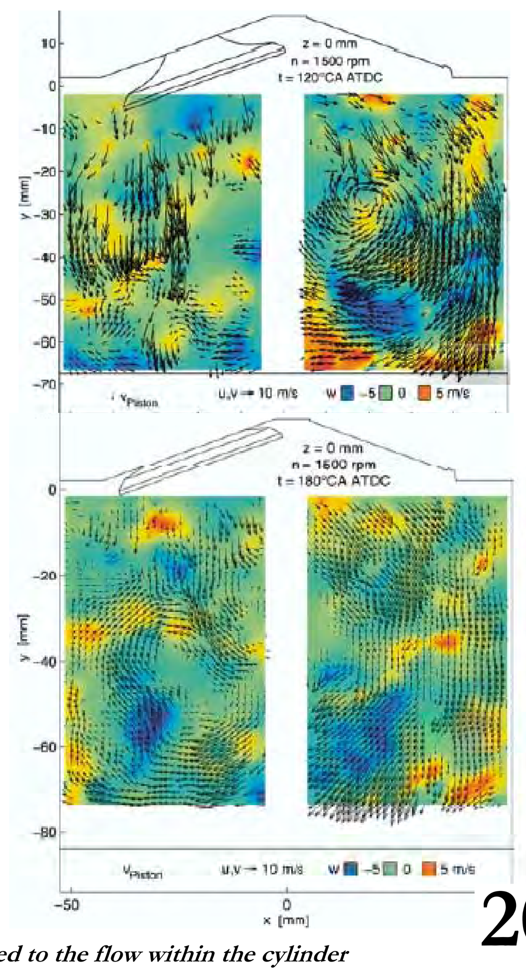
Ch. Brücker: 3D scanning PIV applied to an air flow in a motored engine using digital high-speed video, Meas. Sci. Technol., vol. 8, pp. 1480–1492, 1997

Holographic PIV applied to the flow within the cylinder of a four-valve internal combustion engine





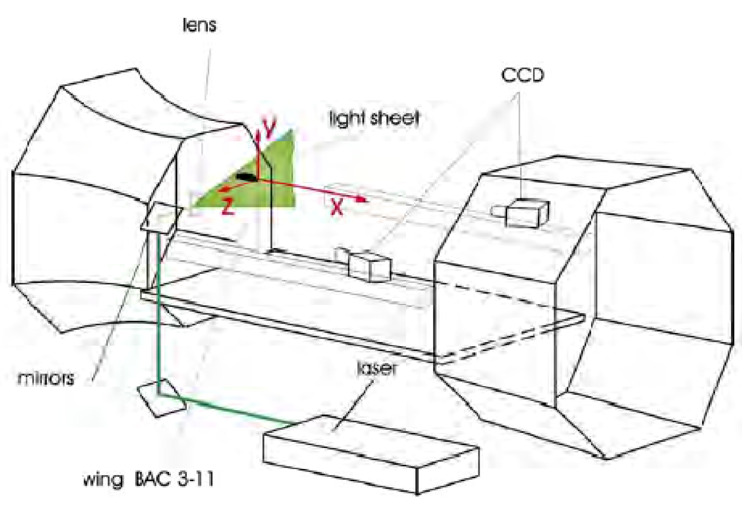
➢ *top:* recording arrangement of image-relay and hologram holder set-up, reference-beam switching and laser set-up, and flow field illumination.
➢ *left:* schematic of optical single-cylinder engine
➢ *right:* unsteady velocity vector field inside the cylinder central plane taken in different engine cycles at 120° and 180° crank angle



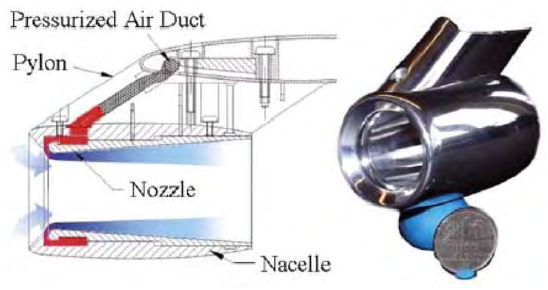
2002

R. Konrath, W. Schröder, W. Limberg: *Holographic particle image velocimetry applied to the flow within the cylinder of a four-valve internal combustion engine*, Exp. Fluids, vol. 33, pp. 781-793, 2002

Investigation of engine jet/wing-tip vortex interference

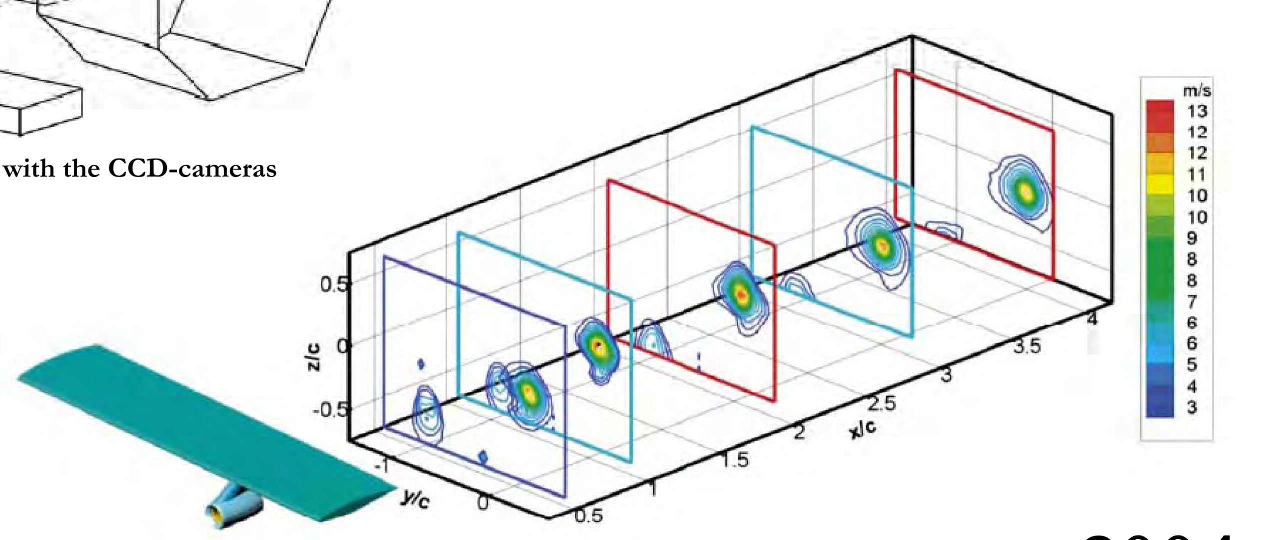


➢ *top:* sketch of the 3C-PIV setup with the CCD-cameras looking upstream



➢ *top:* sketch and photo of the engine model and its three components pylon, nozzle, nacelle.

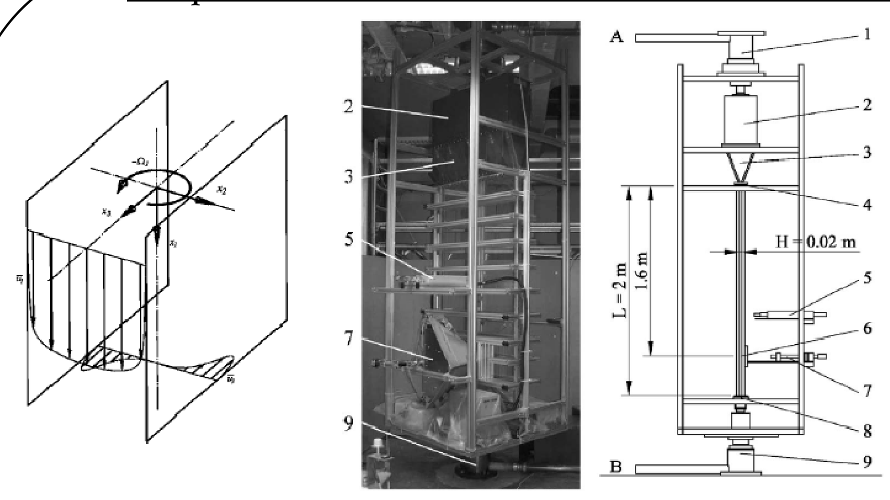
➢ *right:* Velocity contours $V = \sqrt{v^2 + w^2}$ in the wake of the rectangular wing with engine at position A (at $y/c = -1.1$).



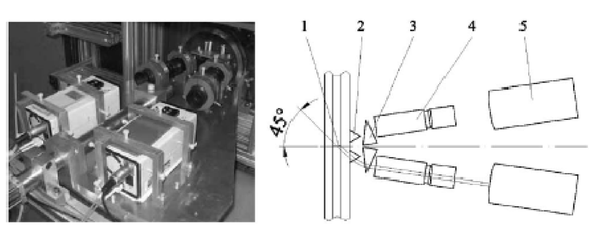
2004

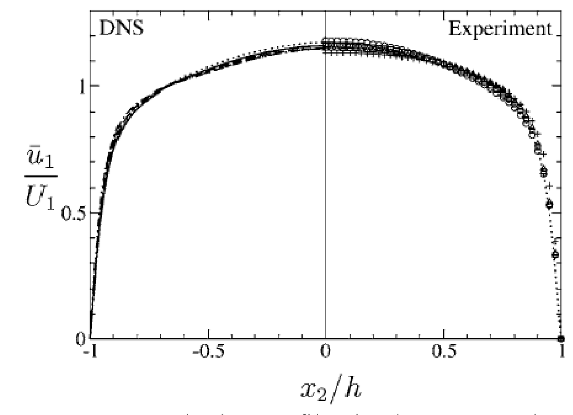
G. Huppertz, E. Fares, R. Abstiens, W. Schröder: *Investigation of engine jet/wing-tip vortex interference*, Aerospace Science and Technology vol. 8, pp.175–183, 2004

Comparison of DNS and PIV data of turbulent channel flow rotating about the streamwise axis

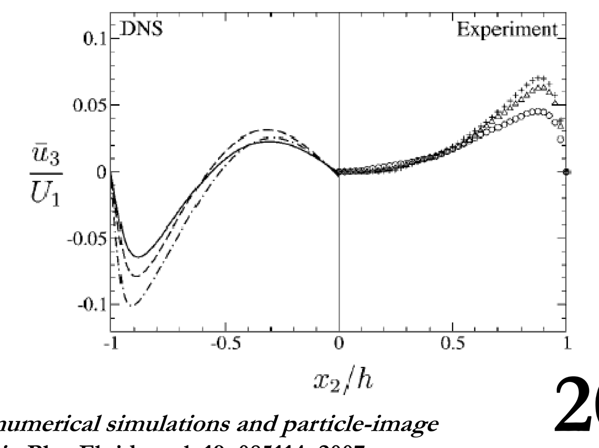


➢ *top:* flow profile and setup of the rotating channel section with 1: rotating union; 2: flow straightener; 5: laser head mount; 6: location of the measuring section; 7: camera mount;
➢ *bottom:* Setup of the stereoscopic camera system with 2: decoupling prism; 3: correction prism; 4: double-sided telecentric lenses; 5: CCD double-shutter camera.





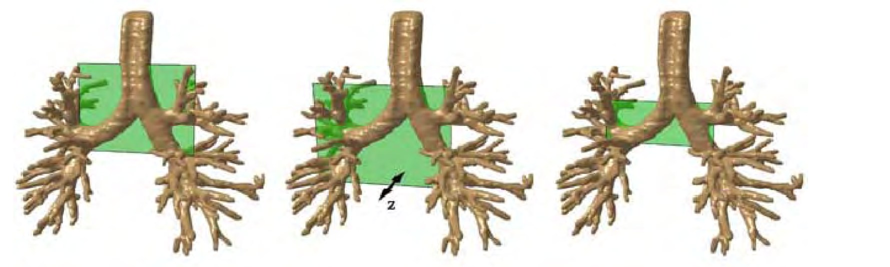
➢ *top:* mean velocity profiles in the streamwise direction
➢ *bottom:* mean velocity profiles in the spanwise direction
Both for different Rossby numbers: Ro_m=65.2 - - - and □, Ro_m=40 - · - and Δ, Ro_m=30 - · · - and +.



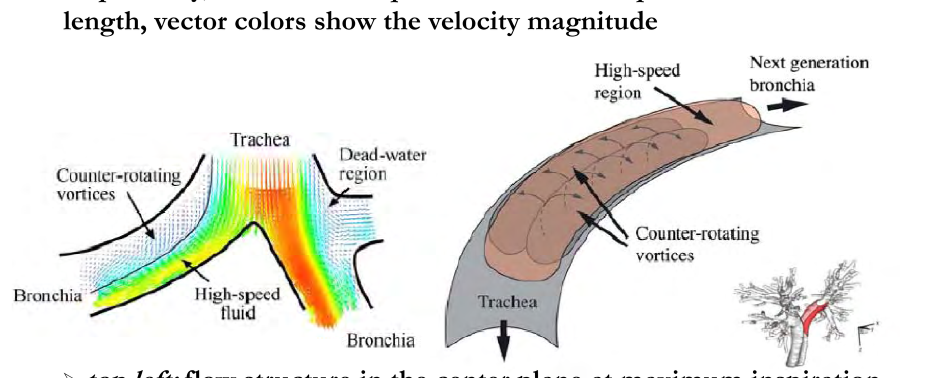
2007

I. Recktenwald, T. Weller, W. Schröder, M. Oberlack: *Comparison of direct numerical simulations and particle-image velocimetry data of turbulent channel flow rotating about the streamwise axis*, Phy. Fluids, vol. 19, 085114, 2007

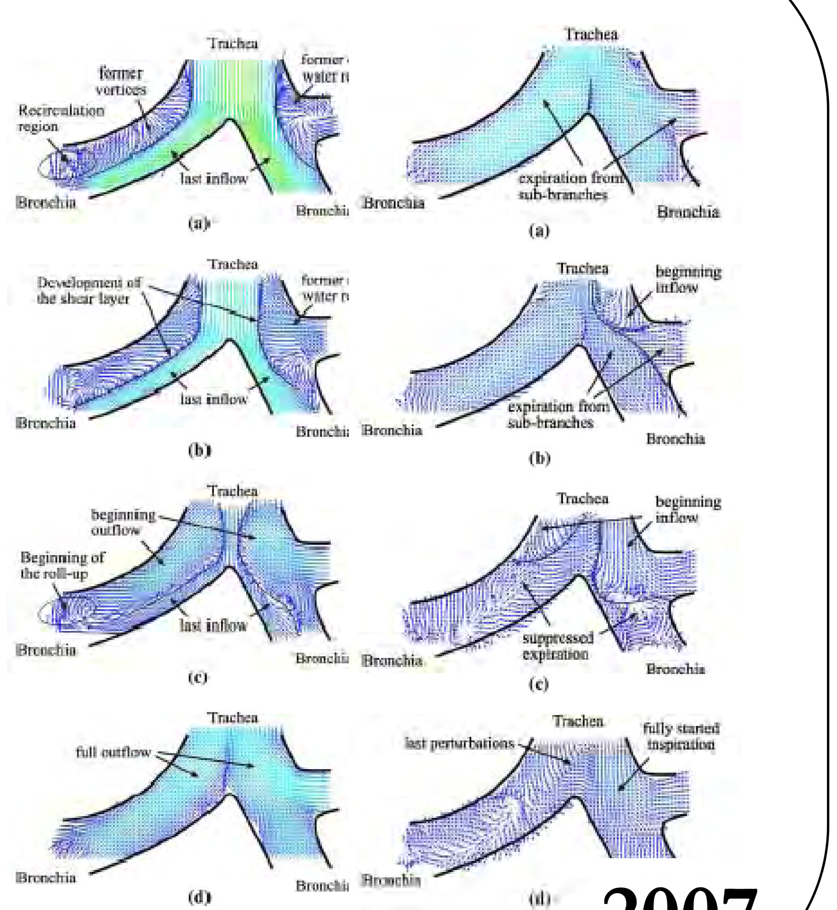
Time resolved analysis of steady and oscillating flow in the upper human airways



➢ *top:* measurement planes in dorsal view for multi-plane measurements (only one plane is illustrated), steady, and oscillating flows (from left to right)
➢ *right:* characteristic flow structures in the center plane of the first bifurcation at the end of inspiration (left) and expiration (right), respectively, for four subsequent times. Vectors possess a uniform length, vector colors show the velocity magnitude



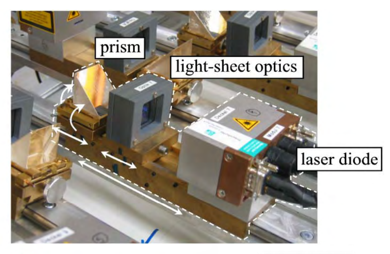
➢ *top left:* flow structure in the center plane at maximum inspiration.
➢ *top right:* schematic of the two counter-rotating vortices evolving along the outer bifurcation.



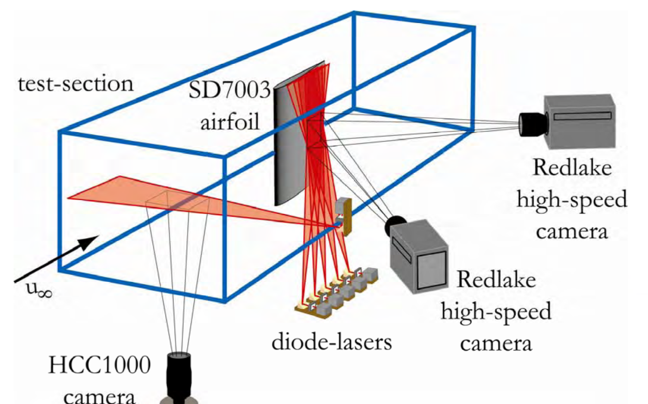
2007

S. Große, W. Schröder, M. Klaas, A. Klöckner, J. Roggenkamp: *Time resolved analysis of steady and oscillating flow in the upper human airways*, Exp. Fluids, vol. 42, pp. 955–970, 2007

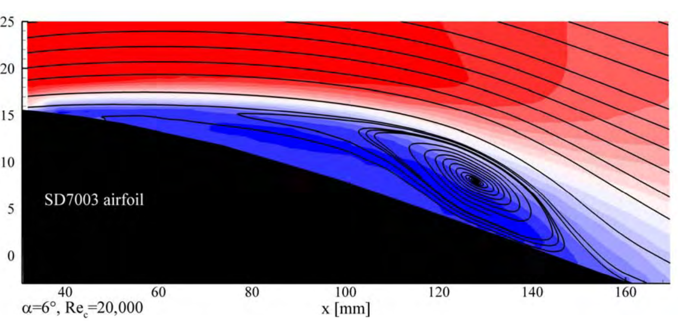
Investigation of the vortex induced unsteadiness of a separation bubble via TR-PIV and Stereo-scanning PIV



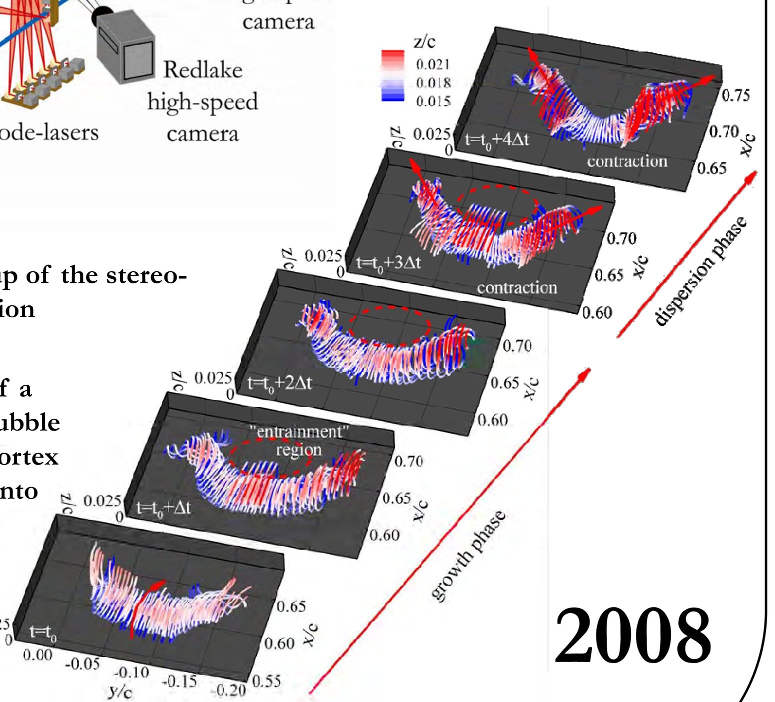
➢ *top:* photo of single laser-diode package and photo of the complete laser-scanning system



➢ *top:* sketch of the set-up of the stereo-scanning PIV configuration



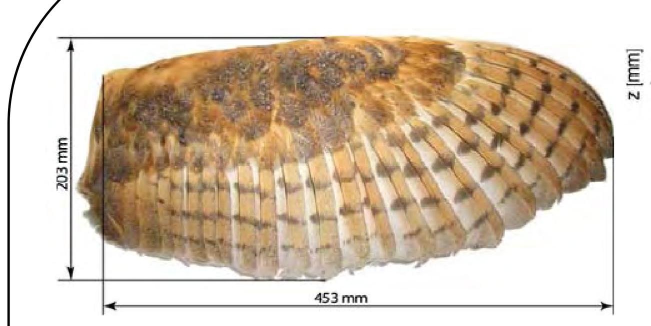
➢ *left:* typical flow field of a transitional separation bubble
➢ *right:* typical c-shape vortex and vortex deformation into vortex arms at the down-stream end of a separation bubble

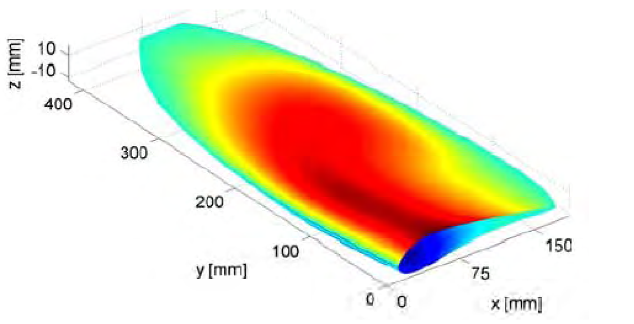


2008

S. Burgmann, W. Schröder: *Investigation of the vortex induced unsteadiness of a separation bubble via time-resolved and scanning PIV measurements*, Exp. Fluids, vol. 45(4), pp. 675-691, 2008

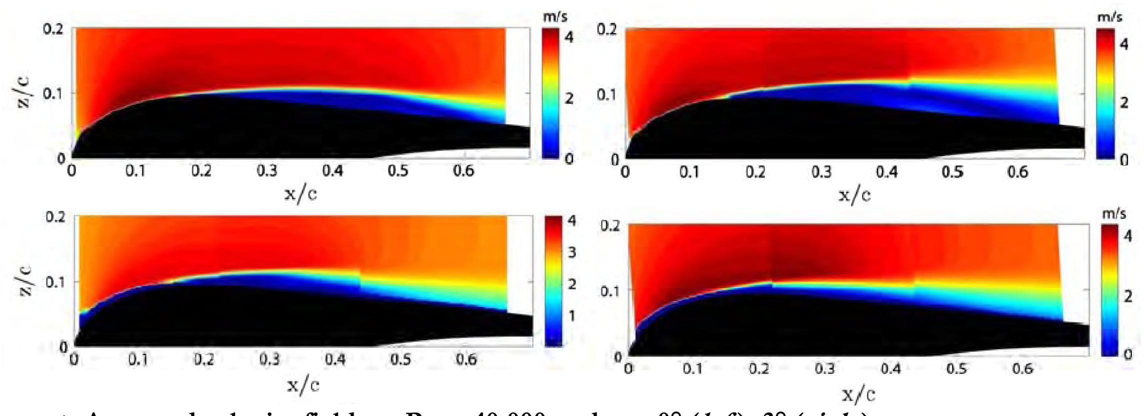
Experimental analysis of the flow field over a novel owl based airfoil





➢ *left:* main dimensions of a natural barn owl wing; *center:* three-dimensional geometry of theartificial wing model; *right:* application of the natural barn owl wing in the test section of the wind tunnel

➢ *top:* surface structure of the natural owl wing (left) and the applied velvet (right). The black bar at the bottom represents a length of 400 μm



➢ Averaged velocity fields at Re_c= 40,000 and α = 0° (*left*), 3° (*right*): for a clean wing (*top*) and a wing with a owl-like velvet (*bottom*)

2009

S. Klän, T. Bachmann, M. Klaas, H. Wagner, W. Schröder: *Experimental analysis of the flow field over a novel owl based airfoil*, Exp. Fluids, vol. 46 (5), pp. 975-989, 2009

Abstracts *PIV today*

PIV applied to strongly inhomogeneous turbulence

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Laboratory for Aero & Hydrodynamics
Delft University of Technology
The Netherlands

One of the unique features of PIV is that it is capable of measuring the instantaneous vorticity field of a flow. In early applications of PIV only one component of the vorticity vector can be measured in a plane, while In modern implementations of PIV, such as multiplane PIV and tomographic PIV, it is possible to obtain the volumetric and time-resolved vorticity field. Given this capability, PIV is capable of providing flow data that cannot be obtained by any other measurement method. This has led to new findings and new insights in understanding the physics of turbulent flows. Of particular interest are strongly inhomogeneous turbulent flows, such as laminar-turbulent transition in pipe flow and the turbulent/non-turbulent interface in free-shear flows. In this contribution to the Symposium it is reviewed how PIV has provided new insights in these classical flow problems, and in particular how PIV has been untilized to obtain flow data that cannot be obtained otherwise with other experimental methods.

In the case of pipe flow, stereoscopic PIV records the fluid motion in a plane normal to the pipe axis. Using high-speed image recording and utilizing Taylor's hypothesis, it is possible to record the quasi-instantaneous fluid motion of flow structures that advect passed the measurement plane. This provides a detailed information on the instantaneous flow structures. This has led to the experimental observation of new solutions to the Navier-Stokes equations, and provided a basis for understanding the transition to turbulence in pipe flow. However, subsequent research showed that the transition to turbulence remains elusive.

For free-shear turbulent flows, irrotational fluid encloses the turbulent domain, where the interface between the turbulent and irrotational regions is very sharp. The propagation of the turbulent flow region into the irrotational flow domain, where irrotational fluid is being entrained in the turbulent domain, has been investigated for many years. PIV has made it possible to provide detailed and accurate measurements of the fluid motion relative to the interface. This has demonstrated that the fluid motion in the vicinity of the interface is a small-scale viscous process. This is contrary to the previous thought that entrainment would be a large-scale inertial process. It was thus possible for the first time to confirm ideas formuleted 50 years ago, and to quantitatively investigate the entrainment process by experimental methods.

In conclusion, PIV has demonstrated its value in providing new insights in the physics of turbulent flows.

Micrometer and Nanometer Spatial Resolution with µPIV

Steve Wereley, Mechanical Engineering, Purdue University

In the autumn of 1997, 13 years after the initial PIV experiments at the University of Oldenburg and DLR, a group of researchers were presented with a problem: obtain a spatially-resolved measurement of the flow through a supersonic microthruster. To make these measurements researchers at the University of California Santa Barbara and the University of Illinois developed the micron-resolution Particle Image Velocimetry or µPIV technique. Initial work began with a simple measurement of flow around a surface irregularity on a frosted glass slide (Santiago, et al., 1998). Subsequently µPIV has grown from a niche technique to one of the most commonly used forms of PIV. The first µPIV article (Santiago, 1998) is the second-most cited paper in Experiments in Fluids history (following Willert and Gharib's 1991 Digital PIV paper) and typically about 100 journal papers per year are published featuring the technique. The typical planar µPIV system has changed little from the apparatus used to make these initial measurements, consisting primarily of an epifluorescent microscope, a sensitive CCD camera, and a light source. While µPIV retains quite a bit of its macroscopic PIV heritage, there are a number of unique constraints and a few opportunities created by working in the microscopic world. For example epifluorescent microscopes are typically used for µPIV which necessitate a number of changes: volume illumination being chief among them. The absence of a light sheet required developing the optics theory underlying the depth of correlation, particle visibility, etc. (Wereley and Meinhart, 2004). However, typically steady flows have allowed development of the correlation averaging algorithm (Meinhart, et al., 2000) which was subsequently used to drive the spatial resolutions down to a single pixel, enabling sub-micron spatial resolutions (Westerweel, et al., 2004). Advances have been made in many areas, including 3D velocity measurement using a variety of techniques: stereo microscopy (Lindken, et al., 2006), 3-hole mask (Yoon and Kim, 2006), defocused diffraction pattern (Park and Kihm, 2006), and astigmatism (Cierpka, et al., 2009).

This talk will begin by discussing the history of µPIV and the development path that brought the technique to its present state. Then it will proceed to discuss the areas where advances are being made today.

Symposium 25 Years of PIV in Aerodynamics, Göttingen, September 23 - 25, 2009

4D-PIV advances to visualize sound generation by airflows

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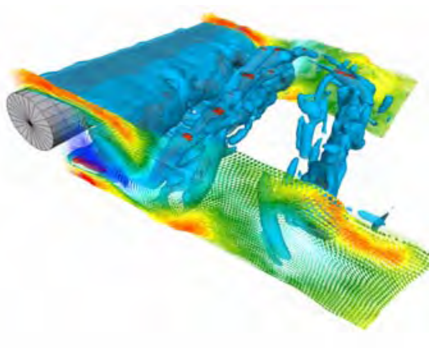
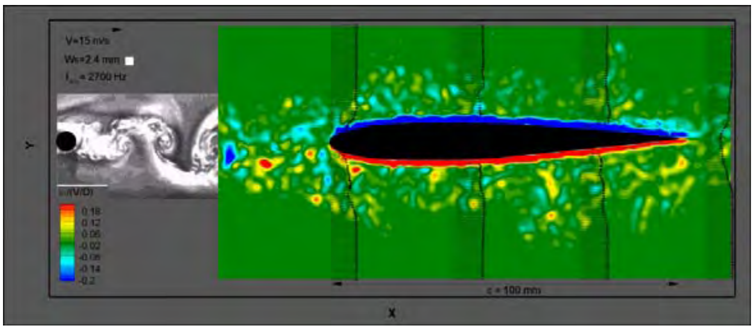
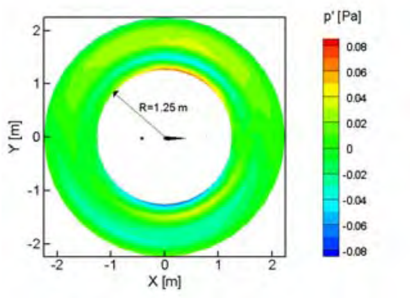
The recent developments of the Tomographic Particle Image Velocimetry technique [1] and data reduction techniques for non-intrusive pressure field characterization method [2] opens unforeseen perspectives in the area of unsteady flow diagnostics and experimental aero-acoustics. As a result of this work it is now possible not only to quantify complex flows in their three-dimensional structure [3], but also to extract quantities such as the instantaneous fluid flow pressure field [4].

The current research is directed towards an innovative approach to experimental aero-acoustics making use of time-resolved Tomographic-PIV experiments to fully describe and quantify the flow pattern around aircraft critical components and the related acoustic source term at its origin. The use of aeroacoustic analogies in conjunction with PIV data will provide the basis for the estimation of sound source identification and noise emissions.

The *flow-visualization inspired aeroacoustics approach* is introduced and its working principles are discussed with a first application of time-resolved planar PIV to the rod-airfoil problem, a benchmark for vortex-structure interaction noise [5]. Also highlights from current activities on 3D experiments on jet-noise will be given.







[1] **Elsinga GE, Wieneke B, Scarano F and van Oudheusden BW** (2006) "Tomographic particle image velocimetry", *Exp. Fluids*, 41, 933-947

[2] **Liu X and Katz J** (2006) "Instantaneous pressure and material acceleration measurements using a four-exposure PIV system", *Exp. Fluids*, 41, 227-240

[3] **Scarano F and Poelma C** (2009) "Three-dimensional vorticity patterns of cylinder wakes", *Exp. Fluids*, 47, 69-83

[4] **de Kat R, van Oudheusden BW and Scarano F** (2008) "Instantaneous planar pressure field determination around a square-section cylinder based on time-resolved stereo-PIV" *14th Int Symp Appl. Laser Tech. Fluid Mech.*, Lisbon, PT

[5] **Lorenzoni V, Tuinstra M, Moore P and Scarano F** (2009) "On the Use of Time-Resolved PIV for an Aeroacoustic Investigation of Rod-Airfoil Noise", *J. Sound Vibr.* (to appear)

Investigating flow stability, turbulence and flow control using PIV

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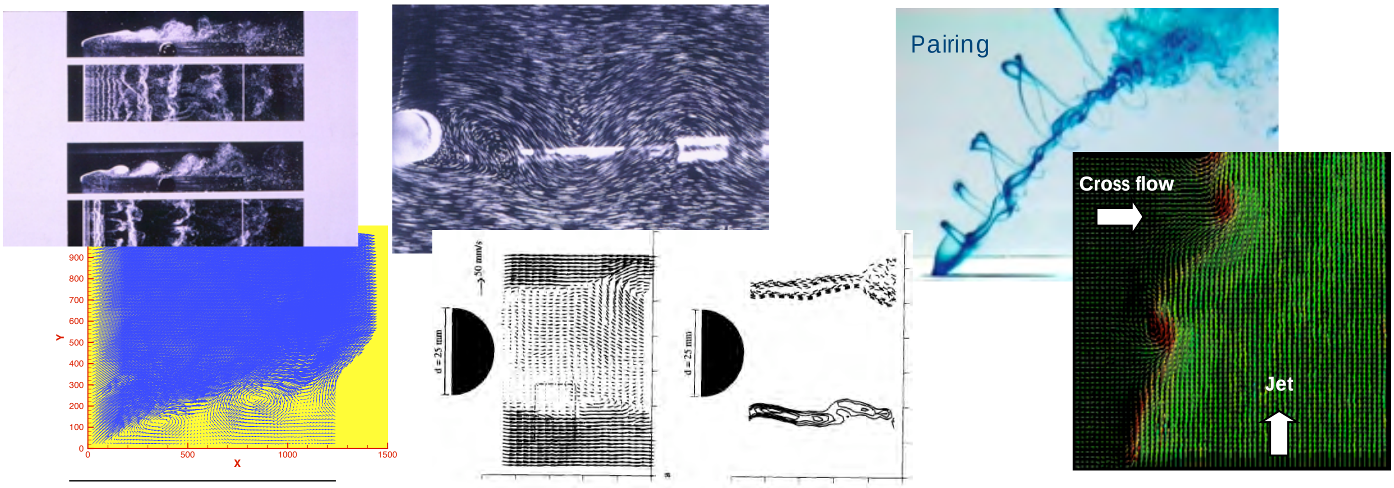
This paper describes a number of studies on flow stability, turbulence and flow control undertaken in Australia and beyond by the author, his students and colleagues and how some of these studies lead to number of PIV analysis developments such as the iterative adaptive cross-correlation PIV analysis that has become known as Multigrid PIV analysis[1, 2, 3].

The flow stability and control studies have been predominantly associated with separated flow from circular cylinders, blunt flat plates and NACA type airfoils. Closely associated with the control of separated flow is the flow physics of oscillatory jet actuators, known as zero-net-mass flux jets or more precisely, zero-net-mass flux jets in cross-flow. Studies of these jets will be reviewed.

The study of the structure of turbulence has focussed on turbulent free shear flows and wall-bounded turbulence. The different variants of PIV methodology which have been used to investigate these flows include 2C-2D PIV, 3C-2D stereo PIV (SPIV) and 3C-3D tomographic PIV (Tomo-PIV). Pertinent PIV measurement results of these turbulent flows will be highlighted and the structure of these flows deduced from these measurements will be briefly discussed.



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[1] J. Soria 1994 Digital cross-correlation particle image velocimetry measurements in the near wake of a circular cylinder Int. Colloquium on Jets, Wakes and Shear Layers, 25.1 - 25.8. Melbourne, Australia.

[2] J. Soria 1996 An adaptive cross-correlation digital PIV technique for unsteady flow investigations. In 1st Australian Conference on Laser Diagnostics in Fluid Mechanics and Combustion, 29 - 48. Dec., Sydney, Australia.

[3] J. Soria 1996 An investigation of the near wake of a circular cylinder using a video-based digital cross-correlation particle image velocimetry technique. Experimental Thermal and Fluid Science 12, 221 - 233.

PIV Applications in Bioengineering

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Visualization plays an essential role for a better understanding of flow phenomenon and their associated mechanisms. PIV is one of the most suitable flow measurement techniques since it enables us to measure velocity distributions instantaneously with good space resolution without disturbing the flow. Due to theses advantages, PIV has been applied to researches in the field of bioengineering such as *in vitro* experiments of cardiovascular flow or microfluidics.

The lecture presents an overview of the recent PIV applications in bioengineering, mainly hemodynamic and microfluidic researches in Japan. Blood flow is multi-scale phenomena and its flow features drastically changes depending on a size of blood vessel. Thus, it is very important to develop a visualization technique to capture the most distinctive flow physics in the particular scale of interest. One of flow visualization techniques based on PIV is a stereo-PIV system to visualize flow structure in an *in vitro* model of cardiovascular flow such as flow in a cerebral aneurysm, which is in the scale of milli-meters[1]. Since an *in vitro* model can be constructed from medical image data, it is challenging to capture complex three-dimensional flow in realistic geometry.

The lecture touches upon a micro PIV system to visualize and measure flow in a droplet in a micro channel or micro multi-phase flow in an arteriole of 100 micrometers[2]. Even though the flow is in a microscopic scale, flow may have complicated three-dimensional features. The paper presents recent advancement in micro PIV such as confocal micro-PIV to examine micro multi-phase flow in a micro scale.

References

1. Bando, Y., Oshima, M., Oishi, M., Saga, T., Kobayashi, T., ‘’Stereoscopic PIV Measurement in Cerebral Artery Model’’, Transaction of JSME vol.72, no.722, pp.2386-2393 (2006)(in Japanese).
2. Kinoshita, H., Kaneda, S., Fujii, T., Oshima, M. “Three-Dimensional Measurement and Visualization of Internal Flow of a Moving Droplet using Confocal Micro-PIV”, Lab on a Chip, vol.7, issue 3, pp.338-346 (2006)

The benefit of European networks and international cooperation for the development of PIV.

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&
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The GARTEUR AG 19 in 1994 has been the start of a succession of European cooperative projects around the development of PIV which has ended only in 2008 with final workshop of the PIVNET 2 thematic network.

These projects which started at the end of the photographic recording of PIV and the very beginning of the digital recording has allowed to build strong and constructive links in the European PIV community, to speed up the development of the technique and its transfer to industrial applications and to strengthen the confidence in the PIV technique.

The GARTEUR AG 19 was the first step, for different groups in Europe, working on the development of the method, to know each other and to start cooperating on the recording and processing issues. A first database of photographic records was shared with the purpose of comparing processing algorithms.

The EUROPIV and EUROPIV 2 projects were two STREPs, funded by the EC, with the objective of developing the digital approach, the stereoscopic approach, the holographic approach to PIV and to demonstrate the potential of the method on test cases of industrial interest in industrial wind tunnels. The test campaign performed in the Airbus Bremen wind tunnel in EUROPIV was certainly a trigger for the industrial interest to the PIV technique which showed a potential which has stayed out of reach of Laser Doppler Velocimetry along the years.

The PIVNET and PIVNET 2 networks, coordinated efficiently by DLR, have played a key role in the rapid diffusion of the method to problems of all kind. By the organisation of a large number of demonstration workshops in real situations of industrial interest, the versatility and adaptability of the technique was largely demonstrated. Several large European facilities such as DNW, Towing tanks and scale 1 car wind tunnels decided to master and use the technique following the PIVNET demonstrations. Besides, these networks provided a framework for annual meetings of the PIV developers, linked to international conferences (Lisbon, PIV Symposium), where the problems encountered where freely presented and discussed. These workshops rapidly came to an international PIV challenge which took place in 2001, 2003 and 2005 and allowed to assess in quite details, the merits and drawbacks of the different PIV processing algorithms proposed by researchers around the world, but mostly in Europe. This networking activity triggered some fruitful cooperations, as for example the one resulting in the recent development of Tomo PIV.

Symposium 25 Years of PIV in Aerodynamics, Göttingen, September 23 - 25, 2009

Developments for Industrial PIV

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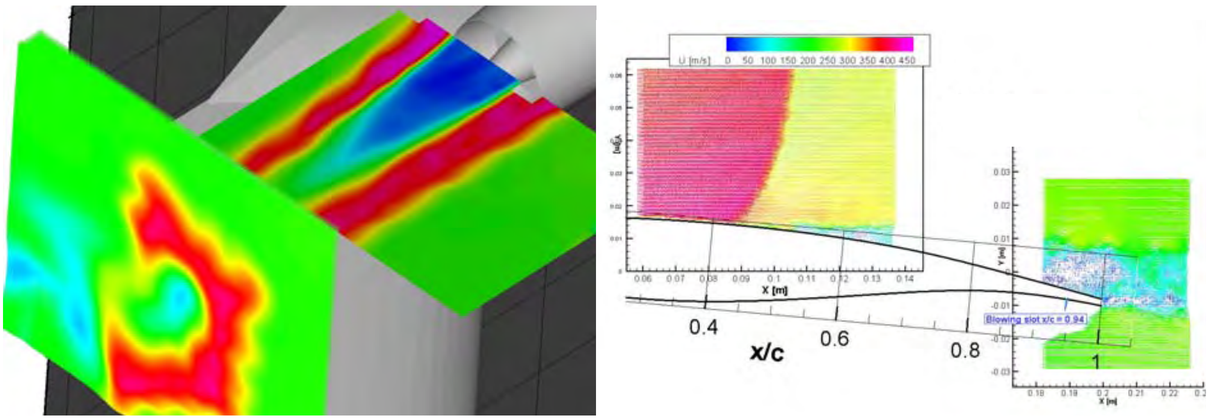
In the past decades several image based measuring systems have been developed for industrial aerodynamic research and in addition to classical wind tunnel measurement methods. These advanced optical and image based techniques are capable to deliver field data of the related physical quantities in a non- or minimal intrusive way: Pressure sensitive paint (PSP) is able to measure pressure distributions on the surface of models, marker based systems are measuring the position of the model during wind tunnel operation, image pattern correlation technique (IPCT) is even able to capture the surface deformation like bending and twist of airfoils quantitatively, temperature sensitive paint (TSP) images show transition line positions e.g. on a wing surface, microphone array techniques are creating maps of sound sources in various frequency domains along the model, background oriented Schlieren (BOS) can detect density gradients present at shocks and along vortex lines and, last but not least, PIV delivers a large number of instantaneous velocity vector fields in planes within the flow field in short wind tunnel run times. All these techniques give valuable information about the status of the fluid mechanical field around or its effects on a model in a wind tunnel test and have been developed for mobile use at DLR in Göttingen.
The first optical field measurement techniques used in industrial wind tunnels by DLR was PIV: Over the years many adaptations of the PIV system have been made in order to match the harsh boundary conditions in industrial wind tunnel facilities. Seeding density and homogeneity, precise triggering, optical path deviations, laser light reflections and vibrations of cameras are problems to be solved in each industrial PIV measurement. The development of industrial 2C PIV and 3C Stereo PIV applications has been matured nowadays. Time-resolved and 3D-3C PIV techniques are in development since a few years and are in the status to be tested in industrial wind tunnel investigations e.g. fat sheet tomo PIV. The most prominent feature of PIV is that it is capable of measuring large numbers of instantaneous velocity vector fields in a plane or volume of a flow with high spatial resolution and within short wind tunnel run times. From these velocity fields it is possible to calculate averages and related RMS- and fluctuation velocity fields, vorticity and other derivatives or products of fluid mechanical significance. PIV data are therefore well suited for validation of numerical codes. In several aeronautical research projects CFD, PIV and other experimental measurement techniques have been used jointly in order to capture a more holistic image of different complex flows.



Averaged 3C velocity vector fields measured behind the turbine power simulator CRUF by Stereo PIV in DNW-NWB (left) and velocity fields in a shock buffet experiment with flow control in transonic flow (right)

Use of PIV in DNW Wind Tunnels

Flow visualization in general and flow visualization by means of a laser light sheet in particular has been an important tool at DNW for a long time. In order to quantify the flow field visualization DNW asked DLR to investigate the feasibility of the implementation a Particle Image Velocimetry (PIV) system in the DNW Large Low-speed Facility.
In 1995 the PIV group of DLR delivered a PIV system, which is suited to measure in large wind tunnels. From that time on PIV was applied in various wind tunnel test campaigns. The first measurements have been performed in the frame work of wake vortex investigations by Airbus Industry. Flow field measurements at cars, helicopters, windmills, etc. followed.
In 1999 the PIV system has been up-graded in order to measure 3 components in a plane by means of a stereoscopic set-up of the cameras. In the mean time DNW had become DNWs, German- Dutch Wind Tunnels. Thus, wind tunnels in Braunschweig, Göttingen, Köln and Amsterdam and on the North- East Polder now belong to DNW. The DNW PIV system is used at all these facilities. A PIV supporting team has been defined in order to perform the measurements in the different wind tunnels. The spectrum of wind tunnel models to be measured increased enormously.
Examples of test set-ups as well as measurement results will be shown in the presentation. In addition some historical facts will be presented.

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25 Years of Particle Image Velocimetry in Aerodynamics.
Göttingen
September 23 -25, 2009

Use of PIV in Aeronautical Industry

Winfried Kühn *
Klaus-Peter Neitzke*
Andreas Schröder**
Jürgen Kompenhans**

Abstract

The Experimental Aerodynamics at Airbus has been involved in Particle Image Velocimetry measurements since about 15 years. A lot of contributions were given in this time to make the method available for industrial testing in large wind tunnels. This was only possible thanks to the excellent cooperation with research institutes achieved during a considerable number of PIV projects. Garteur activities were the starting point followed by a number of national and European projects devoted to different aspects of more and more complex flows. In parallel to the ever increasing complexity of the flow, the requirements for the data accuracy were increased. The environment of industrial wind tunnel testing resulted in special developments of PIV hardware and software including a significant development of the testing efficiency.
A number of test campaigns is highlighted in the presentation. The spectrum covers a very first treatment of high lift phenomena via more sophisticated investigations of gap and trailing edge flows. The effect of model supports on the flow field around the model and wake vortex flows in air and water were further milestones. Measurements in the thin 3D-boundary layer of slightly vibrating big wind tunnel models provided excellent results even for industrial applications and under the disturbing effect of a still incomplete suppression of surface reflections. Last but not least, investigations of propellers were done by PIV using phase locking technique and Image Pattern Correlation Technique to determine the blade deformation of rotating model propellers.

The PROs and CONs to do PIV are given from an industrial point of view including some requirements to get further progress in the future.

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High quality PIV data for numerical validation

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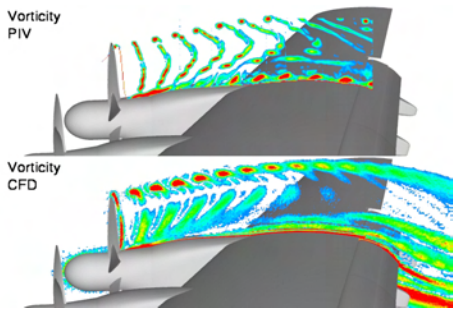
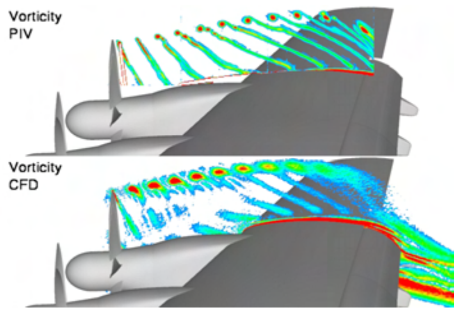
Particle Image Velocimetry (PIV) is in particular suitable, perhaps exclusively, for the analysis of (instantaneous) velocity vector fields. In addition, well prepared PIV measurements provide an extensive database with velocity-derived quantities (vorticity, instantaneous fluctuations, velocity fluctuations, turbulence kinetic energy, Reynolds stresses) that can be used to compare and characterize the capabilities of computational methods with respect to turbulence properties as well as for computational aero-acoustic simulations.

From a point of view regarding the validation of propeller flow for example there is only little literature available. Apart from validation and verification of numerical codes, advanced research on propeller flow influence is needed in order to estimate the effects of airframe engine installation and to establish the propeller slipstream effects on the wing. A mutual approach by considering both vorticity and turbulence properties based on experimental and computational data is believed to be best suited to characterize the overall effect those properties have on the aircraft design.



Comparison of vorticity in propeller symmetry plane



Comparison of vorticity outside propeller symmetry plane

Thus, in a combined effort CFD and PIV has been applied to investigate vortical structures, which dominate propeller flow. There is, however, a remarkable difference between PIV and CFD in the vortex structure organization of the blade wakes and in the wing boundary layer-slipstream interaction due to strong dissipative terms in the uRANS models. This is further supported by the difference in the circulation distribution in the tip vortices region. One objective of this research is to provide a database of experimental and computational data that can be used in a comparison and validation of several velocity derived quantities. This contribution describes the ongoing work of validating and expanding existing CFD tools for the analysis of propeller flow with experimental velocity (PIV) data.

Ref: Roosenboom, E.W.M., Stürmer, A., Schröder, A., "Comparison of PIV measurements with unsteady RANS calculations in a propeller slipstream", AIAA 2009-3626, 27th AIAA Applied Aerodynamics Conference, San Antonio, TX, USA, June 2009 (accepted for publication in Journal of Aircraft)

Post-processing tools from PIV measurements

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In parallel to the development of PIV, a number of tools associated with the analysis of flow velocity measurements have also been proposed during the last years. Correlation tensors were first calculated to isolate the main and regular events of the flow or to follow vortex structures. Beyond this approach, the correlation tensor is also used to calculate Proper Orthogonal Decomposition which gives a simplified representation of the flow optimized for the energy. Other approaches consist in modeling the flow with polynomial orthogonal basis. Finally, with the possibility to obtain time-resolved measurements, computation of the acceleration and pressure fields is now possible, which provides complementary information on the dynamics of the flow. In particular, loads and vorticity conservation can now be predicted and validated.

D. Calluaud, L. David, A. Texier, 2005: Vortex shedding process investigation downstream a surface mounted block. *Journal of Visualization,* Vol. 8, N°2, pp. 99-108.

L. Chatellier, J. Fitzpatrick, 2005: Spatio-temporal correlation analysis of turbulent flows using global and single-point measurements. *Experiments in Fluids*, Vol. 38, N°5, pp. 563-575.

A. Santa Cruz, L. David, J. Pécheux, A. Texier, 2005: Characterization of the passive stabilizer control effect downstream a half cylinder wake formation with a proper-orthogonal-decomposition tool. *Experiments in Fluids*, Vol. 39, 730-742.

R. Vernet, L. Thomas, L. David, 2009: Reconstruction of a pulsed jet in cross flow by multi-plane snapshot POD. Experiments in Fluids (sous presse).

M. Druon, B. Tremblais, B. Augereau, L. David, 2008: Modélisation simplifiée d'écoulements fluides par approximation polynomiale. Étude temporelle et comparaison avec la décomposition orthogonale aux valeurs propres. 11ème Congrès Francophone de Techniques Lasers, 319-326, Poitiers.

M. Druon, B. Tremblais, B. Augereau, 2009: Robust and Efficient Camera Caraterization using Orthogonal Polynomials. *Signal Processing: Image Communication (submitted).*

L. Perret, P. Braud, C. Fourment, L. David, J. Delville, 2006: 3-Component acceleration field measurement by dual-time stereoscopic particle image velocimetry. *Experiments in Fluids,* 40, 813-824

L. David, F. Scarano, P. Braud, 2006: Accéléromètrie plane par PIV-RT ou double plans : avantages et limitations. 10ième CFTL, Toulouse.

D. F. Kurtulus, F. Scarano, L. David, 2007: Unsteady aerodynamic forces estimation on a square cylinder by TR-PIV. *Experiment in Fluids*. 42:185–196.

T. Jardin, L. Chatellier, A. Farcy, L. David, 2009: Correlation between vortex structures and unsteady loads for flapping motion in hover. *Experiments in Fluids* DOI 10.1007/s00348-009-0658.

Stereo-PIV as a tool for optimization of flow control devices

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Abstract

Active flow control earns growing interest for manufacturers of large transport aircraft because of the constant need to improve these aircraft in terms of less fuel consumption, higher efficiency, steep approaches and departures and less weight. Flow control devices that are based on fluidic actuators, e.g. vortex generator jets (VGJs), have shown a promising potential to influence separating boundary layers and keep them attached (e.g. *Godard & Stanislas (2006a-c); Johari. & Rixon (2003); Johnston & Nishi (1990); Mc Manus et al. (1996); Ortmanns et al. (2008a); Pauley & Eaton (1988); Scholz et al. (2006)*). For an efficient operation such devices need to be optimized regarding their ability to influence the flow. However, optimization turns out to be very challenging because of the vast parameter space and the lack of an adequate "figure of merit". The proposed contribution will discuss the possibility to assess and optimize such devices by analyzing the velocity fields from stereoscopic PIV measurements.

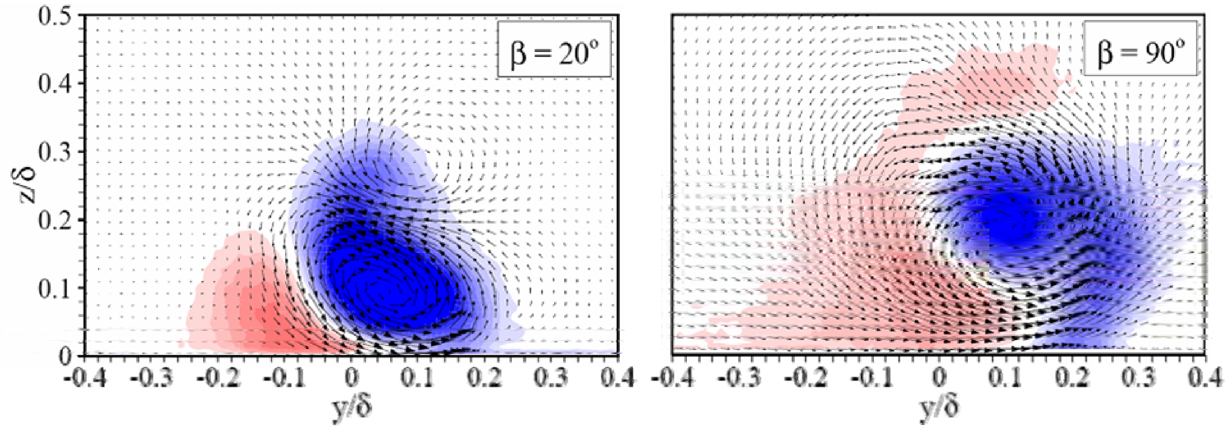

Figure 1: Velocity fields of (Left) 20° skewed rectangular jet and (Right) 45° pitched and 90° skewed circular jet; vectors are in-plane velocities and colours denote the change of out-of-plane velocity due to the vortices; red colour is accelerated flow, blue colour is retarded flow

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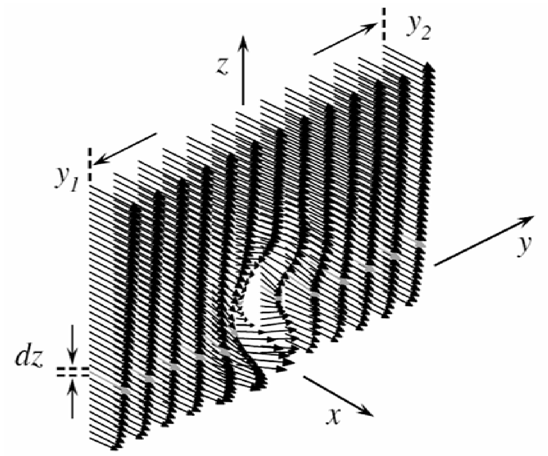
Experimental Setup

For the experiments different low-speed windtunnels located at the "Institut für Strömungsmechanik" in Braunschweig were used. The velocity fields were acquired using a stereoscopic PIV system (Two 11 Mpxs camera LaVision Imager Pro X 11M; Quantel Brilliant Twins 150mJ Nd:YAG-Laser; LaVision DaVis 7 Software) with the light sheet orthogonal to the bulk flow direction and orthogonal to the plate. The influence of pulsed VGJs was determined by synchronizing the PIV system to the actuator process and acquiring phase locked datasets in a variety of different phase angles.

After correlation the velocity data was processed, e.g. by subtraction of flow field of undisturbed boundary layer. The vortices were detected using the vorticity distribution and the discriminant; circulation of the vortices as well as the vortex core position and radius were determined.

The idea was to assess the ability of VGJs to prevent separation, although in ZPG flat plate boundary layers no separation is present. To do so the ability of the vortices to shift momentum from the outside regions of the boundary layer closer to the wall must be analyzed. A new parameter ΔR_{Vx} was defined that calculates the change of longitudinal momentum relative to the base flow. This parameter is appropriate to analyze the influence of different geometries and of the amplitude (namely λ, the ratio of jet exit velocity to freestream velocity), the downstream behaviour as well as the behaviour and the temporal evolution of the vortices when the jet is pulsed.



$$R_{Vx}(x,z) = \rho\, dz \int_{y_1}^{y_2} u(x,y,z)^2\, dy$$

$$\Delta R_{Vx} = \frac{R_{Vx} - R_{Vx0}}{R_{Vx0}} = \frac{\int_{y_1}^{y_2} \left(u(x,y,z)^2 - u_0(x,y,z)^2 \right) dy}{\int_{y_1}^{y_2} u_0(x,y,z)^2\, dy}$$

Figure 2: Definition of the coordinate system, the longitudinal momentum flux R_{Vx} and the change of momentum relative to the base flow ΔR_{Vx}

The parameter ΔR_{Vx} is very sensitive on errors in spatial arrangement, especially in z-direction. Therefore stochastic vibrations of the PIV-images were corrected using a shift-correction with the reflection line as reference. Each dataset was then shifted to a constant reference position. This was done to ensure constant positions of the interrogation windows in all datasets and thereby minimizing (or at least equalizing) errors due to the velocity gradient in z-direction.

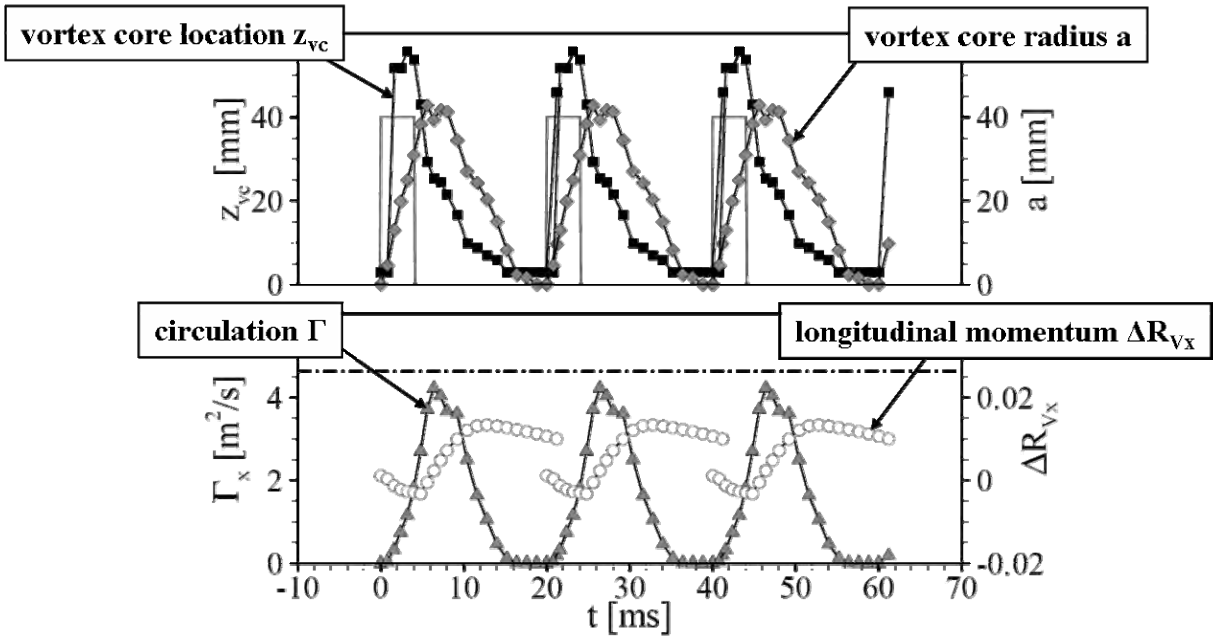


Figure 3: Dynamic evolution of different properties for the vortices created by pulsed VGJs; The grey line in the upper figure is the pulsing signal for the valves with frequency 50 Hz and duty-cycle 20 %; the jet is active from 0 ms to 4 ms, then inactive from 4 ms to 20 ms, and so on

Exemplary Results

The results indicate that stereoscopic PIV is well suited to assess the efficiency of vortex generator jets. In Fig. 3 the temporal evolution of different vortex parameters are outlined when the jets are pulsed. It can be seen that vortex circulation Γ and vortex core location z_{vc} act somehow against each other: When the vortex has a high circulation its core is far apart from the wall. When the jet itself is stopped (t=4 ms) the circulation decreases but the z-position of the core decreases as well, therefore the change of longitudinal momentum ΔR_{Vx} increases. This might be the reason why the pulsing of the jets is often believed to be superior to static operation.

The contribution is proposed for oral presentation at the symposium. The presentation will deal with the details of the experimental setup, with the ways to analyze the data with a view to the optimization of flow control devices as well as with exemplary results, problems and challenges during data acquisition and analysis.

Literature

GODARD G. & STANISLAS M. (2006a). Control of a decelerating boundary layer. Part 1: Optimization of Passive Vortex generators. Aerospace Science and Technology, 10(3):181–191.

GODARD G. & STANISLAS M. (2006b). Control of a decelerating boundary layer. Part 2: Optimization of slotted jets vortex generators. Aerospace Science and Technology, 10(5):181–191.

GODARD G. & STANISLAS M. (2006c). Control of a decelerating boundary layer. Part 3: Optimization of round jets vortex generators. Aerospace Science and Technology, 10(6):455–464.

JOHARI H. & RIXON GS. (2003). Effects of Pulsing on a Vortex Generator Jet. AIAA Journal, 41(12):2309–2315.

JOHNSTON JP. & NISHI M. (1990). Vortex Generator Jets–Means for Flow Separation Control. AIAA Journal, 28(6):989–994.

MC MANUS K., DUCHARME A., GOLDEY C. & MAGILL J. (1996). Pulsed Jet Actuators for Suppressing Flow Separation. AIAA Paper 96-0442, 34th Aerospace Sciences Meeting & Exhibit, Reno, USA.

ORTMANNS J. (2008). Aktive Grenzschichtbeeinflussung mittels pneumatischer Wirbelgeneratoren bei großen Reynoldszahlen. Dissertationsschrift, TU Braunschweig, Institut für Strömungsmechanik.

ORTMANNS J., BITTER M. & KÄHLER CJ. (2008a). Dynamic vortex structures for flow control applications. Experiments in Fluids, 1–12.

PAULEY WR. & EATON JK. (1988). Experimental Study of the Development of Longitudinal Vortex Pairs Embedded in a Turbulent Boundary Layer. AIAA Journal, 26(7):816–823.

SCHOLZ P., ORTMANNS J., KÄHLER CJ. & RADESPIEL R. (2006). Influencing the Mixing Process in a Turbulent Boundary Layer by Pulsed Jet Actuators. New Results in Numerical and Experimental Fluid Mechanics V, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, (92):265–272 .

A Volume PTV

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The purpose of the study is to construct a new 3D-PTV algorithm (a Volume PTV) based upon a hybrid fitness function. In the algorithm, a coherency fitness function is also introduced beyond space and time. The developed algorithm has been employed to probe the turbulence properties of the cylinder wake. Fig. 1 shows the experimental setup for the experiments. The measurement system consists of two-high-definition-cameras(1k x 1k), a Nd-Yag laser and a host computer. The Reynolds numbers with the cylinder diameter (d=10mm) are 360, 540, 720, 900, 1080 and 1260. Fig. 2 shows a hybrid fitness function. This function was used to sort out the correct particle pairs between the two camera images. Before employing this function, two-dimensional displacements of the particles of each camera's images have been utilized to reduce the calculation loads. Fig. 3 shows the constraints (PN and PM) for reducing the calculation loads. More than 10,000 instantaneous 3D vectors have been obtained by the constructed algorithm. The constructed algorithm could recover more than 80~90% of the particle numbers in the experimental images. The optimal parameters in the algorithm were PM[particle movements] =8 pixels, PN[particle neighborhood] =5mm. Fig. 4 shows the primary vortex structure when the Reynolds number is 360. The structures of the wake and the turbulence properties will have been quantified in detail from the results obtained by the constructed system.

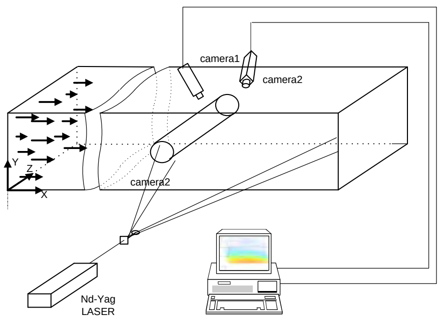

Fig. 1 Experimental setup.

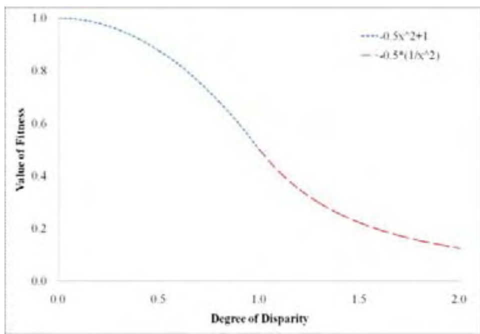

Fig. 2 Hybrid fitness function for sorting the particle pairs.

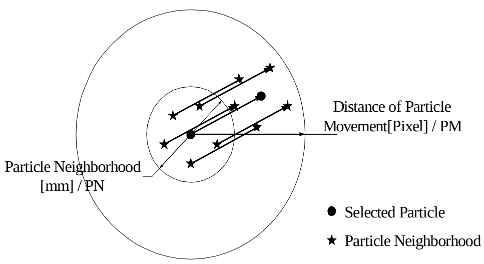

Fig. 3 The particle neighborhood[PN] and the distance

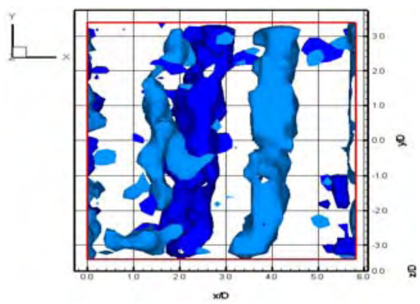

Fig. 4 **Primary vortex structure at Re=360.**

25 Years of Particle Image Velocimetry in Aerodynamics
DLR Göttingen, Germany, September 23-25, 2009

Accelerated Tomographic Particle Image Velocimetry for 3C-3D Velocity Measurements

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ABSTRACT

Particle image velocimetry (PIV) has evolved rapidly with the adoption of digital processing and the principles of stereopsis and more recently tomography. By combining efficient digital imaging and evaluation with multiple views of a measurement region, the data yield of PIV has been extended from standard two-component two-dimentional (2C-2D) measurements to three-component two-dimensional (3C-2D) Stereo-PIV and three-component three-dimensional (3C-3D) Tomo-PIV. Stereo-PIV is now considered a relatively mature method for obtaining 3D flow measurement, but being a planar technique, is unable to deliver information about the 3D volumetric structure of the flow or the full velocity gradient tensor. Information contained in the velocity gradient tensor not only forms an important part of the Navier-Stokes equations, but is also required by the most popular vortex identification schemes. Acquiring this information requires instantaneous measurements in two planes, as in dual plane PIV, or even better through three or more planes using Tomo-PIV.

Tomo-PIV uses three or more cameras with angular-offsets and calibration procedures similar to those of Stereo-PIV, Tomographic reconstruction techniques are used to determine the 3D particle intensity field in a measurement volume such that the images recorded by each camera are instantaneously satisfied. Reconstructed volumes are then 3D cross-correlated to determine the 3D flow velocity in multiple planes within the reconstructed volume, enabling calculation of the velocity gradient tensor via finite differences or least square fitting. Unfortunately the extension to 3D does not come without its share of difficulties. Principle among these is the reconstruction and cross-correlation times. Reconstruction of a $1200 \times 1200 \times 180$ point discretized volume with the commonly used MART algorithm requiring over 2 hrs per volume, with a precalculated calibration based weighting matrix of 34 GB per camera, and Fast Fourier Transform (FFT) based 3D cross-correlation of 64^3 point interrogation regions with a 75% overlap requiring approximately 3 hrs per volume pair. Each 16-bit volume also requires 495 MB of storage, resulting in processing requirements well beyond those of planar or Stereo-PIV. Recent studies of a turbulent boundary layers have required the use of computer clusters and months of processing time, representing significant obstacles to the widespread industrial use of Tomo-PIV.

Reconstruction time can be significantly reduced by using a multiplied line-of-sight estimation of the particle locations combined with an instantaneous SMART intensity correction, without loss of accuracy. Reconstruction of the previously mentioned $1200 \times 1200 \times 180$ point volume with an image seeding density of 0.04 particles per pixel (ppp) can now be performed in 10 minutes on a single CPU without any pre-calculated weight matrices. This method corrects the intensity in the volume one point at a time, making it possible to reconstruct sub volumes in a matter of seconds for rapid feedback on the reconstructed seeding density and velocity magnitudes as needed to optimising an experimental setup.

Accelerated Tomo-PIV is currently being applied to measure the 3D structure of a zero pressure gradient turbulent boundary layer at $Re_\theta = 7800$ and 13000 with measurement volumes corresponding to $440^+ \times 66^+ \times 440^+$ and $857^+ \times 128^+ \times 857^+$, respectively. Tomo-PIV can provide information about the flow at conditions well beyond what can currently be achieved by direct numerical simulation (DNS), making it a valuable addition to the study of turbulence.

Endoscopic Stereoscopic PIV Measurements in Turbomachines

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For several years Particle Image Velocimetry (PIV) has been successfully used for the determination of planar velocity fields. With the introduction of the Stereoscopic PIV (SPIV) all components of internal velocity fields can be captured in enclosed spaces. This method has proved to be particularly suitable for the investigation of strongly unsteady, turbulent flow structures in turbomachines.

However, compared to conventional applications, PIV measurements in tubomachines are more challenging. Limited access to measurement section, light reflections, camera calibration, and machine vibration must be taken into account, to name but a few. The implementation of endoscopic PIV in turbomachines gives an advantage for investigating more complex measurement setups and even real machines.

At the Institute of Turbomachinery and Fluid Dynamics (TFD), endoscopic PIV is developed and applied to different turbomachines, for instance to the axial diffuser test rig, which is a 1:10 scaled model of a heavy duty gas turbine exhaust diffuser. The purpose of the PIV measurement is to capture unsteady structures in the diffuser flow and to find information about their influence on the flow separation. Microspheres are used for seeding.

In a more complex test rig of a 700 kW 7-stage air turbine, SPIV is employed to study the wake structures behind the last stage. For a medium loading with 40% mass flow and 83% of design speed, 3-component velocity fields are recorded.

In a third application, the IGV-impeller interaction is investigated by means of SPIV, in the centrifugal compressor test facility. Here, section-wise SPIV measurements, accompanied by conventional probe measurements, are used to capture the 3D velocity field upstream of the impeller.

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Large-scale coherent motion in turbulent pipe flow

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Fully-developed turbulent pipe flow at bulk Reynolds numbers ranging from $Re_b = 10\,000$ to $44\,000$ has been investigated experimentally using high-speed PIV in a plane perpendicular to the mean flow. A stereoscopic setup has been used to enable the reconstruction of all three components of the entire azimuthal velocity field. The application of Taylor's hypothesis allows to reconstruct the quasi-instantaneous streamwise extension of the flow field. Individual recording sequences cover more than 150 bulk scales based on the bulk velocity U_b and the pipe radius R such that even the largest expected streamwise extends of the large-scale flow structures in the entire azimuthal plane are captured. The azimuthal flow field scaling is found to be consistent with results reported in previous studies. The poster will present details of the azimuthal scaling. The streamwise dimension of coherent structures and ways to correctly assess it will critically be discussed.

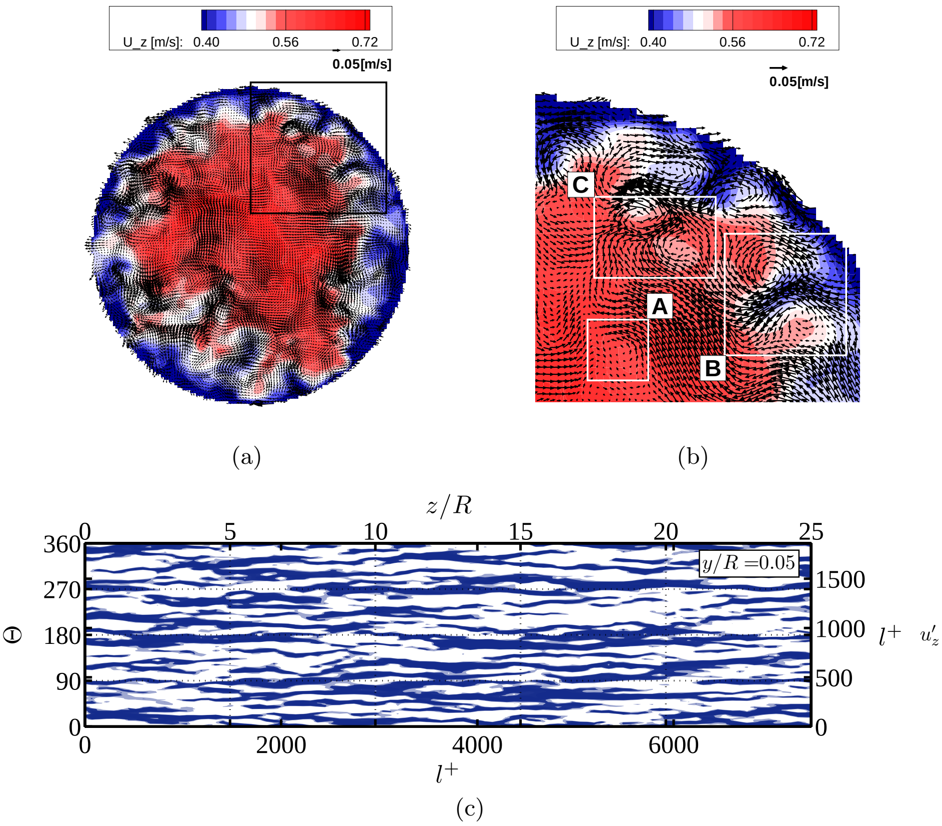

Fig. 1. (a) Instantaneous velocity field at $Re_b = 20\,000$. Contours indicate the streamwise velocity u_z. Vectors show the cross-plane velocity field $u_r,\ u_\Theta$. (b) Close-up of the region highlighted in a with different events highlighted: A : vortex region in the bulk, B : counter-rotating vortex pair with ejection event, C : counter-rotating vortex pair with sweep event. (c) Representative contours of streamwise velocity fluctuations at $y/R = 0.05$ at $Re_b = 10\,000$. For reasons of better visibility only contours for low-speed regions are shown.

Symposium 25 Years of PIV in Aerodynamics, Göttingen, September 23-25, 2009

PIV-Messung selbsterregter periodischer Strömungen

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Abstract

Ein neues Mess- und Auswerteverfahren zur Identifikation instationärer, selbsterregter periodischer Strömungsfelder wird dargestellt. Mit dem Ziel, derartige Vorgänge mit herkömmlichem PIV-System zu untersuchen, wird parallel neben der PIV mit der Hitzdrahtanemometie gemessen. In Turbomaschinen treten derartige instationäre selbsterregte Phänomene auf, wie die von Weidenfeller[3] und März[2] untersuchten Rotierende Instabilitäten. Die Karmansche Wirbelstrasse und die Rotierenden Instabilitäten stellen beide selbsterregte periodische Strömungsvorgänge dar. Die Ähnlichkeit der beiden Strömungsformen wird in der vorliegenden Arbeit genutzt, um mit Voruntersuchungen die Funktionalität des Verfahrens nachzuweisen.
Die Grundidee der Auswertemethode ist es, den PIV-Bildern eine Phasenlage relativ zur periodischen Wirbelablösung zuzuordnen. Hierzu wird das Hitzdrahtsignal herangezogen und mit einem FFT-basierenden statistischen Verfahren analysiert, um die PIV-Bilder zu gruppieren und jeweils ein Ereignis zuzuordnen. Die aufgenommenen Bilder werden auf der Zeitachse mit markiert. Um die so gekennzeichneten PIV-Messungen wird ein hinreichend großes Fenster gelegt und das Hitzdrahtsignal einer FFT-Analyse unterzogen. Dabei liefert die Frequenz mit der größten Amplitude einen Hinweis auf die Grundfrequenz. Als Kriterium dient die Entwicklung der Amplitude der Grundfrequenz. Mit der Festlegung des Zeitfensters kann dann der PIV-Aufnahme ein Phasenwinkel zugeordnet werden und es ergibt sich ebenfalls die Periodendauer. Damit können die einzelnen PIV-Aufnahmen anhand ihrer Phasenwinkel verschiedenen Klassen zugeordnet werden. Die statistische Auswertung der PIV-Aufnahmen einer Klasse erfolgt dann in üblicher Weise. Als Ergebnis einer derartigen Analyse zeigt Abb. 1 exemplarisch das Feld der Geschwindigkeitsvektoren, wobei zur Verdeutlichung der Wirbelstrukturen eine mittlere Geschwindigkeit von 0,9 m/s subtrahiert wurde. Die Untersuchungen in Luft fanden bei einer Reynolds-Zahl von $Re = 120$ und einer Strouhal-Zahl von $Sr = 0.18$ statt

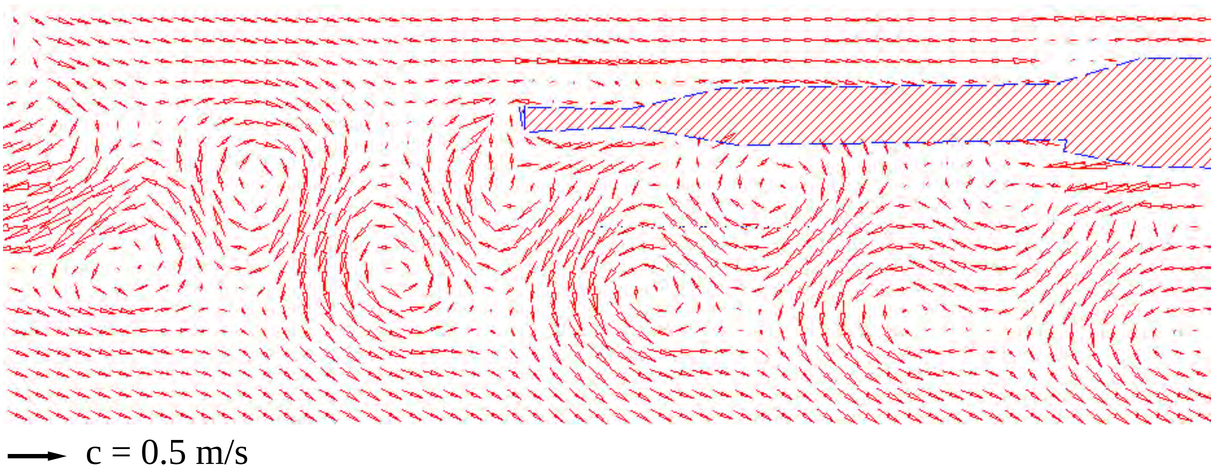

Abb. 1: Feld der Geschwindigkeitsvektoren als Ergebnisse der PIV-Messung [1]

Literatur

[1] Rana Badreddine and Martin Lawerenz. Zeitaufgelöste Messung selbsterregter Strömungsfelder durch Kopplung von Hitzdrahtanemometrie und Particle Image Velocimetry. In *Lasermethoden in der Strömungsmesstechnik, 8.-10. Sepetember, Universität Erlangen*. Deutsche Gesellschaft für Laser-Anemometrie GALA e.V., 2009.

[2] J. März, C. Hah, and W. Neise. An experimental and numerical investigation into the mechanisms of rotating instability. In *Proceedings of the ASME TURBOEXPO 2001, ASME Paper 2001-GT-536*, 2001.

[3] J. Weidenfeller and M. Lawerenz. Time resolved measurements in an annular compressor cascade with high aerodynamic loading. In *Proceedings of the ASME TURBOEXPO 2002*, 2002.

Application of PIV in Acoustic and Aeroacoustic Experiments

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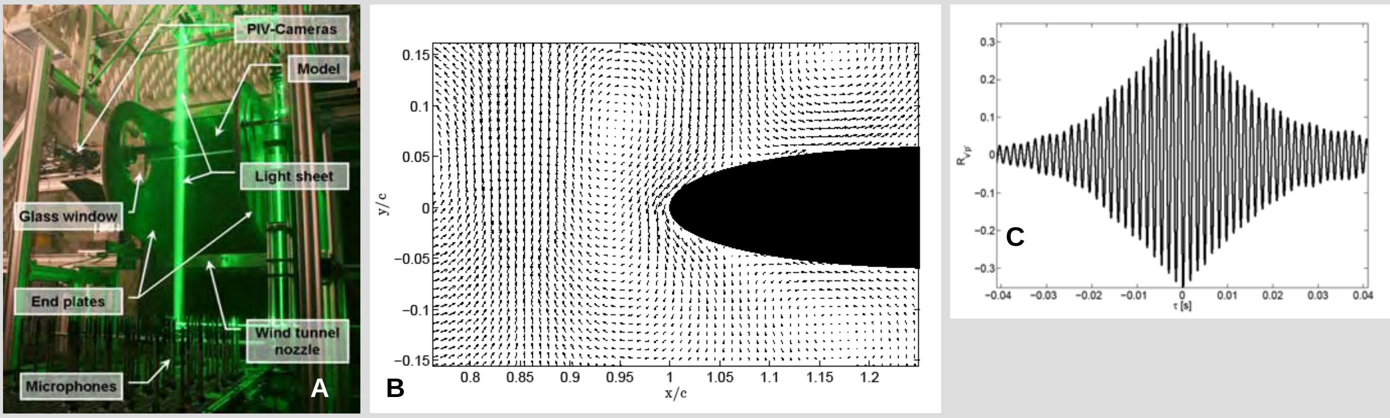
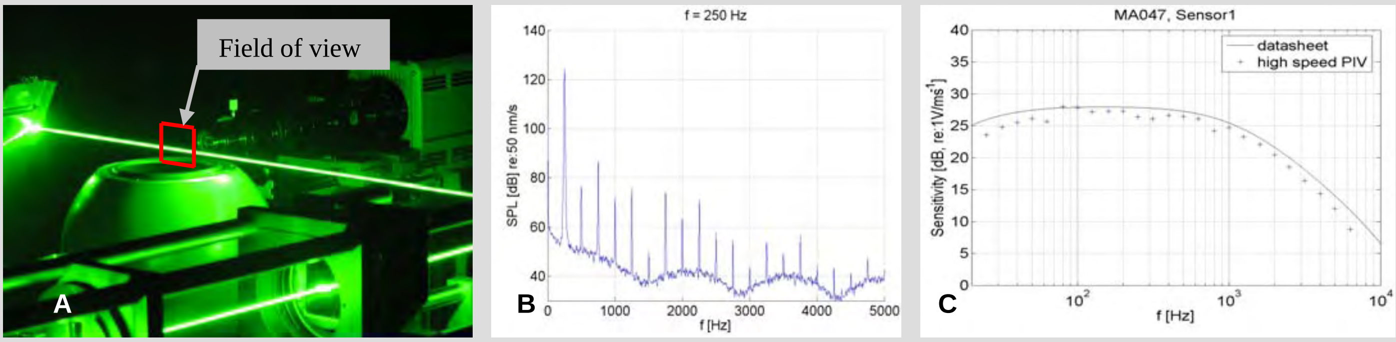
Abstract: Different applications of the PIV technique in the field of acoustics and aeroacoustics are presented. This includes the investigation of cavity resonance and the calibration of a p-u probe, which is used for acoustic intensity measurements. Additionally, we present applications of the causality correlation technique by means of simultaneous PIV and microphone measurements. The method is used for the identification of flow structures that are involved in the generation mechanism of aeroacoustic noise sources.

Causality Correlation by means of simultaneous PIV and Microphone-Array measurements



Velocity-components u and v are measured with PIV. Pressure fluctuations p‘ are obtained by means of an microphone-array measurement in the far-field. **A:** Experimental setup of a rod-airfoil configuration. **B:** Instantaneous distribution of the cross correlation coefficients ($R_{u';p'}$,$R_{v';p'}$) for τ = 0 ms as a vector plot near the airfoil leading edge. **C:** The temporal evolution of the cross correlation coefficients $R_{v';p'}(\tau)$ near the leading edge of the airfoil.

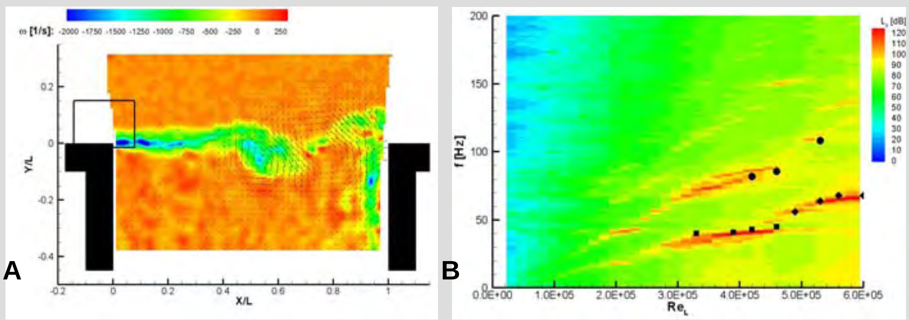
Calibration of a particle velocity sensor using High-Speed-PIV



A: Detailed view of the laser light-sheet illuminating the near field region of the HF loudspeaker. In the background the long-distance microscope and the high-speed camera are visible. **B**: Spectral representation of the measured time signal. Depicted is SPL [dB] re: 50 nm/s measured with the high-speed PIV system in the near-field of the HF loudspeaker at 250 Hz.**C**: Sensitivity [dB re:1V/ms-1] of the p-u probe measured with the high-speed PIV system. The black line shows the calibration curve given by the manufacturer.

High-Speed-PIV investigation of cavity resonance

The buffeting effect is investigated on a generic large scale cavity. **A**: Instantaneous velocity distribution. **B**: Re-Number dependent frequency distribution.



PIV-LIF techniques for multiphase flows diagnostics. Recent results of Institute of Thermophysics

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Abstract.
The present work describes recent experimental studies of two-phase gas-liquid flows performed in Institute of Thermophysics via non-intrusive optical techniques, namely, PIV and LIF.

A turbulent bubbly free jet flow was studied in details by means of PIV for fluorescent tracers and Planar LIF for bubbles imaging. The application of PIV allowed to estimate the spatial distributions of the mean velocity of the liquid and second- and third-order moments of liquid velocity fluctuations in the central plane of the jet. A great influence of bubbles (depending on volumetric gas content) on turbulent structure of the jet was observed near the nozzle exit. The use of PLIF approach for bubbles imaging in the vicinity of the laser sheet and application of a correlation approach for bubble identification and PTV for their velocity estimation, respectively, allowed to obtain the planar distributions the average void fraction, bubbles' mean velocity and the second-order moments of gas-phase velocity pulsations. In particular, a strong correlation of bubble-liquid velocity fluctuations was revealed that indicated that stochastic motions of bubbles were mainly caused by turbulence in the liquid phase.

The work also describes the recent results on LIF application for film thickness measurements in gravitational and gas-sheared liquid film flows. In particular, shape of solitary 3D waves on gravity-driven films and its interactions with stationary waves was investigated.

The LIF technique was also successfully applied for investigation of wavy structure of annular gas-liquid flow in regimes with and without liquid entrainment. It was shown that the wavy structure is quite similar in both cases, providing grounds to develop essentially new models of entrainment phenomenon and transition to entrainment.

25 Years of Particle Image Velocimetry in Aerodynamics

Documents

A wiki-like webportal is under preparation to collect documents (photos, diagrams, PIV recordings, text documents) related to the history of PIV. Owners of such documents will be asked to upload electronic copies to this web portal after its finalization. It is planned to make this information available to the public once sufficient input has been received. In addition, a questionnaire asking for your personal opinion about milestones, turning points, surprising discoveries etc. in PIV development will be circulated.

Abstracts

All authors are asked to prepare an abstract of the contents of their presentation including their full address (max. length of abstract: one page). A compilation of the abstracts will be made available together with the final schedule via the website prior to the symposium. Deadline for submitting abstracts: August 15, 2009.

Oral presentations

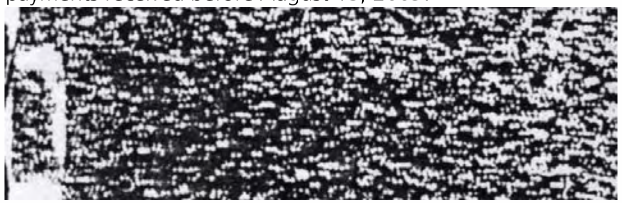
Authors of oral presentations will be asked to send an electronic copy of their presentation. This electronic copy will be made available via the symposium website. Deadline for submitting electronic copies of presentations: September 10, 2009.

Posters

Authors of poster contributions will be asked to prepare a poster according to a format made available via the website and to send an electronic copy of their poster. This electronic copy will be made available via the symposium website. Deadline for submitting electronic copies of posters: September 10, 2009.

Registration

Registration is requested via the symposium’s website (check for further details). The registration fee is 120 €. A reduced registration fee of 80 € will apply for registrations and payments received before August 15, 2009.



Please, forward this announcement to anyone who might be interested, in particular to those who have actively participated in the early development of the PIV technique.

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http://25-years-PIV.dlr.de

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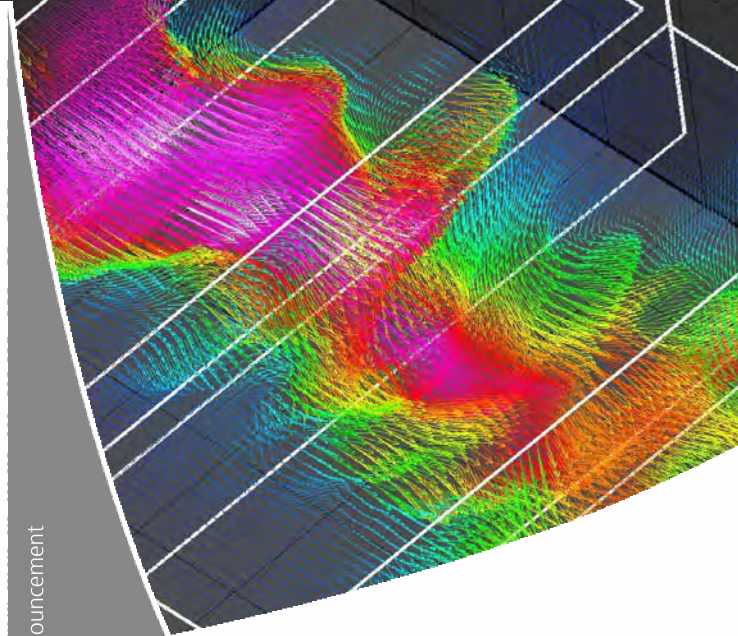


Second Announcement

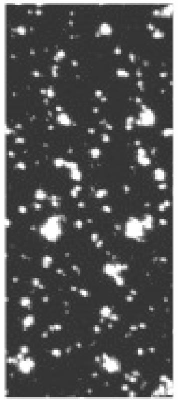
25 Years of Particle Image Velocimetry in Aerodynamics

DLR, Göttingen
Germany
September 23 – 25, 2009

25 Years of Particle Image Velocimetry in Aerodynamics

Background

In summer 1984 teams of the University of Oldenburg and DLR carried out measurements of the instantaneous flow field by means of Particle Image Velocimetry for the first time in a wind tunnel of DLR Göttingen. In those days the recording of the PIV images had to be done photographically. Also, the evaluation of the recordings to obtain the displacement of the images of the tracer particles, added to the flow, had to be performed optically. A few months later DLR had the first double oscillator Nd:YAG laser at its disposal and started the development of a PIV system applicable for aerodynamic research in large industrial wind tunnels. Around 1995 a major breakthrough in the development of PIV, which has been a prerequisite to bring this technique out of the laboratory and into use at research organizations for applications of relevance to industry, has been made. Then, digital video cameras, allowing capturing the two frames of a PIV recording within a short time interval and with full spatial resolution became available. In the following decade the PIV technique has been widely spread and differentiated into many distinct applications ranging from micro flows to combustion and supersonic flows, both for research and industrial needs. This was made possible mainly due to further technological progress in video techniques, lasers and the development of sophisticated evaluation algorithms. In particular in Europe, the progress has been strongly accelerated in the field of aerodynamics by international cooperation of the leading PIV developers supported by European research grants. Nowadays the PIV technique is considered a 'validated tool' by the aeronautical industry and used in large industrial wind tunnels to support the design of new aircraft.

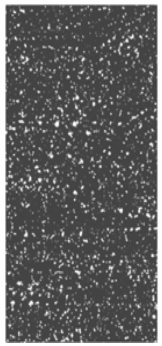


Objective

The twenty fifth return of the day when the first PIV measurements in a wind tunnel have been performed in Göttingen is considered to be a good opportunity to commemorate the early developments of the PIV technique and to contrast the technical possibilities of those days to the state-of-the-art of PIV today. Decisive inventions will be acknowledged at this occasion as well as many small but significant contributions to the development of the PIV technique, - made in the past two and a half decades by many researchers world wide. New users of the PIV technique, in most cases employing off-the-shelf commercial PIV systems, shall be familiarized with problems that had to be faced in the past due to inadequate technology of those days. In addition, as there are still documents (photos, PIV recordings, lab notes, etc.) available describing the research work from the early development of the PIV technique, it shall be discussed with experts in the field of the history of science whether an annotated compilation and archiving of such documents would be feasible.

Participation

In particular the symposium is aiming at the participation of 'pioneers' of the early days of PIV and of those scientists who provide major contributions to the state-of-the-art of PIV. Quite a few reckognized experts in the field from the US, Asia and Europe have already confirmed their interest in the symposium. More general, all persons who are interested to obtain a comprehensive overview of the history of PIV and the progress made at this technique within a time interval of 25 years are invited to attend this symposium.



Scientists who own interesting material related to the early development of PIV or who can present state-of-the art applications of PIV which are of interest to a broader public are kindly requested to contact the organizers to find out whether their contribution can be considered for contribution to the free discussion or as poster. Deadline for offering such contributions: August 15, 2009

Schedule of Symposium

Wednesday, September 23, 2009

PIV yesterday

- Fifteen lectures by J. Kompenhans, R. Adrian, R. Meynart, M. Riethmuller, K. Hinsch, R. Kelnberger, B. Lecordier, M. Raffel, C. Willert, A. Boutier, M. Gharib, C. Kähler, K. Okamoto, KC Kim, C. Westergaard
- Free contributions, posters
- Discussion of aspects of early development of PIV
- Dinner

Chairman: Prof. Klaus Hinsch, University of Oldenburg

Thursday, September 24, 2009

PIV today

- Ten lectures by J. Westerweel, S. Wereley, F. Scarano, J. Soria, M. Oshima, M. Stanislas, A. Schröder, K. Pengel, W. Kühn, U. Herrmann
- Free contributions, posters
- Visit of PIV laboratories and test facilities
- Discussion of future prospects of PIV

Chairman: Dr. Jürgen Kompenhans, DLR, Göttingen

Friday, September 25, 2009

History in the Making – You are part of the History

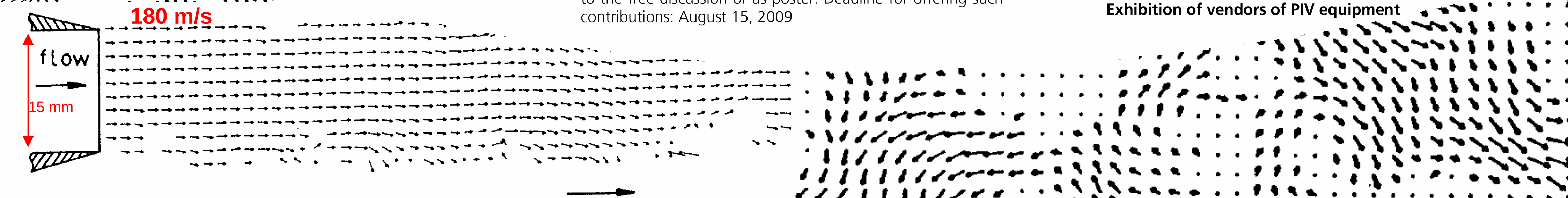
Five sessions of about one hour of discussion, each with a short introductory statement

- Prehistory of PIV
- Is there more than one history of PIV?
- Success! What Success?
- Milestones and Turning Points
- Is there a Social History of PIV?

Chairman: Dr. Falk Rieß, Center of Didactics and History of Physics, University of Oldenburg

September 23 - 24, 2009

Exhibition of vendors of PIV equipment



Questionnaire

The Local Organizing Committee of the Symposium '25 Years of Particle Image Velocimetry in Aerodynamics' would like to receive feedback from the participants about the organization and format of the symposium.
Please, make your comments/suggestions and return this questionnaire to the registration desk (with or without your name) or send it by fax or e-mail (form available as download from website) to the Local Organizing Committee after the symposium.

Your comments will help to improve the organization of such kind of symposium.

General remarks/Overall organization:

Lectures (PIV yesterday, PIV today):
(oral presentations)

Posters (PIV yesterday, PIV today):

Seminar History in the Making – You are part of the History'

Open sessions

Exhibition:

Social Events

Technical Excursion

Others:

Name (optional):

25 Years of Particle Image Velocimetry in Aerodynamics

http://25-years-PIV.dlr.de

Jürgen Kompenhans and Klaus Hinsch
Chairmen Symposium '25 Years of Particle Image Velocimetry in Aerodynamics'

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