Experimental Fluid Mechanics

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Particle Image Velocimetry

A Practical Guide

With 165 Figures and 24 Tables

Springer

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Preface

That moment, when after many months of work, the endeavored result turns into shape as printed pages, is a good opportunity to lean back and to reflect on the history of the subject of this book: particle image velocimetry (PIV). The rapid development, which this measuring technique that allows us to capture the flow velocity of whole flow fields in a fraction of a second, has undergone in the past decade can best be characterized by the experience of the authors gained during their research work in the Institute of Fluid Mechanics of the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The first applications of particle image velocimetry outside of the laboratory in wind tunnels as performed in the mid-eighties were characterized by the following time scales: time required to set up the PIV system and to obtain well focused photographical PIV recordings was 2 to 3 days, time required to process the film was 0.5 to 1 day, time required to evaluate a single photographical PIV recording by means of optical evaluation methods was 24 to 48 hours. Today, with modern video cameras and fast computers it is possible to focus on line, to capture up to several hundred recordings per minute, and to evaluate a digital recording within a few seconds.

Even more important than this remarkably improved performance of the PIV technique, is its unique ability to capture instantaneous flow fields and thus to allow the detection of spatial structures in unsteady flows quantitatively, which is not possible with other experimental techniques. A number of investigations in very different areas from aerodynamics to biology, from turbulence research to applications in the space shuttle, from fluid mechanics to two phase flows have proven this. Due to this wide range of possible applications of PIV the number of research groups employing the PIV technique world wide has increased from a handful at the beginning of the eighties to far beyond a thousand today.

The third reason for the increasing interest in PIV is the demand for experimental flow field data for the validation of numerical codes. For this purpose the development of the PIV technique must go on in order to achieve higher accuracy, higher spatial and temporal resolution, and larger observation areas and volumes of experimental data.

Due to the number of different applications of PIV and due to the number of different possibilities to illuminate, to record and to evaluate, the many different technical modifications of the PIV technique have been developed in the past. Even for experts it was not always easy to decide which implementation of the technique would be best suited for a given application. During the last few years this has changed. Due to the development of modern cross correlation video cameras and appropriate fast software algorithms, the digital implementation of PIV seems to be the first choice for most applications. Therefore, the authors of this book felt that it was timely to compile the knowledge about the basic principles of PIV and the main guidelines for its implementation in practice. Most of the material covered in this book has already been published in conference proceedings or in scientific journals. However, this information is widespread and cannot be easily found by someone who wants to start employing the PIV technique for his special problems. Moreover, most publications illuminate the problems only from a specific point of view.

Organization of the book

The intention of this book is to present in a more general context mainly those aspects of the PIV technique relevant to applications. This strategy is supported by the experience of the authors which is based on their own work in the development of PIV for nearly 15 years and more than 30 different applications of DLR's mobile PIV system in aerodynamics and related areas ranging from subsonic to transonic flows, from turbulence research to the investigation of sprays, and from small test facilities to large industrial wind tunnels. The authors have also considerably contributed to the Courses on Particle Image Velocimetry held during the last 5 years in their laboratory. The presentation of the material in this book takes into account the feedback from the participants of these courses as well.

This practical guide to particle image velocimetry provides in a condensed form all that information relevant for the planning, performance and understanding of experiments employing the PIV technique. It is mainly intended for engineers, scientists and students, who have already some basic knowledge of fluid mechanics and nonintrusive optical measurement techniques. For many researchers and engineers, planning to utilize PIV for their special industrial or scientific applications, PIV is just an attractive tool with unique features which may help them to gain new insights in problems of fluid mechanics. These people are usually not interested in becoming specialists in this field first before starting their investigations. On the hand side some of the basic properties of particle image velocimetry must be well understood before a correct interpretation of the results is possible. Our hope is that this practical guide on particle image velocimetry will serve this purpose by providing an easy transfer of the know how gathered by the authors during many years to the readers of this book. It will help the readers to avoid beginners' errors and bring them to a position to obtain high quality results when employing PIV right from the beginning of their work. For those, already working in the field of PIV, this book may serve as a reference to further publications containing more details, which may be first consulted in case of open questions. As with all publications, also in this book the amount of information which can be presented must be limited. Nevertheless, it is our hope that we have been able to collect all information relevant to practical work with PIV.

About the authors

Markus Raffel received his degree in mechanical engineering in 1990 from the Technical University of Karlsruhe and his doctorate (Ph.D.) in 1993 from the University of Hannover, Germany. He started working on particle image velocimetry at DLR Göttingen in 1991 with emphasis on the development of PIV recording techniques in high-speed flows. In this process he applied the method to a number of aerodynamic problems mainly in the context of rotorcraft investigations.

Christian Willert received his BS degree in Applied Science from the University of California at San Diego (UCSD) in 1987. Subsequent graduate work in experimental fluid mechanics at UCSD lead to the development of several nonintrusive measurement techniques for application in water (particle tracing, 3-D particle tracking, digital PIV). After receiving his Ph.D. in Engineering Sciences in 1992, he assumed post-doctoral positions first at the Institute for Nonlinear Science (INLS) at UCSD, then at the Graduate Aeronautical Laboratories at the California Institute of Technology (Caltech). In April 1994 he joined DLR Göttingen's measurement sciences group as part of an exchange program between Caltech and DLR (i.e. Center for Quantitative Visualization, CQV). There he continues to work in the development and application of PIV techniques with special emphasis on wind tunnel applications.

Jürgen Kompenhans received his doctorate in physics in 1976 from the University of Göttingen. Since 1977 he has been employed by DLR, the German Aerospace Center. First, he performed experimental research work on problems of aero-acoustics. For nearly 15 years now he has been involved in the development of nonintrusive measurement techniques for aerodynamic research in wind tunnels (mainly particle image velocimetry). Presently he is working in the Institute of Fluid Mechanics at DLR's research center Göttingen. Since 1985 the PIV-group, headed by J. Kompenhans, has developed and continuously improved a PIV system dedicated to the application of PIV in the rough environmental conditions of large, industrial-scale wind tunnels. This system has been successfully applied to a number of different investigations within national and international projects.

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During the past decade a number of colleagues, some of them being members of our group only for a limited time, have contributed to the progress of our work: technicians, students and scientists. Among these we especially want to acknowledge the contributions of Hans. R. Höfer, Aymeric Derville, Matthew Gaydon, Markus Fischer, Markus Wiegel, Christian Kähler, Andreas Schröder, Olaf Ronneberger, Hannes Reichmuth, Rainer Höcker, Andreas Vogt, Bernward Bretthauer, Heinrich Vollmers, and Boleslaw Stasicki. Our work has been financially supported by DLR, as well as by other national and international institutions. We always found a strong interest in our work and support from our colleagues from the Measurement Methods and Flow Analysis Section of the Institute of Fluid Mechanics of DLR and its head, Karl-Aloys Bütefisch.

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Stereo: The projection equations and the necessary nonlinear least squares fitting algorithms for stereoscopic PIV were brought to the attention of the authors by Heinrich Vollmers.

Dual-plane: For the first time dual-plane PIV was implemented during Markus Raffel's and Olaf Ronneberger's visit to Caltech. Alexander Weigand's generous offer of his experimental set-up and stimulating discussions with Jerry Westerweel and Thomas Roesgen are greatly appreciated. In fact, the cooperative work carried out in the Center for Quantitative Visualisation, jointly operated by GALCIT of Caltech and DLR, was quite successful. Special thanks to Mory Gharib.

Flow field investigations by means of PIV, discussed in this book, have been performed at the facilities of different research organizations such as DLR, the German–Dutch Wind Tunnel (DNW) with the special support of its director, Hans Ulrich Meier, Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation (ZARM), Institut Franco–Allemand de Recherches de Saint-Louis (ISL), and others.

The comments made by Klaus Hinsch, Dirk Ronneberger and Andreas Vogt on the draft version of this book are greatly appreciated as well.

We are deeply indebted to all friends and colleagues of the worldwide PIV community who helped us to better understand the different aspects of the PIV technique during recent years by their work, their publications and conference contributions, and by personal discussions.

The authors, Göttingen, September 1997

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Chris Willert
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