Industrial applications of image based measurement techniques in aerodynamics: problems, progress and future needs

Jürgen Kompenhans

Department Experimental Methods, Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), 37073 Göttingen, Bunsenstrasse 10, Germany, Tel.: + 49 [551] 709 2460, Fax: + 49 [551] 709 2830, E-mail: juergen.kompenhans@dlr.de

Abstract

Since two decades technological progress at lasers, video techniques, optoelectronics, computers and evaluation algorithms allows to extract quantitative information from images of flows, even in complex environments. Continuous improvement of such image based measurement techniques and decreasing costs of equipment enabled many research groups to exploit these techniques for extraction of 2-dimensional or even 3-dimensional data mainly for fundamental research. Since a decade ago many image based measurement techniques have found interest in aerodynamics and are even used as a matter of routine in industrial applications, especially in large wind tunnels or at in-flight testing. Application is mainly performed in the scope of large industrial projects in European co-operation. For this purpose mobile measurement systems have been developed, which can be flexibly adjusted to particular testing environments. All data is acquired non-intrusively so that no interference of the flow field by the measurement is to occur. In consequence, the methods developed are particularly suited for the aero-dynamical and aero-acoustical analysis of complex, unsteady three-dimensional flow fields. The paper will report on the state-of-the-art of the application of image based measurement techniques in aerodynamics and will describe some of the current problems and future needs.

Keywords: Image based measurement techniques, aerodynamics, wind tunnels, in-flight testing

1. Introduction

Quantitatively measurable values of interest for aerodynamics and the respective measurement method are pressure (Pressure Sensitive Paint, PSP), velocity (Particle Image Velocimetry, PIV), location of transition lines (Temperature Sensitive Paint, TSP), density (Background Oriented Schlieren Method, BOS), and sound pressure (Acoustic Microphone Array Technique), in parallel with the determination of deformation (Image Pattern Correlation Technique, IPCT) and position of the model in the wind tunnel or of the wing of an airplane in flight (Position and Deformation Measurement System, PDMS) [1, 2]. Today PIV, PSP and deformation measurement techniques are the most advanced and mostly used of these techniques in industrial wind tunnels. The qualitative and quantitative improvements achieved during the past few years will be demonstrated in the next chapter taking applications of these techniques in industrial wind tunnels and feasibility studies performed at ground or flight testing of aircraft as examples.

The main areas of application of PIV, PSP and deformation measurement techniques in aerodynamics at DLR in wind tunnels are at present: high lift configurations, engine integration, propeller flows, wake vortices, delta wings, separated flows and turbulent and transitional boundary layers. The main problems involved with all these techniques are limited optical access in the closed test section of wind tunnels, reflections from the model
under investigation, image distortions due to density gradients in case of transonic flows, and the time required for setting up and adjusting the equipment and for the calibration of the imaging conditions. Due to its physical properties PSP works better at high speed transonic flows (low pressure) and PIV works better at low speed flows (no problem of velocity lag of tracer particles and amount of required tracer particles for seeding the flow).

Another problem receiving more and more attention today is that the application of non intrusive optical measurement techniques such as PIV, PSP etc. requires the transmitting and receiving optics to be located far away from the object under investigation in order not to disturb the flow. This has the consequence that the instrumentation cannot be rigidly attached to the object. Especially, if measuring close to the surface of the object the exact position of the area under observation by means of the chosen optical measurement technique and the location of the object are required simultaneously. In addition, models in a wind tunnel to be investigated at high-speed flows will deform under the loads of the flow. This means that the location of a model in the wind tunnel as well as its deformation have to be determined carefully during the measurement, especially, when applying optical diagnosis tools. In addition, such information on the actual location and shape during the experiment is also absolutely required when utilizing these experimental data for validation of numerical calculations. The need to perform model location and deformation measurements in different wind tunnels for different aerodynamic investigations requires developing a modular and mobile system for model deformation measurements as well.

On the other hand, the development of versatile deformation measurement techniques for wind tunnel methods has stimulated the transfer and use of such techniques for complete airplanes either in ground or flight tests as will be shown in chapter 2.3.

2. Image based measurement techniques for aerodynamics

Next a few examples of the application of the PIV, PSP and deformation measurement technique in industrial projects will be given.

2.1 Particle Image Velocimetry

Particle Image Velocimetry, PIV in its configuration as stereo PIV is - after more than two decades of development - considered to be a reliable tool for the investigation of unsteady velocity fields in industrial wind tunnels today. Small tracer particles added to the flow are illuminated in a plane by two strong laser pulses within a time interval of a few microseconds. The light scattered by them is recorded by two high resolution, high sensitivity CCD cameras. The local velocity is determined from the displacement of the tracer particles between the two

Fig. 1. Shear layer and wake development behind a CRUF TPS measured by stereo PIV with phase locking to single fan blades in DNW-NWB low speed wind tunnel.

Fig. 2. Propeller slipstream development with wing interaction measured by PIV in an industrial low speed wind tunnel.
illuminations employing sophisticated evaluation algorithms.

Flow configurations under investigation in modern industrial aerodynamics and research are complex, unsteady and fully three dimensional. For example the velocity field in flows behind a turbine powered simulator (TPS) (Fig. 1) or a propeller (Fig. 2 and 4) or around a 3D complex high lift configuration with strake vortex (Fig. 3) can be investigated by stereo PIV measurements. A large number (~several thousands) of spatially highly resolved instantaneous velocity vector fields in planes within the flow can be captured and evaluated within a few minutes (typical observation area 20 x 30 cm², observation distance 1 … 5 m, 30,000 vectors per PIV recording). These data fields give valuable insight into unsteady flow topologies and their interaction with model structures. Averages and RMS –values can be derived as well as vorticity and velocity gradients.

In numerical simulations such unsteady flows require a special treatment. Classical codes need to model e.g. the propeller as an actuator disk, are neglecting viscosity effects, and are facing problems in (turbulent) wake and shear layer development as present for example in the flow behind a TPS. Distinguishing between numerical dissipation and turbulence decay is another problematic topic in CFD. Thus, advanced CFD methods for calculating unsteady and separated flows which are in strong development nowadays require reliable field data for the validation of such advanced numerical codes. Especially the ability of stereo PIV to provide fluctuation velocities and gradients in whole flow fields matches the validation requirements and offers at the same time quantitative visualization of the flows for direct comparisons with CFD results. As an example, a comparison of the vorticity as obtained in the experiment and from CFD calculations, as performed by the Department of Transport Aircraft, is shown in Fig. 4. In the PIV data there are pronounced secondary vortices present, starting at the leading edge of the airfoil. In the numerical calculations these appear to be smoothed, which is probably caused by the effect of numerical dissipation. This highlights the need for proper validation of CFD codes.

2.2 Pressure Sensitive Paint

The Pressure Sensitive Paint technique, PSP, allows determining the pressure not only point-wise as with conventional pressure transducers but on the whole surface of a wind tunnel model. The model has to be coated with a special organic paint and requires dedicated illumination (wavelength) and recording (filters) together with sophisticated evaluation software in order to be able to provide the pressure data at all points of the numerical grid of the model. The state-of-the art of PSP is that measurements in the transonic flow regime can be performed with accuracy comparable to that of conventional pressure transducers, which allows obtaining the loads on the model or parts thereof by integration of the pressure data.
Application of PSP in low speed flows provides valuable quantitative information, but due to the paint available up to now, it cannot replace conventional techniques at present.

A typical steady PSP result for a model investigated in transonic flow is given in Fig. 5. The two dimensional PSP images have been mapped to the three dimensional CFD grid of the model. All the different pressure maps obtained in the different viewing directions must be merged excluding overlapping regions. The calculated pressure values based on the intensity values measured with PSP are presented in pseudo-colors. The pressure distribution in Fig. 5 clearly shows the vortex trajectories as “footprints” on the model surface. Flow field topology such as vortex interactions can therefore be easily visualized already only a few minutes after having performed measurements for different angles-of-incidence and Mach numbers. The comparison of the pressure coefficients as measured with the PSP technique and the conventional pressure tap technique (PSI) shows a good agreement. In average on each grid point of the model a standard deviation of $c_p \leq 0.05$ was achieved.

The investigation of unsteady flow phenomena, such as aeroelastic investigations, turbo machinery and helicopter rotors requires the knowledge of the unsteady pressure distribution. Thus, recently unsteady PSP has been developed and successfully applied up to framing rates of 100 Hz. A high porosity paint in which the luminescent dyes are incorporated in a porous polymer has been developed. In a first application in cooperation with the Institute of Aeroelasticity a 2D-wing-profile model, which is pitch oscillating with a frequency at up to 30 Hz, was investigated in DNW-TWG. The experimental result presented in Fig. 6 was performed at angles-of-incidence $\alpha = 1.12^\circ \pm 0.6^\circ$ at $Ma = 0.72$.

2.3 Image Pattern Correlation Technique

The bend and twist as well as the local deformation of the skin of an aircraft’s wing are of high interest for structural and aerodynamic design. Advanced optical measurement techniques like Image Pattern Correlation Technique, IPCT give the potential to measure these parameters in a planar and non-intrusive way. Within the EC funded AIM project the wing deformation of a Piaggio P180 is measured. A pre-test on ground had been performed to show
the potential of IPCT. Two cameras had been used to measure the deformation of the outer wing of the P180 which had been equipped with a random dot pattern and was excited by a shaker. Fig. 7 shows a picture of the measurement setup and some sample results of these IPCT deformation measurements. In addition to the wing deformation measurements investigations on the deformation of rotating propeller blades at the Piaggio P180 are performed as well. Fig. 8 presents the results of the propeller blade deformation measurement during ground tests. Flight tests are planned in 2009 for both applications.

3. Outlook

The quality of the data obtained in complex unsteady flow fields by means of image based measurement techniques allows detailed comparison with the results of numerical calculations. It is expected that this fast and immediate comparison will change the way wind tunnel tests will be organized in the future from a top-down approach with a given test plan to a rather interactive procedure. This, however, will require the development of tools for fast alignment and calibration of the experimental set up and on-line evaluation, for comprehensive post-processing and data reduction tools in order to compare and analyze experimental and numerical data during the test, and for easily understandable presentation of the results to the end user. Moreover, the advanced image based experimental techniques for measurement of pressure, velocity, temperature, density and model deformation must be further developed in order to be able to employ them in parallel (especially in unsteady flows) to provide the complete information about the flow field. As an example, recent technological developments allow using high repetitive pulse lasers and CMOS cameras capable to acquire images in the kilohertz regime combined in a time resolved PIV system to capture the complete flow field development and especially the acoustically relevant temporal and spatial interaction of vortices with edges of a model quantitatively. Simultaneous acoustic measurements enable the characterization of the related far field emission and provide the possibility to correlate velocity fluctuations in the source region with the pressure fluctuations measured in the far field, not being possible a few years ago.

4. Acknowledgments

Many persons have contributed to the results presented in this paper: previous and current colleagues from the Department of Experimental Methods, colleagues from international teams performing the tests with advanced measurement techniques and the teams from the large industrial wind tunnels and commercial aircraft manufacturers where the tests have been carried out. Without their continuous strong support these results would not have been possible.

References