©2007 The Visualization Society of Japan
Journal of Visualization, Vol. 10, No. 1 (2007)25-28

Review Report

Experimental Methods for Multi-Diagnostics of Flow Fields in Wind Tunnels

Kompenhans, J.*

* Institute of Aerodynamics and Flow Technology, German Aerospace Center, Bunsenstrasse 10, 37073 Göttingen, Germany. E-mail: juergen.kompenhans@dlr.de, http://www.dlr.de/as

Received 30 November 2006

1. Introduction

For thousands of years human beings had to observe flows in nature individually in their own interest in order to survive dangers of nature. A few hundred years ago famous scientists like Leonardo Da Vinci prepared qualitative descriptions of flows in nature or man-made by writing or drawing to pass their personal knowledge to others. The invention of photography 170 years ago allowed for the first time to record flow phenomena in a more objective way, as the recordings allowed later qualitative description and analysis of flows by further experts independently. Since two decades technological progress at lasers, video techniques, optoelectronics, computers and evaluation algorithms allow to extract quantitative information from images of flows as well, mostly for those of technical interest. Continuous improvement of such image based measurement techniques and decreasing costs of equipment enabled many research groups in universities to exploit these techniques for extraction of 2-dimensional or even 3-dimensional data mainly for fundamental research. The number of scientific publications increased and scientific journals such as the Journal of Visualization, dedicated to the topic of visualization, have been established a decade ago. Since then many image based measurement techniques have found interest and are even used as a matter of routine in industrial applications, especially in aerodynamics and wind tunnels. This explains why research establishments like the German Aerospace Center operate a Department of Experimental Methods with the objective to develop optical and acoustical field measurement techniques for the acquisition of fluid-mechanical and aero-acoustical quantities and to apply them mainly in large industrial wind tunnels for aerodynamics.

Quantitatively measurable values of interest for aerodynamics 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 (Position and Deformation Measurement System, PDMS); Kompenhans et al. (2006a, 2006b). Application is mainly performed in the scope of large industrial projects in European co-operation. For this purpose mobile measurement systems have been developed by the department, 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 acquired data sets constitute a reliable basis for the validation of numerical codes.

Increasingly, these image based measurement techniques are applied in parallel to obtain a more complete description of the flow field by determining several physical quantities simultaneously. In the following a few results on multi-diagnostics in flows in wind tunnels shall be reported.

2. Multi-Diagnostics in Flow Fields

The first example concerns the parallel application of **PSP and PIV** in the frame of the International Vortex Flow Experiment 2 (VFE-2), where wind tunnel tests were carried out on a 65° delta wing at sub- and transonic speeds applying both techniques. Since 2003 the VFE-2 is being carried out within the framework of the task group AVT-113 of RTO (NATO's Research and Technology Organization). The objectives of this working group are to perform new wind-tunnel tests on a delta wing by using modern measurement techniques and to compare these data with results of numerical state-of-the-art codes (Hummel, 2005). For the tests the delta wing model, provided from NASA Langley, was equipped with sharp as well as with rounded leading edges.

With PSP the pressure distributions on the model surface measurements were determined, which serve as "pathfinder" tests. Their results gave first information of the flow topology over the delta-wing for a large range of angles of attack. The PIV measurements were performed in a second test campaign for which specific angles of attack and locations of the measurement planes above the delta wing were selected on the basis of a first analysis of the PSP results. The measured velocity fields provide detailed information of the instantaneous and time averaged flow fields.

The Stereo-PIV set-up (Fig. 1) allows for flow velocity measurements above the delta wing within planes perpendicular to the model axis at different chord stations. The light-sheet and the cameras can be translated along the model axis during wind tunnel operation. The arrangement also incorporates rotary plates in order to adjust quickly the set-up for different angles of attack.

For the current delta wing configuration a specific flow topology occurs in the rounded leading edge case. In addition to the well known outer primary vortex another inner primary vortex develops which was first evidenced within the VFE-2 group for M = 0.4, R_{mach} = 3 million and an angle of attack of 13° by a flow computation of W. Fritz (EADS-Munich, see Hummel 2005). This computation was invoked by the PSP results and used the measured pressure distributions to set up simulation parameters. The PIV results obtained later agree with the computed flow topology. The flow topology can be seen in Fig. 2 showing the measured pressured distribution on the model surface together with the measured velocity and vorticity distributions in planes of the different chord stations. In this case the flow separates at the leading edge at $x/c_r = 0.5$ and the primary vortex is formed, which produces a strong suction peak in the pressure distributions. However, another weaker suction peak can be detected more inboard with a highest peak height just downstream the origin of the outer primary vortex. The velocity distributions at x/c_r= 0.6 reveal that this suction peak is produced by another vortex co-rotating to the outer one. This vortex develops form a thin vortex structure which occurs more upstream close to the surface, i.e. x/c_r = 0.4. Instantaneous PIV results show (Konrath et al., 2006) that this vortex structure consists of several small co-rotating vortices spreading in the spanwise direction. The occurrence of the outer primary vortex leads to a vortex merging and a circular inner vortex is formed. More downstream the inner vortex gradually decreases in strength since vorticity is

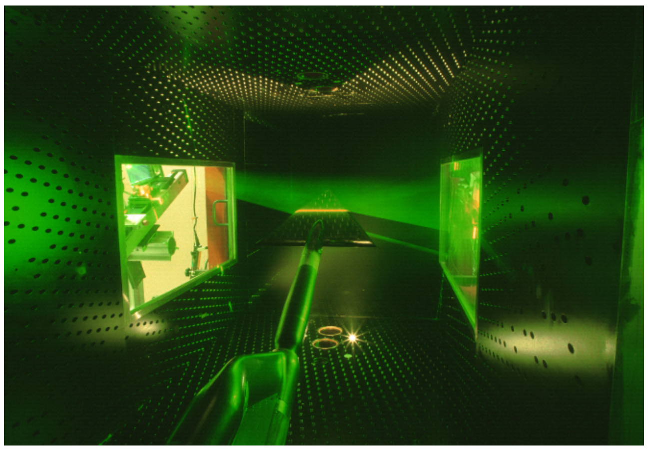

Fig. 1. Stereoscopic PIV arrangement inside the perforated test section of the transonic wind tunnel DNW-TWG showing the coated delta-wing and light sheet.

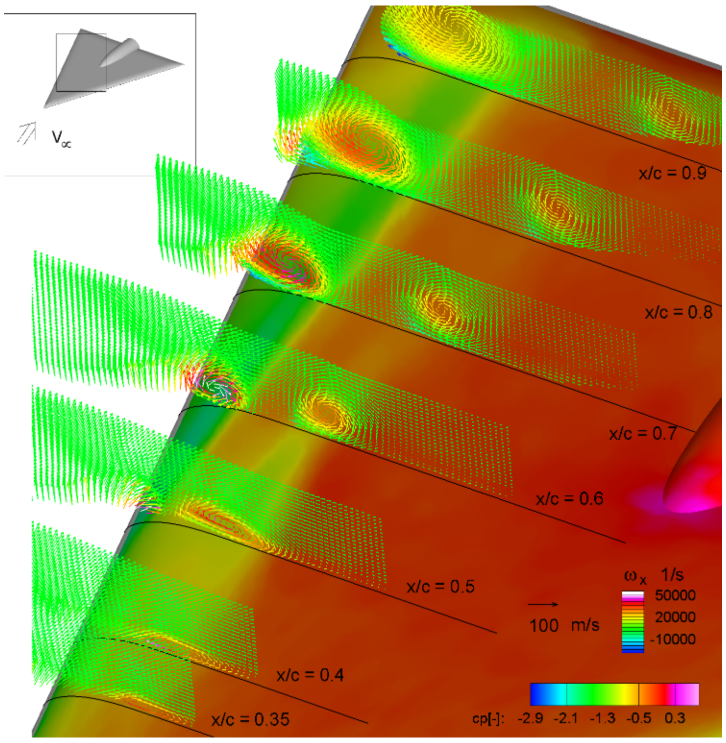

Fig. 2. Time averaged pressure, velocity and vorticity distributions above the delta wing with rounded leading edges for α = 13.3°, M = 0.4 and R = 3 million. The in-plane velocity vectors are plotted in different planes perpendicular to the delta wing axis. The color of the vectors corresponds to the out-of-plane vorticity. The colors at the surface are related to the local pressure coefficient.

fed only into the outer primary vortex.

The second example is related to the parallel application of **PIV and PDMS** (i.e. the measurement of the location and deformation of a model in the wind tunnel). The problem associated with all optical measurement techniques, where, in order to work non-intrusively, the illumination and recording equipment is located outside of the flow and of the test section of the wind tunnel, is that the exact location and deformation of the object under investigation needs to be know in order to relate the observation area of the image based measurement method to the real model co-ordinates. (Sensors attached to or embedded in the model (pressure probes, hot-wire sensors etc.) do not have this problem, but they will provide only information at a single point). In the same application as described above, the objective was to determine the actual angle of attack of the delta-wing in transonic flow (H. Frahnert in Kompenhans et al., 2006a). It was suspected that the inclination of the model increases under wind-load. The evaluation was carried out in conjunction with the PIV-measurement at Ma = 0.4 and Ma = 0.8.

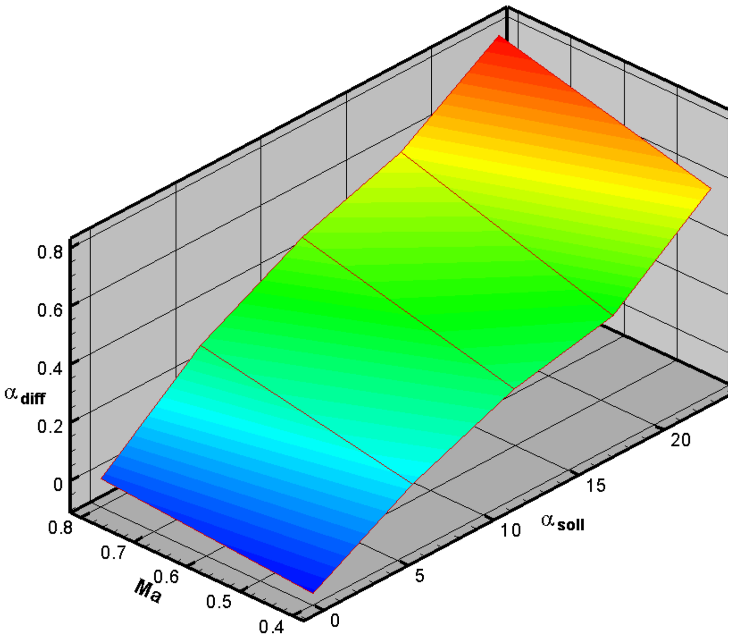

Fig. 3. Deviation of real angle of attack from the nominal angle of attack as function of Mach number and nominal angle of attack.

In order to solve this task, markers for position detection have been applied to the lower side of the delta wing. They have been recorded with two cameras looking through the floor of the test-section (circular windows in Fig. 1). Comparison of the nominal angle of attack – as adjusted with the model support – and the measured one shows a systematic deviation with increasing Mach-number and angle of attack. The analysis (Fig. 3) reveals that the actual angle of attack is up to 0.8° higher than the nominal one (at the highest wind-load at Ma = 0.8 and a nominal angle alpha$_{\text{soll}}$ = 24°).

The last example deals with the parallel application of **PIV and the Acoustic Microphone Array Technique**. As jet engines of modern aircraft become much quieter airframe noise will become more recognizable, especially at take-off and landing of the airplane. The reduction of airframe noise and especially of its high-lift devices, which are required in these phases of the flight, is therefore an important goal of the next decade. Käpernick et al. (2005) have carried out investigations of the unsteady flow field inside a leading edge slat cove of a generic swept constant chord half model (SCCH) by means of the standard PIV technique. Figure 4 shows the instantaneous velocity field inside the slat cove for α = 12° and U_∞= 30 m/s. A free shear layer emanates from the slat cusp, becomes unstable and breaks up into discrete vortices. From such data it is possible to calculate the two-dimensional distribution of the sound source term q via an acoustic analogy (for details see Käpernick et al., 2005). An important issue for further investigations is how to relate these sound sources in the flow to the noise as detected from the far field, for example by means of the Acoustic Microphone Array Technique (Fig. 5). Such problems will be subject of major research efforts employing the Acoustic Microphone Array Technique, high speed PIV and the numerical methods of Computational Aeroacoustics (CAA) in future investigations.

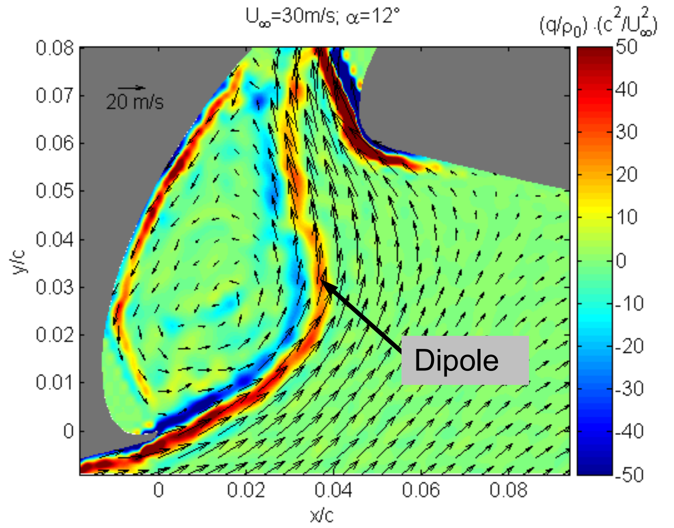

Fig. 4. Instantaneous distribution of normalized sound sources in the flow field within the slat cove.

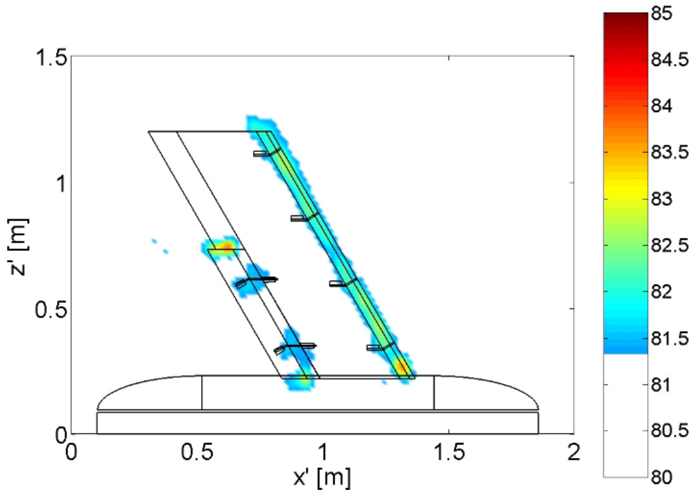

Fig. 5. Slat noise at α = 8°, u_∞ = 30 m/s, f_m = 5000 Hz as detected from the far-field by means of the Acoustic Microphone Array Technique.

3. Conclusions

Optical and acoustical field measurement techniques made great progress during the last two decades, mainly due to technological developments. Many of these techniques are now ready to be used as a matter of routine for applications at industrial problems in large test facilities. In future the combined use of such experimental techniques will allow multi-diagnostics of complex unsteady flow fields in order to gain a much better understanding of such phenomena which become more and more important to solve the environmental challenges of the next two decades when noise, pollution and energy consumption of aircraft need to be reduced considerably.

Journals such as the Journal of Visualization form an important element in the chain of transfer of ideas and knowledge of flow visualization techniques from university laboratories to industrial test facilities. Thus, its contribution to this transfer process is greatly appreciated and expected to be of even greater value to industrial end users of flow visualization techniques in the next decades.

References

Hummel D., The Second International Vortex Flow Experiment (VFE-2) - Objectives and First Results, Proceedings of the 2nd International Symposium on Integrating CFD and Experiments in Aerodynamics, Cranfield University (Shrivenham), UK, (2005), 1-12.

Käpernick, K., Koop, L. and Ehrenfried, K., Investigation of the unsteady flow field inside a leading edge slat cove, Proceedings of the 11th AIAA/CEAS Aeroacoustics Conference (Monterey, California, USA), (2005), 1-16.

Kompenhans, J. Agocs, J., Egami, Y., Engler, R., Fey, U., Frahnert, H., de Groot, K., Henne, U., Kirmse, T., Klein, C., Klinge, F., Konrath, R., Koop, L., Mattner, H., Otter, D., Pallek, D., Sachs, W., Schröder, A. and Stasicki, B., Recent developments of image based measurement methods for application to transonic flows in industrial wind tunnels, Chinese Journal of Aeronautics, 19 (2006a), 115-125.

Kompenhans, J. et al., Website of Department of Experimental Methods, Institute of Aerodynamics and Flow Technology, German Aerospace center, (2006b), http://www.dlr.de/as.

Konrath, R., Klein, C., Schröder, A. and Kompenhans, J., Combined application of Pressure Sensitive Paint and Particle Image Velecimetry to the flow above a delta wing, Proceedings of. 12th International Symposium on Flow Visualization, (Göttingen, Germany), (2006), ISFV12-67.2., ISBN 0.9533991-8-4.

Author Profile

Jürgen Kompenhans: He received his doctor´s degree in physics in 1977 from the Georg-August University of Göttingen. Since 30 years he is working for DLR in Göttingen, Germany, mainly developing and applying non-intrusive measurement techniques for aerodynamic research. At present he is head of the Department of Experimental Methods of DLR's Institute of Aerodynamics and Flow Technology. Within this department image based methods such as Pressure Sensitive Paint, Temperature Sensitive Paint, Particle Image Velocimetry, model deformation measurement techniques, density measurement techniques, acoustic field measurement techniques etc. are developed for application as mobile systems in large industrial wind tunnels.