24 Th EUROPEAN ROTORCRAFT FORUM
Marseilles, France - 15th-17th September 1998

TE 08

Advanced flow velocity field metrology and their application to helicopter aerodynamics

M. Raffel, T. Dewhirst, B. Bretthauer, H.Vollmers

DLR, Institut für Strömungsmechanik
Bunsenstraße 10, D-37073 Göttingen, Germany

Particle image velocimetry (PIV) is increasingly used to investigate unsteady velocity fields instantaneously. PIV allows the recording of a complete velocity field in a plane of the flow within a few microseconds. It thereby provides information about unsteady flow fields which is difficult to obtain with other experimental techniques. The short acquisition times and fast availability of data reduce the operational time and hence cost in large-scale wind tunnels and test facilities. This is especially interesting for investigations related to noise emission of helicopters, which become more and more important, and for studies related to adaptive blade profiles. The induced velocities of the blade tip vorticies, the vortex strength, and miss-distance relative to the advancing rotor blades are object of many wind tunnel investigations. Measurements of local flow vectors at positions close to the rotor blade tips were performed in the Large Low-speed wind tunnel Facility (LLF) of the German-Dutch Wind tunnel (DNW). Aditionally, measurements on pitching airfoils including adaptive techniques are presented and discussed. These tests were conducted in DNW's transonic wind tunnel (TWG) in Göttingen.

1. INTRODUCTION

With increasing use of civil helicopters the problem of noise emission of helicopters became more and more important within the last decade. Therefore, helicopter noise has been subject of many research projects (Lowson 1991). Blade Vortex Interactions (BVI) are known as a major source of impulsive noise. As BVI-noise is governed by the induced velocites of tip vorticies, it depends on vortex strength and miss-distance, which itself depends on vortex location and orientation and convection speed relative to the path of the advancing blade. The study of these phenomena is of particular interest for progress towards quieter helicopters. Such vortical structures at a helicopter rotor model in a wind tunnel have been studied by optical measurement techniques, since only non-intrusive techniques are capable to obtain velocity data within the rotor plane. Particle image Velocimetry (PIV) is a promising non-intrusive optical flow field measurement technique, which requires no conditional sampling for the investigation of unsteady flow phenomena. This technique allows to capture the flow velocity in a two-dimensional plane of the flow within a few microseconds. It enables to obtain complete velocity field data even in case of large cycle to cycle variations. The fact, that the measuring time, necessary for the application of PIV is small (≈12µs) compared to the time required for one revolution cycle (≈40.000µs) makes PIV a useful tool for the investigation of flow fields of rotor systems.

2. 3D-PIV MEASUREMENTS OF HELICOPTER TIP VORTICES IN A LARGE LOW-SPEED WIND TUNNEL

Measurements of the flow velocity without additional knowledge about quantities such as pressure and density are rarely conclusive. Therefore, more detailed investigations employing PIV, surface pressure and accoustic measurements at an 1:4 scaled rotor are planed in the large low-speed facility (LLF) of DNW. Very detailed studies of the feasibility of PIV rotor measurements in this large scale facility must be made because of the special problems encountered in such a facility e.g. long observation distance, seeding problems, and the robustness and remote control capabilities of the systems.

2.1 Seeding

The most common seeding particles for PIV investigations of air flows are oil droplets with a diameter in the micron region. These particles are typically generated by means of a Laskin nozzle into which pressurised air is fed, the nozzles being immersed in either olive oil or DEHS (Di-2-Ethylhexyl-Sebacat). In order to allow repeatable seeding of large areas a large number of Laskin nozzles must be used, with the particles subsequently being introduced into the flow in such a manner that the flow is not significantly altered while at the same time a homogenous isotropic seeding is obtained.

Due to the size of the region of interest which was to be seeded, three seeding generators, each containing fourty Laskin nozzles, were used. Each generator consists of a closed cylindrical container with five air inlets and one aerosol outlet. A horizontal circular impactor plate is placed inside the container, with a small gap of about 2mm being left between the edge of the impactor plate and the inside wall of the container. Compressed air with a pressure of between 0.5 and 1.5 bar is applied to the inputs, creating air bubbles within the seeding fluid. The shear stress induced by tiny sonic jets creates small droplets which are then carried towards the suface of the seeding fluid inside air bubbles. The larger particles are stopped by the impactor plate while the smaller seeding particles are passed through the gap reaching the aerosol output. The particle concentration can obviously be changed by altering the number of inlets which are operational in each generator. The mean size of the particles which are formed is highly dependent on the seeding fluid used, however only slightly dependent on the applied air pressure. The resulting mean particle diameter when using DEHS or olive oil is approximately 1μm.

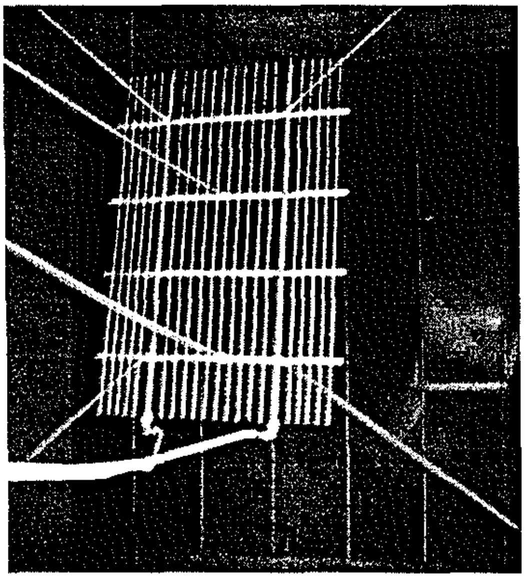

Figure 1: Seeding rake installed in settling chamber

Once the particles have been generated they have to be introduced into the flow; this can be done by either globally seeding the windtunnel if the facility is closed loop in design, or by injection into a small stream tube at the correct location. In the LLF the seeding was introduced locally. As the existing tubulence in many test facilities is not sufficiently strong to allow thorough mixing of the seeding the particles have to be supplied through a large number of points in the flow (see Figure 1). Distributor rakes are used to supply the seeding particles to the correct location in the flow. The rake used contains of the order of a few hundred holes and is 2.5 x 2m . The seeding rake was placed in the setting chamber upstream of the honeycombs and screens of the low speed wind tunnel. The rake was also mounted on a remote controled traverse which allowed the location of the seeding to be moved during the measurements. As the settling chamber of the LLF is 18 x 24m this is an important factor in allowing the measurements to be conducted in a minimum amount of time, allowing the optimisation of the seeding in real time and thereby improving the quality of the PIV recordings while also reducing the wind tunnel operational costs.

2.2 Recording

In spite of all its advantages, the PIV method underlies some shortcomings that make further developments on the basis of instrumentation necessary. One of these disadvantages is the fact that the 'classical' PIV method is only capable of recording the two-dimensional projection of the velocity vector. A variety of approaches capable of recovering the complete set of velocity components have been described in the literature (Hinsch 1995, Royer and Stanislas 1996). The mot straightforward method is perhaps that of stereoscopic PIV (Westerweel and Nieuwstadt 1991, Prasad and Adrian 1993, Gaydon *et. al.* 1997), whereby a second PIV recording is made at a different viewing axis. This technique can also be carried out with a single camera with suitable modification(Arroyo and Greated 1991), however most measurement configurations employ two seperate cameras.

To adapt the stereoscopic approach to an industrial wind tunnel environment a number of additional developments are necessary. First of all the optical access in wind tunnels rarely permits the imaging configuration to be symmetric as given in all of the previous implementations. Another requirement is that the small seeding particles, typically in the 1μm range, have to be imaged over large distances exceeding 9 meters. This makes the use of large focal length lenses with large light collecting capability (i.e. small f#-numbers) necessary. As the measurement precision of the out-of-plane component increases as the opening angle between the two cameras reaches 90 degrees, it is not always possible to mount the cameras onto a common base, much less to provide a symmetric arrangement. Because the location of the cameras is usually in an area with restricted access while the wind tunnel is operating, the remote control of the focus of the cameras is essential. This is achieved by a simple system powered by a small DC motor. The control of the motor can be operated from the central control point, allowing the focus to be optimised while the wind tunnel is in operation.

In the following paragraphs a description of the general non-symmetric stereoscopic PIV imaging system developed by DLR Göttingen is given. The measurements were carried out in the DNW-LLF (Deutsch-Niederländischer Windkanal, Large Low-speed Facility) on a rotorcraft model. The measurements were designed to investigate the unsteady flow field of the rotorcraft model blade tip vortex.

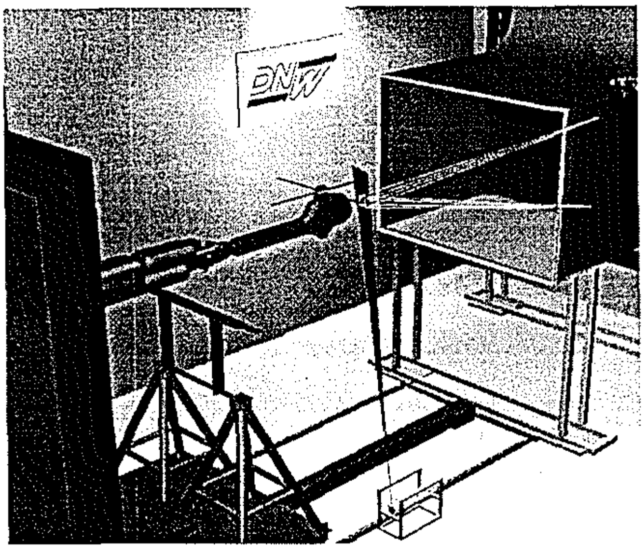

Figure 2: Experimental arrangement of the stereoscopic PIV measurement of a helicopter rotor flow in the large wind tunnel of DNW.

The measurement equipment was arranged as shown in Figure 2. The two recording cameras were located on the side of the nozzle of the open jet test section, and were placed in a vertical plane intersecting the observation area. The angle between the the Camera axes and the normal of the observation area was approximately 12°. The experimental configuration used two sensitive (12-bit A/D converter, cooled sensor) and high spatial resolution (1300x1000 pixels) CCD Cameras to image the experimental region of interest, an area approximately 25 x 30 cm over 9.5 m from each camera. The cameras were of the interline transfer type, and so allowed two images to be captured with a short interframe separation (Vogt *et al.* 1996). The interface between camera and optics was achieved with a specially designed Scheimflug adapter, allowing the CCD arrays to be tilted thereby allowing all particles across the field of view to remain in focus. While this does introduce a distortion into the image, this distortion can be removed by carefully pre-processing the images (Willert, 1997).

Analysing the images with a 32x32 pixel interrogation area yields a spatial resolution of about 30x40 vectors, a density similar to that of 35mm photographic film (Willert 1996). As the output from the cameras is non-standard, the data had to be transfered to a computer which interfaced with the cameras by means of a dedicated frame acquisition card. The inter-connection between the cameras and computers was achieved by fibre optic link which allowed the cameras to be placed a long distance from the data acquisition computers and also allowed very effective isolation from electrical noise present in the wind tunnel.

2.3 Illumination

The region of interest was illuminated by two frequency doubled pulsed Nd:YAG lasers driven at a repitition rate of 10Hz. As two independent oscillators were used the time separation between the illuminating pulses could be altered freely without changing the pulse energies. The pulse energy at λ=532nm was 2 x 320mJ. PIV measurements over long distances not only requires powerful lasers but also excellent spatial intensity distribution characteristics, co-linearity, beam Poynting vector stability (< 100µrad) and energy stability (<5%). The lasers used were Quantel Brilliant 'B'. To obtain a thick light sheet (by PIV standards), with a thickness of typically 10mm, the laser beam was passed through a number of coated spherical and cylindrical lenses, the arrangement of which allowed for the easy manipulation of the light sheet width and thickness independently of each other. The thick lightsheet is required due to the lightsheet normal being parallel to the main flow velocity. The recording parameters were optimised such that the particle displacement normal to the light sheet was between 3 and 4mm while the maximum in-plane displacement was of the order of 3mm. With the observation area of 25 x 30cm this translates to a displacement of 10 pixels, providing a dynamic range of at least 100 (the noise level in the recovered displacement data is of the order of 0.1-0.005 pixel). To allow the laser to be optimised while the tunnel was running, the adjustment screws of the second harmonic generators were connected to two small independent DC motors, allowing the phase matching to be done from the control room. The triggering of all components of the measurement system were carried out by a micro-processor controlled sequencer which allowed the lasers to be run at 10Hz while only acquiring images when the rotor was at a pre-defined azimuthal angle.

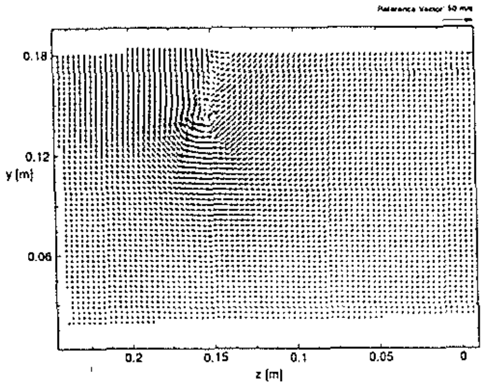

Figure 3a: In plane velocity components of the tip vortex and the wake of the blade (both Figures 2a and 2b have been rotated by 90° anticlockwise with respect to Figure 1)

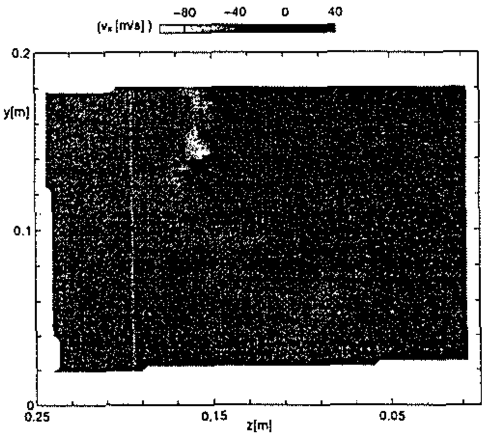

Figure 3b: Out-of-plane velocity components

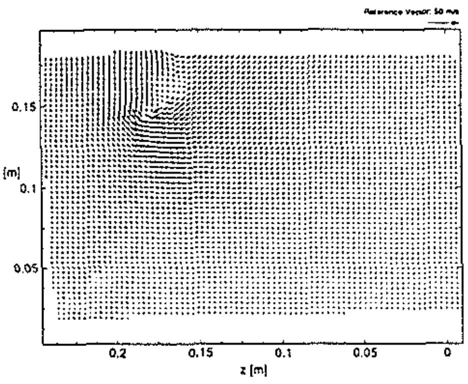

Figure 4a: In plane velocity components of the tip vortex and the wake of the blade (both Figures 3a and 3b have been rotated by 90° anticlockwise with respect to Figure 1). The azimuthal angle during recording was 10° larger than in Figure 2.

Figures 3 and 4 show some of the resulting vector maps from this measurement. The vector maps were taken at different azimuthal angles and it can be seen that there are clear differences in the maps. The rotor blade tip, which had just passed the observation area in the out-of-plane direction when the recordings were made, had given rise to the vortices present in the velocity vector maps. The out-of-plane velocity component (shown greyscale coded) shows strong spatial gradients between the wake of the blade and the tip vortex centre.

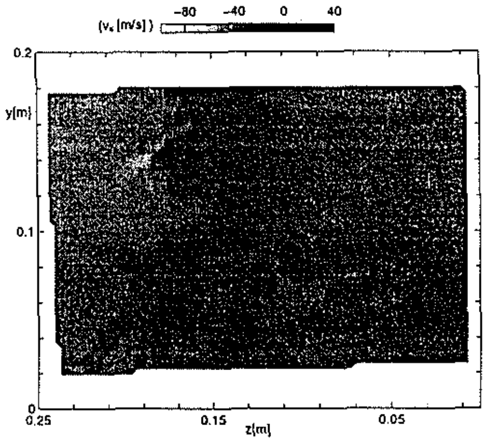

Figure 4b: Out-of-plane velocity components

3. HIGH RESOLUTION FLOW FIELD MAPPING ON AN ADAPTIVE HELICOPTER BLADE MODEL

Another area in which PIV measurements can prove useful is in the optimisation of adaptive rotor blades. Adaptive helicopter rotor blades are assumed to be one of the key technologies for helicopter performance enhancement in the coming decade. In a national project (AROSYS), the German industry (ECD and Daimler Benz Forschung) and the German Aerospace Research Establishment (DLR) have combined their efforts to reach reliable solutions for adaptive rotor systems. One of the first promising results was a piezoelectric actuator small enough to be integrated into a full scale rotor blade, and strong enough to drive a servo flap at the trailing edge of the outer blade area (see Figure 5). Since performance estimations and blade profile optimisations can effectively be obtained by instationary Navier-Stokes simulations (see e.g. Wernert *et al.* 1996) there is a great interest in validating these codes and to subsequently apply then to adaptive blade geometries and concepts.

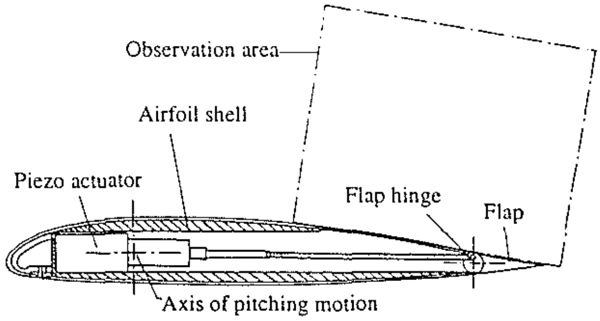

Figure 5: Helicopter blade model and observation area

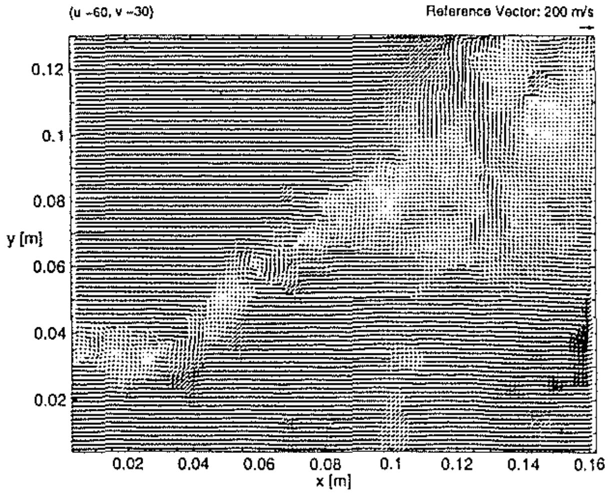

Figure 6a: Instantaneous flow velocity field above the adaptive blade at a Mach number of 0.33, pitching at 7 Hz (14.5° +/- 5°), with a flap motion of 14 Hz, +/- 3°.

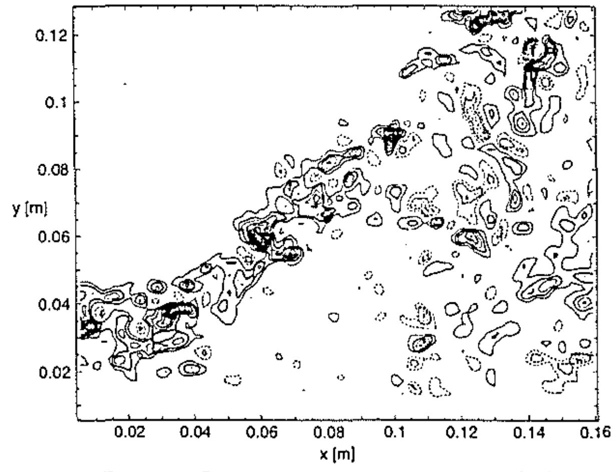

Figure 6b: Instantaneous out-of-plane component of vorticity computed from flow velocity data shown in figure 6a.

A wind tunnel test was recently performed in the transonic wind tunnel (TWG) in Göttingen in which forces, moments and surface pressure distributions were measured dynamically for different Mach numbers, pitching amplitudes and frequencies. The tests were performed at different flap frequencies and phase relations by the Institute for Aeroelasticity of DLR. In order to complete this information, PIV measurements of an area above the trailing edge flap, which was pitching in phase with the airfoil frequency, were performed.

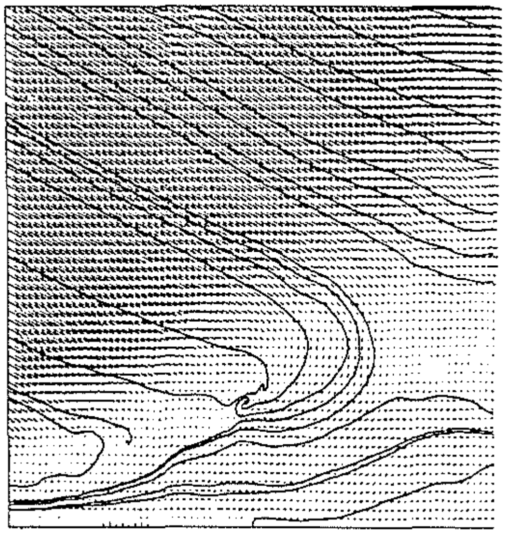

Figure 6c: Averaged flow velocity field above the adaptive blade with the same conditions as in Figure 6a. Stream lines are also shown.

These measurements were carried out using the same cooled, high resolution CCD camera employed in the previous sections. However, for this test a smaller laser system was employed, using again two independent oscillators running at a repitition rate of 10Hz, but with only 2 x 150mJ per pulse. Also, the light sheet forming optics were adjusted to provide a sheet thickness of between 2 and 3mm, as the out-of-plane component of the flow was not as strong as in the highly three dimensional previously reported.

First results of these measurements at a phase angle of 320° are shown in Figure 6a and its vorticity distributions in Figure 6b. A shear layer between the separated flow area and the mean flow and the influence of the dynamically pitching flap can be seen. Figure 6c shows the average velocity field with stream lines superimposed. The flap angle varied by +/- 3° at a frequency of 14 Hz and the airfoil was operated at a mean angle of attack of 14.5° with 5° amplitude at 7 Hz. Laser and camera were phase locked with the pitching motion at pre-selected phase angle. The chord length of the blade was 0.3 m, the span 1m. High quality schlieren windows gave excellent optical access to the perforated transonic test section of the tunnel. Due to the high camera resolution, the high seeding density and homogeneity, and improved correlation algorithms described by Ronneberger et al. (1998) up to 125 by 100 velocity vectors could be measured with an overlap of 50 %.

4. ANALYSIS

One difficulty often encountered in applying DPIV to air flows is that due to the small size of the seeding particles and the need for diffraction limited imaging, the particle images which are then present on the CCD array can be small in diameter. Once the particle image diameters become comparable in size to the „pixels" on the CCD array there is an increase in systematic error which results in the calculated displacements being biased towards integer values. This effect is generally referred to as „peak-locking". The effects of peak locking can be reduced by applying non-linear peak fitting algorithms to the correlation plane to extract the sub-pixel displacement. This work is currently the subject of investigation by, amongst others, Ronneberger (1998).

5. CONCLUSIONS

The application of DPIV in large windtunnels is always a challenge, especially if stereo measurements are to be made. The correct choice of equipment and the modification of it so that all parameters of the recording process can be optimised on-line allows this process to be streamlined, reducing the occupancy time of the tunnel while simultaneously improving the data yield of the PIV measurements.

The current development efforts regarding the DLR PIV systems are now focused on oblique as well as stereoscopic imaging arrangements. Aside from providing image access in areas that cannot be viewed in a classical PIV imaging configuration, the oblique viewing geometry can greatly improve the sensitivity of the system especially in a forward scattering configuration. Ultimately this also permits the imaged area to be increased without a need to further increase the laser power.

PIV continues to be a powerful and high quality flow measurement tool for the optimisation and investigation of helicopter aerodynamics.

ACKNOWLEDGEMENT

The tests in the transonic wind tunnel in Göttingen (TWG) were performed in the frame of the national AROSYS project. Special thanks to Dr. Schewe, Dr. Wendt, Dr. Schimke, and Mr. Jänker for the fruitful cooperation during the tests. The high motivation of the wind tunnel teams in LLF, and TWG is greatly appreciated.

REFERENCES

Arroyo M.P., Greated C.A., 1991:
Stereoscopic particle image velocimetry. Meas. Sci. Technol., Vol. 2, 1181-6

Gaydon M., Raffel M., Willert C., Rosengarten M. and Kompenhans J., 1997:
Hybrid stereoscopic particle image velocimetry. Exp. Fluids, Vol. 23, 331-334

Hinsch K.D. 1995:
Three-dimensional particle velocimetry
Meas. Sci. Technol., Vol 6, 742-53

Keane R. D., Adrian R. J., 1990:
Optimisation of particle image velocimeters. Part I: Double pulsed systems. Meas. Sci. Technol. Vol. 1, 1202-1215

Keane R. D., Adrian R. J., 1992:
Theory of cross-correlation analysis of PIV images. Appl. Sci. Res. 49, 191-215

Lowson M.V., 1991:
Progress towards quieter civil helicopters.
Proceedings of the 17th European Rotorcraft Forum, paper 91-59, Berlin, Germany.

Prasad A. K. and Adrian R. J., 1993:
Stereoscopic particle image velocimetry applied to liquid flows. Exp. Fluids, Vol. 15, 49-60

Raffel M., Seelhorst U., Willert C., Vollmers H., Bütefisch K. A., Kompenhans J., 1996:
Measurement os vortical structures on a helicopter rotor model in a wind tunnel by LDV abd PIV, Proc. 8th Intl. Symp. On Appl. Os Laser Techniques to Fluid Mechanics, Lisbon, paper 28.1

Ronneberger O., Raffel M., Kompenhans J., 1998:
Advanced evaluation algorithms for standard and dual plane particle image velocimetry. Proc. 9th Intl. Symp. On Appl. Os Laser Techniques to Fluid Mechanics, Lisbon, paper 10.1

Raffel M., Leitl B., Kompenhans J., 1993:
Data validation for particle image velocimetry, in 'Laser Techniques and Applications in Fluid Mechanics', Eds. Adrian R. J., *et. al.* Springer-Verlag, 210-226

Royer H. and Stanislas M., 1996:
Stereoscopic and holographic approaches to get the third velocity component in PIV
von Karman Institute for Fluid Dynamics, Lecture Series 1996-03, Particle Image Velocimetry

Vogt A., Baumann P., Gharib M., Kompenhans J., 1996:
Investigations of a wind tip vortex in air by means of DPIV. Proc. 19th AIAA Advanced Measurement and Ground Testing Technology, New Orleansm LA., 17-20th June 1996

Wernert P., Geißler W., Raffel M., Kompenhans J., 1996:
Experimental and numerical investigations of the dynamic stall process on a pitching NACA 0012 airfoil. AIAA Journal, Vol. 24 No. 5, 982-989

Westerweel, J. and Nieuwstadt F.T.M., 1991:
Performance tests on 3-dimensional velocity measurements with a two-camera digital particle image velocimeter. Laser Anemometry Advances and Applications, Vol. 1, ed. Dybbs A. and Ghorashi B. (New York: ASME) 349-355

Willert C., 1996:
The fully digital evaluation of photographic PIV recordings. Appl. Sci. Res., Vol. 56, 79-102

Willert C., 1997:
Stereoscopic digital particle image velocimetry for application in wind tunnel flows. Meas. Sci. Technol., Vol. 8 No. 12