Experimental aspects of PIV applied to a Bo 105 helicopter in hover-flight condition

M. Raffel, H. Richard, J. Agocs, D. Otter, H. Mattner, U. Göhmann

Abstract PIV experiments have been performed in order to derive quantitative flow velocity data of the blade tip vortex of a helicopter at full-scale. Due to relatively rough outdoor conditions e.g. to the helicopter induced wind, the ambient light, the large observation distances and changing winds, the seeding illumination and recording of this type of flow was challenging. This paper describes technical aspects of the measurement and presents first results.

1 Introduction

With increasing use of civil helicopters the problem of noise emission of helicopters has become increasingly important within the last decades. Helicopter noise has been subject of many research projects (Lowson 1991). Blade vortex interactions (BVI) have been identified as a major source of impulsive noise. As BVI-noise is governed by the induced velocities of tip vortices, it depends on vortex strength and miss-distance, which itself depends on vortex location, orientation, and convection speed relative to the path of the advancing blade. Blade vortex interaction can occur at different locations inside the rotor plane depending on flight velocity and orientation of the blade tip path plane. Since noise emission of parallel blade vortex interaction considerably depends on the vortex structure, Reynolds number effects have to be considered (Cardonne et al. 1988, Splettstößer et al. 1984, McCroskey 1995, Leishman and Bagai 1996). Investigations of the acoustic near and far-field (e.g. Ehrenfried et al. 1991, Burley et al. 1991) were based on the interaction of the blade with vortices, which were described by mathematical models. Experimentally obtained velocity information about the structure and strength of the real rotor tip vortices at full-scale and their interaction with the blade were hardly available even if remarkable efforts were taken in order to obtain flow field data at large scales (e.g. Splettstößer et al. 1995, Raffel et al. 1998). It is understood, that the study of these phenomena is of particular interest for progress towards quieter helicopters. In our investigations the vortex structures of a helicopter rotor have therefore been studied by conventional (two component) particle image velocimetry (PIV).

2 Helicopter and test condition

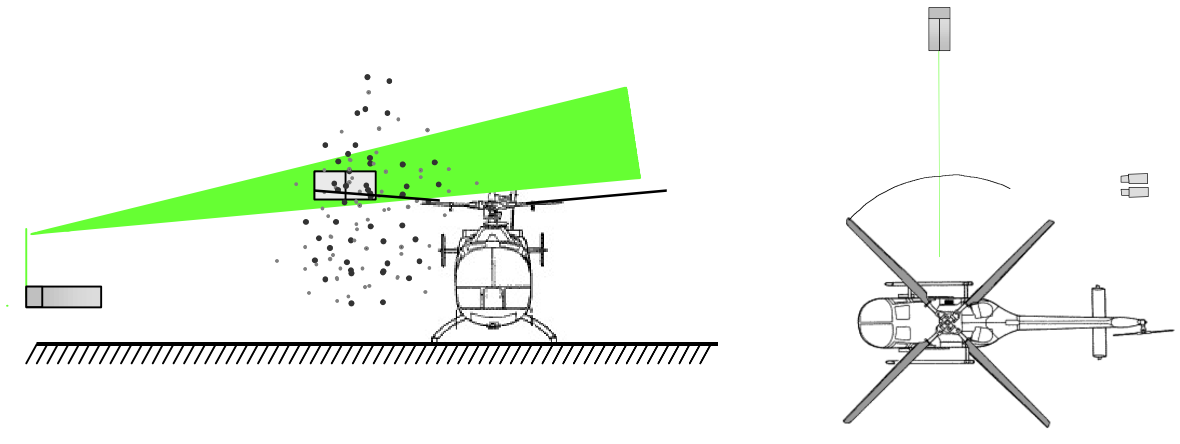

Figure 1: Sketch of the helicopter, light sheet and observation areas

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The helicopter used for the investigation is a MBB Bo 105 of the German aerospace establishment DLR in Braunschweig. It has a hingeless rotor (glass fiber reinforced blades) operating in counter-clockwise rotation (from above). The rotor has a diameter of 9.82 m according to a blade area of 5.25 m² and consists of four blades with 0.270 m chord length and rectangular tips. The airfoils have a NACA 23012 mod. Profile (with tab). During the test the helicopter was operated in hover condition generating a total lift of $2\ 10^3$ kg. The helicopter was bound to the ground in order to keep the rotor position constant with respect to the observation area. The rotor rotational frequency was 7.07 revs s^{-1} (424 rpm) leading to a tip speed of 218 m/s. The blade twist was -8° at this condition. Figure 2 shows the helicopter during the run.

Figure 2: The Bo 105 helicopter during test

3 Recording equipment

A pulsed Nd:YAG laser system with two independent oscillators has been utilized as light source. The laser has been driven at a repetition rate of 10 s^{-1}, the pulse energy at λ = 532 nm is typically 2 x 320 mJ. The available maximum pulse energy is an important parameter of the PIV system as it finally determines (together with the sensitivity of recording sensor) the minimum size of the tracer particles. The PIV measurements over long distances do not only require powerful lasers but also excellent characteristics of the spatial intensity distribution of the laser beam (hole-free without hot spots, especially in the midfield where it is most difficult to get), excellent co-linearity between the two beams of the two different oscillators and beam pointing stability (< 100 µrad).

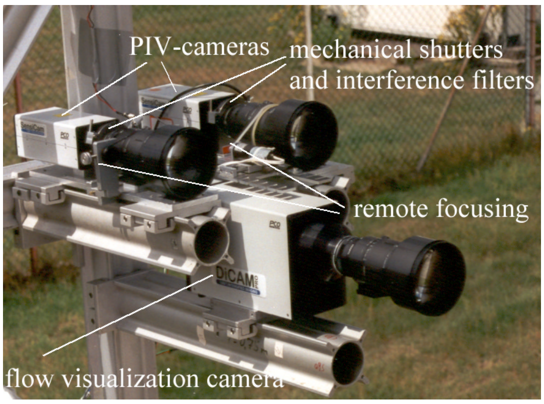

Figure 3: The recording cameras

For PIV recording video cameras incorporating progressive scan, full-frame interline CCD technology have become available recently, which, contrary to the more common interline transfer CCD sensors, are capable of shuttering (exposing) and storing the entire array of pixels, not just every other line. Thus, these sensors immediately offer the full vertical resolution when the CCD is used in the shuttered mode. Such 'cross correlation' cameras allow the first illumination pulse to be placed at the end of the first (full) frame and the second illumination pulse to be placed at the beginning of the second (full) frame (Vogt et al., 1996). Following this general approach, the present PIV camera systems additionally feature a non-standard, high resolution, digital video format consisting of 1024 by 1280 pixels. The advantage of these cameras is, that they have both a sufficiently high resolution and a sensor cooling which reduces the black current and increases the dynamic range to 12 bit. The gain in sensitivity is of the order of several f-numbers, allowing a much larger observation area with the same pulse laser. Using a 32^2 pixel interrogation window, the size of the CCD sensor translates to a spatial resolution of up to 32 by 40 discrete vectors. A fiber optic transmission link allows for very long distances between camera and frame grabber. The focusing of the cameras is remotely controlled. Two cameras, viewing perpendicular to the light sheet have been used in order to obtain a larger observation area. An additional camera, equipped with an image intensifier and an 85 mm lens, has been used in order to record the blade tip position and a gray level flow visualization image simultaneous with the PIV recordings. The PIV cameras had 300 mm lenses and were additionally equipped with interference filters (532 n m +/- 1 n m) and computer controlled mechanical shutters with and rise time of approximately 1 ms. Due to the limited availability of the helicopter we were not able to perform phase locked measurements.

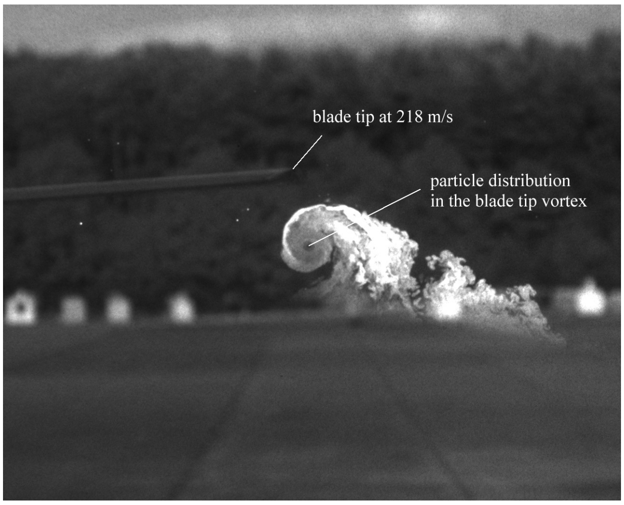

Figure 4: Typical recording of the blade tip and the vortex (PIV recordings have been taken simultaneously).

4 Flow seeding

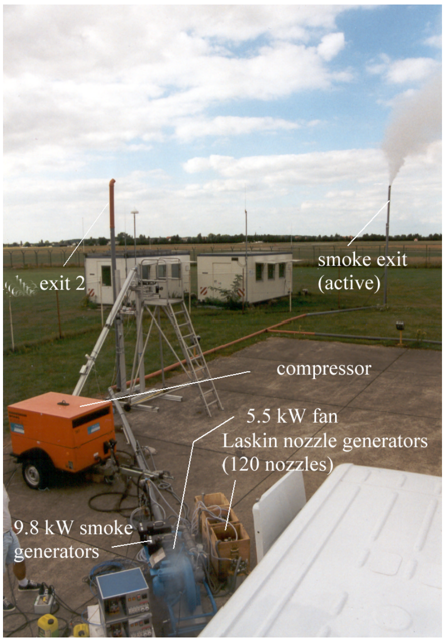

Figure 5: The seeding equipment

PIV requires tracer particles to determine the flow velocity indirectly from the velocity of the tracer particles. In order to obtain a set of velocity data without gaps, a high and uniform seeding density in the region of interest is required. According to statistical simulations, at least 10 pairs of particle images per interrogation window are required to apply statistical evaluation methods. This leads to a seeding density, which is equivalent to ≈ 5 particles/mm^3.This must also be achieved under practical conditions in regions where strong re-circulation or velocity gradients are present. The most common seeding particles for PIV investigation of gaseous flows are oil droplets which are generated by means of Laskin nozzles, see Echols and Young (1963). Each of such aerosol generators, which have been used for the test, contains 40 Laskin nozzles and produces oil particles with an aerodynamic diameter of about 1 μm. The amount of particles could be controlled by switching different valves at the nozzle inlets.

As already mentioned for complete velocity vector fields a uniform seeding is required. Figure 4 shows a part of a the rotor blade, 15° before the light sheet plane and the flow visualization of the tip vortex of the previous blade. The seeding inside the vortex was very homogeneous on most of the PIV recordings. However, an area with reduced seeding density due to the velocity lag of the tracer particles (an effect, which is integrated in the time from the vortex formation until the recording) and due to the reduced air density inside the vortex core can be observed. This reduced seeding density, together with the strong velocity gradients inside the vortex core, lead to data drop out in this part of the observation area.
The particles have been generated by four Laskin nozzle generators with 120 individual nozzles in total. They have been connected to an air compressor, which had a maximum mass flow rate 0.1 kg/s at 5 10^5 Pa. An electrical fan with 5.5 kW power has been used in order to transport the particle laden flow to different positions above the rotor disk. Depending on the wind, the exit locations have been changed in order to bring the particles to the observed rotor area. Additional four electrically driven smoke generators have been used in order to inspect the particle flow trajectory by eye. The most crucial part of the test was guiding the particles to the right position. A device allowing a remote controlled positioning of the seeding flow and a higher exit velocity should be chosen for future tests.

6 Preliminary results

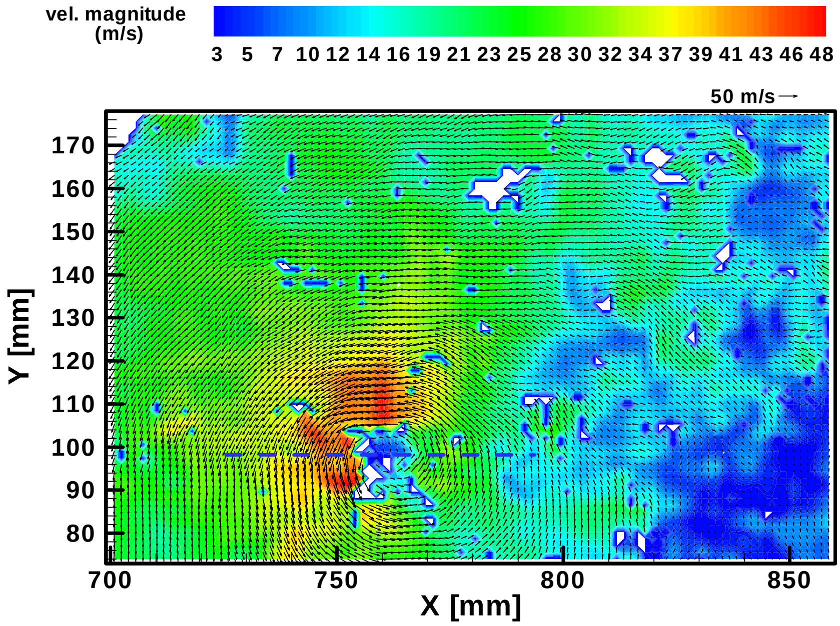

Figure 6: First result obtained by a 32 x 64 pixel FFT based standard evaluation (50% / 75% overlap in length)

PIV measurements of blade tip vortices were taken at an azimuth angle of $\psi \approx 90°$ on the advancing blade side. The observation area was nearly parallel to the trailing edge of the blade and orthogonal to the axis of the vortices. Figure 6 shows an instantaneous velocity vector field obtained at this angle. The tip vortex, which has just been generated (age ≈ 75°), was located at Y = -0.13 m, X = -0.15 m relative to the average blade tip position at $\psi \approx 90°$. In Figure 7 the tangential velocity profile of the tip vortex from the single PIV velocity data set shown in figure 6 has been plotted along a line through the vortex center.
From these data the vortex core diameter has been estimated to be approximately 5% of the blade chord. The maximum tangential velocities (approximately +/-35 m/s) are in the order of 16% of the tip speed. When taking optical magnification and pixel spacing into account, the sampling (interrogation) window (32 pixel x 64 pixel) for the evaluation had a size of 6.4 mm in radial (horizontal) direction and of 12.8 mm in tangential (vertical) direction. Therefore, the data points represent a spatial average over ~2.4% of the chord length corresponding to ~50% of the measured core radius. The interrogation step width of 16 pixel corresponds to roughly 5 data points inside the vortex. This parameters have been improved by an manual evaluation as described below.

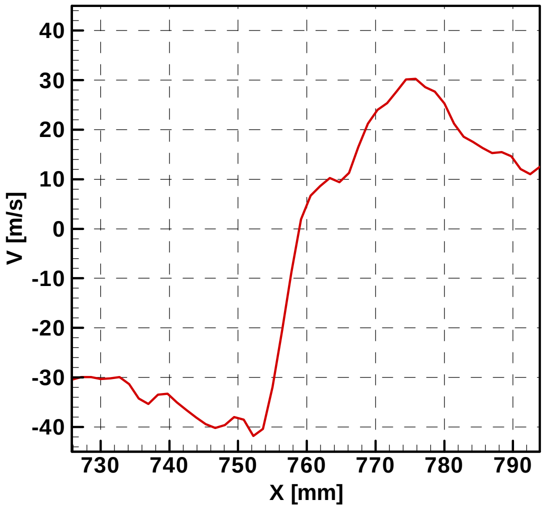

Figure 7: First result of the tangential velocity profile obtained from data shown in figure 6

However, this results are preliminary and were obtained by our "quick look software". Further efforts are undertaken in order to improve the evaluation with respect to accuracy and spatial resolution by the application of software allowing rotated interrogation windows. For the time being the best we could do was a carefully performed manual interrogation of the same data set with a smaller interrogation area in radial direction. The decreasing velocity inside the vortex core could not been measured due the strong gradients in this area and a reduced sharpness of the particle images (due to density gradients) and reduced intensity of the particle images (due to a reduced average size of the particles). The results of this interactive evaluation are given in table 1. By this evaluation slightly larger peak values and smaller core dimensions have been measured.

line direction	**coor-dinate**	U_{max}/U_{min} V_{max}/V_{min}	$U_{max}-U_{min}$ $V_{max}-V_{min}$	$X_{max}-X_{min}$ $Y_{max}-Y_{min}$	**"core - radius"**	**velocity gradient**	**sampling size radial**
horizontal cut	X	-38.3 m/s +35.6 m/s	73.9 m/s 34%	29.0 10^{-3}m	14.5 10^{-3}m 5.4%	2.55 10^{3} s^{-1}	3.2 10^{-3}m 1.19%
vertical cut	Y	-42.2 m/s +49.6 m/s	91.8 m/s 42.3%	24.2 10^{-3}m	12.1 10^{-3}m 4.5%	3.8 10^{3} s^{-1}	3.2 10^{-3}m 1.19%
normalized with			tip speed		chord length		chord length

Table 1: Results of interactive evaluation with 16 x 64 pixel (64 x 16 pixel) interrogation windows

7 Discussion

In spite of the difficult experimental conditions high quality PIV data were obtained with, at least some, spatial resolution. The two-component PIV measurements yielded to interesting results concerning the structure of the blade tip vortices. In addition to geometric parameters like location of the vortex relative to the rotor plane, the vortex core size, and velocity gradients have been derived. However, since conventional PIV measures only two velocity components, data, like the orientation of the vortex axis in space and axial velocity of a vortex, could not be derived without changing the viewing direction. In future, using the second camera in a stereoscopic arrangement would allow the measurement of all three velocity components without averaging data of different cycles.
Encouraged by the success in obtaining data under difficult conditions, we would like to improve the quality of future tests with respect to the following parameters:

- Spatial resolution. This could be obtained by improved PIV evaluation schemes for vortex flows and lenses with larger focal length. A more precise adjustment of the polarisation direction will then be needed, because of the critical scattering characteristics of the small particles inside the vortex core.

- Avoiding the ground effect or getting experimental data from model tests taken under similar conditions. Most of the numerical and experimental results, which have been published up to now, have been obtained without ground effects.
- Particle distribution. The particle distribution obtained was quite satisfying with respect to the homogeneity and scattering material inside the young vortex. However, getting the particles to the measurement volume was difficult and depending on wind.
- Phase locked measurements. Measurements which were phased locked with the rotor position have been taken during many PIV tests in the past. Since the helicopter offers a reference signal and the trigger electronic was readily programmed for such a measurement, we should be able to take advantage of this – next time.

8 References

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