High-speed PIV investigation of the flow created by the model rotor in hover mode

V F Kopiev, M Yu Zaytsev and V A Kopiev
Aeroacoustic Department, Central Aerohydrodynamic institute, Zhukovsky street 1, Zhukovsky city, 140180, Russia
Email: vkopiev@mktsagi.ru

Abstract. A study of the instantaneous and average velocity and vorticity fields in the flow created by the model helicopter rotor in the hover mode was carried out. The velocity fields of the flow generated by the model rotor were obtained by a two-dimensional TR PIV system, which provided two components of the velocity vector in the diagnostic light plane. The processing of the obtained raw images was carried out using a two-frame algorithm with adaptive interrogation windows. The experiments carried out have shown the possibility of using the PIV technique to visualize the tip vortex structure descending from the rotor blade. This possibility seems to be especially interesting as one of the means of validation of the numerical methods for calculating rotor aerodynamics and acoustics.

1. Introduction
The problem of helicopter noise is one of the key environmental issues affecting the increase in the intensity of flights near populated areas. In particular, blade-vortex interaction (BVI) noise during an approach is a major issue that needs to be addressed. BVI noise arises from the rapid change in pressure on the blade surface caused by the interaction of the tip vortex from the previous blade with the subsequent one. When analyzing BVI noise, it is necessary to accurately estimate the geometry of the propeller wake, as well as the vorticity of the tip vortex and the size of its core.

Early studies of the rotor flow field were conducted using qualitative flow visualization techniques and invasive probe techniques such as hot-wire anemometry and pressure transducers [1]. Since the early 1970s, non-invasive methods such as laser Doppler velocimetry (LDV) have been developed and applied for rotor measurement [2–3].

However, the need to measure instantaneous velocity over the large field of view has led to the development of particle imaging velocimetry (PIV). Since the late 1990s [4] PIV has become a modern method for measuring rotor flow field. Thanks to the use of instantaneous measurements over the entire plane, obtaining the characteristics of the unsteady flow has become experimentally possible. The first applications of PIV in helicopter wind tunnel tests were made in the early 1990s, and since then PIV has undergone rapid development (see recent reviews on subject in [5, 6]). The complexity of the flow around the helicopter rotor requires that numerical simulations be carried out in parallel with experimental studies. Despite recent advances in the development of numerical prediction capabilities for main rotor and tail rotor components, detailed experiments are required to
validate the results of comprehensive CFD/CAA studies and to gain a deeper understanding of helicopter noise generation mechanisms.

2. Experimental setup
In order to study blade tip vortex development of the helicopter main rotor in hover condition, velocity field measurements using two-component (2C) PIV were conducted. The studies were carried out for various rotational speeds (5805, 7463, 8292 and 9123 rpm). PIV measurements were conducted in anechoic acoustic chamber AC-2 simultaneously with acoustic measurements (figure 1). The scheme of the PIV experiment is shown in figure 2.

The main parameters of the model three-bladed rotor are as follows: the blades are composed of asymmetric profiles NACA-64 (1) -212, the rotor diameter $D_r = 400$ mm, the chord of the blade in the root section $b = 29$ mm, the number of blades 3, solidity $\sigma = 0.11$.

The integrated hard- and software complex FlowMaster HS-PIV from LaVision was used. The illumination source of the PIV setup consisted of a double oscillator, frequency-doubled Litron LDY300 Nd:Yag laser (with wavelength 532 nm, energy 20 mJ/pulse at repetition frequency 1 kHz). Light sheet forming optics with cylindrical lens ($F = 10$ mm) which were bolted above the rotor. The light plane was vertical and passed through the rotor axis. The waist thickness of the light plane in the field of view was 1–2 mm; the field of view was about 35x35 cm. The flow was seeded with Di-Ethyl-Hexyl-Sebacat (DEHS) tracer particles with a mean particle diameter about 1 μm. To deliver the tracers to the rotor area, a slow airflow at a velocity of about 4 m/s. was used through a nozzle with a diameter of 60 cm. Particle images were recorded using Photron High Speed Star 8 CMOS camera (1024x1024 pixel 2, 12 bit, pixel size 20 μm), placed at 1.2 m distance from the measurement plane. The camera was equipped with Nikon $f = 50$ mm lens.

Figure 3 shows a frame of the seeded flow high-speed shooting at a rotor rotation speed 5800 rpm. The flow direction is from right to left. The coordinate origin of $s$ (point (0,0) in figure 2), hereinafter, corresponds to the blade base. This point is located at distance of 3 cm from the rotation axis.
Registration frequency was 500 pairs of frames per second. The time delay between the two laser pulses was $dt = 200 \mu s$. It was chosen in accordance with the rule of 1/4 the size of the initial interrogation window, with expected flow velocities of the order of 25 m/s.

3. PIV results

PIV raw image processing was performed using a double-frame cross-correlation multipass algorithm with adaptive interrogation window which was realized in software package DaVis 10.1 (LaVision FlowMaster Software DaVis 10.1).

The vorticity field calculation included three main stages: the raw images filtering, velocity field calculating using the multi-pass algorithm with variable interrogation windows, and vorticity calculating behind the propeller blade (figure 4). The raw image filtering necessity was caused by significant intense non-stationary reflections and spurious illumination induced by the rotating parts of the model. Instantaneous velocity fields were calculated using multypass iterative cross-correlation algorithm with final adaptive interrogation window size of $16 \times 16$ pix 2 with 75% overlap, providing a final flow field resolution of 2 mm. Spurious vectors were removed using a local median filter.

Figure 2. Sketch of PIV measurement (view from above).

Figure 3. Visualization of the flow created by the rotor.
The vorticity field was calculated using the method of phase averaging, similar to the stroboscopic imaging technique. This allowed us to separate a blade tip vortices from the turbulent pulsations. Figure 5 shows the vorticity z-component fields for four investigated velocity of rotor rotation. The flow direction is from right to left.

Figure 4. The list of processing operations.

Figure 5. Isolines of vorticity z-component for four different rotation frequencies: 5805 rpm (a), 7464 rpm (b), 8292 rpm (c), 9123 rpm (d).
One can see from figure 5 that, the performed experiments showed the possibility to visualize the vortex structure shedding from the blade tip. In the visualization plane (laser plane), the blade tip passes through the point with coordinates (0, 170), this point corresponds to the vortex wake origin in the visualization plane.

Figure 6 shows the transverse profiles of the axial velocity component (along the vertical axis) of the flow generated by the rotor at different rotation frequencies. For convenience of comparison, all graphs are shown on the same scale. Zero on the horizontal axis corresponds to the base of the blade (blade length is 17 cm). The profiles are given for three distances from the rotor rotation plane, see figure caption. As can be seen from the graphs, with rotational velocity increase from 5805 rpm to 9123 rpm lead to longitudinal velocity increase about ~ 25% (see figure 7).

4. Conclusion
Thus, the performed research showed the ability of the 2D HS-PIV complex from LaVision to visualize the blade tip vortices. This possibility is particularly interesting as one of the means of validating the numerical methods for calculating various rotors that have been actively developed in recent years. It also seems very useful and advisable to conduct further research in this area using the PIV methodology. It is supposed to conduct experiments on a larger scale model, for different modes...
of rotor operation, as well as with different orientations of the diagnostic plane relative to the rotor blades.

![Graph showing variation of axial velocity for different rotor frequencies.](image)

**Figure 7.** Variation of axial velocity for different rotor frequencies.

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**References**

[1] Harris FD 1973 Aerodynamic and dynamic rotary wing model testing in wind tunnels and other facilities *Helicopter Aerodynamics and Dynamics*, AGARD LS-63

[2] Scully M and Sullivan J P 1972 *Helicopter Rotor Wake Geometry and Airloads and Development of Laser Doppler Velocimeter for Use in Helicopter Rotor Wakes* MIT Aerophysics Laboratory AD-752628

[3] Boutier A, Lefèvre J B and Micheli F 1996 Analysis of helicopter blade vortex structure by laser velocimetry *Exp. Fluids* 21 33–42 https://doi.org/10.1007/BF00204633

[4] Raffel M, Willert C and Kompenhans J 1998 *Particle image velocimetry* Springer Verlag, Berlin, Heidelberg, Germany

[5] Raffel M, Bauknecht A, Ramasamy M., Yamauchi G K and Heineck J T and Jenkins L N 2017 Contributions of particle image velocimetry to helicopter aerodynamics *AIAA Journal* 55(9) 2859–74 doi:10.2514/1.j055571

[6] Gardner A D, Wolf C C and Raffel M 2019 Review of measurement techniques for unsteady helicopter rotor flows *Progress in Aerospace Sciences* 111 https://doi.org/10.1016/j.paerosci.2019.100566