Analysis of helicopter blade vortex structure by laser velocimetry

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Abstract In descent flight, helicopter external noise is mainly generated by the Blade Vortex Interaction (BVI). To understand the dynamics of this phenomenon, the vortex must be characterized before its interaction with the blade, which means that its viscous core radius, its strength and its distance to the blade have to be determined by non-intrusive measurement techniques. As part of the HART program (Higher Harmonic Control Aeroacoustic Rotor Test, jointly conducted by US Army, NASA, DLR, DNW and ONERA), a series of tests have been made in the German Dutch Wind Tunnel (DNW) on a helicopter rotor with 2 m long blades, rotating at 1040 rpm; several flight configurations, with an advance ratio of 0.15 and a shaft angle of 5.3°, have been studied with different higher harmonic blade pitch angles superposed on the conventional one (corresponding to the baseline case). The flow on the retreating side has been analyzed with an especially designed 3D laser velocimeter, and, simultaneously, the blade tip attitude has been determined in order to get the blade-vortex miss distance, which is a crucial parameter in the noise reduction.

A 3D laser velocimeter, in backscatter mode with a working distance of 5 m, was installed on a platform 9 m high, and flow seeding with submicron incense smoke was achieved in the settling chamber using a remotely controlled displacement device. Acquisition of instantaneous velocity vectors by an IFA 750 yielded mean velocity and turbulence maps across the vortex as well as the vortex position, intensity and viscous radius. The blade tip attitude (altitude, jitter, angle of incidence) was recorded by the TART method (Target Attitude in Real Time) which makes use of a CCD camera on which is formed the image of two retroreflecting targets attached to the blade tip and lighted by a flash lamp. In addition to the mean values of the aforementioned quantities, spectra of their fluctuations have been established up to 8 Hz.

1 Introduction

The helicopter, due to its excellent hover and low speed flight capabilities, is well suited for missions requiring take off and landing in areas inaccessible by other vehicles. However in these flight conditions, the most important disadvantage comes from the high external noise level, generated when rotor blades interact with the tip vortices shed by the preceding blades. This high noise level leads to the flight interdiction of helicopter over towns or to a traffic limitation.

The reduction of this phenomenon, known as Blade Vortex Interaction (BVI) noise, has required a better insight into the mechanisms which create it. It was shown that the BVI noise intensity strongly depends on the vortex strength as well as the blade-vortex miss distance, parameters which can be influenced by superposing a higher harmonic blade pitch angle on to the conventional one: this process is called Higher Harmonic Control (HHC) (Spiegel et al. 1992).

The HART (HHC Aeroacoustic Rotor Test) programme (Gmelin et al. 1995) has been jointly conducted by US Army, NASA, DLR, DNW and ONERA in order to improve physical understanding and modelling of the HHC effects on BVI noise and vibration generation by means of theoretical and experimental studies.

Various experimental studies were performed in DNW (German Dutch Wind Tunnel, Emmeloord, The Netherlands) (Kube et al. 1994); however this paper will particularly focus on the way the flowfield has been characterized in details by ONERA on the retreating side, using laser velocimetry in connection with the TART method (Target Attitude in Real Time) which sampled at each turn the blade tip attitude. These non intrusive optical methods allow an accurate description of the vortex before it interacts with the blade (vortex core radius, vortex strength), as well as vortex location relative to the blade in flight (blade-vortex miss distance); all these parameters are fundamental in noise generation and reduction. Three flight configurations have been mainly studied, with an advance ratio of 0.15 and a shaft angle of 5.3°, in order to understand the involved phenomena: a baseline case, a second case with an HHC adjustment for which noise is minimized, and a third case where vibrations are minimized (but noise is unfortunately increased).

The experimental environment at DNW, due to the size of the facility, presented a series of specific difficulties which were
overcome by developing dedicated instruments and new measuring procedures which are reported in this paper. This technical challenge has contributed to the extension of the application domain of laser velocimetry to very large scale industrial facilities. Preliminary data processing was done very often in quasi real time in order to check the vortex location in the measured field; then a complete data reduction was achieved, taking into account both velocity fields and blade position measurements.

2 Experimental environment

The experimental difficulties mainly come from the large sizes of the facility and of the rotor model; in fact the same spatial resolution as in smaller facilities is required. This is the first time that such optical techniques have been implemented in DNW. Moreover since the flow is periodic, stroboscopic measurements must be used, leading to long data acquisition times which must be minimized.

The model of the helicopter rotor (provided by DLR) is attached to the DNW sting mechanism in the open jet test section (10 x 8 m²); the blade is 2 m long, its chord is 120 mm wide, the rotation speed is set at 1040 rpm. The rotor plane is at a height of nearly 10 m relative to the ground. Since the vortex core must be evaluated to a fraction of a chord, a field of a few hundred mm² must be accurately analyzed at an altitude of 10 m relative to the ground, i.e. at blade level. Optical and mechanical setups must be installed outside the main flow, which requires a working distance of 5 m.

To measure the highly three dimensional flow, a 3D laser velocimeter was installed on a platform 9 m high; its emitting optics must create a small probe volume (400 µm in diameter as usually in smaller wind tunnels, in order to have an appropriate spatial resolution) at a 5 m working distance, and the receiving optics must have an aperture of nearly f/10 to detect the submicron particles which are the only ones able to follow the important flow velocity gradients (existing, of course, in vortices); thus beam expanders (5 x magnification) are used in the emitting part and a Cassegrain telescope, 450 mm in diameter, is placed in the receiving part. The scale of the facility has required the use of large and expensive optics in order to keep the same measurement quality for laser velocimetry as that usually obtained in smaller research facilities.

In order to minimize disturbances at the probe volume level, flow seeding is usually performed in a wind tunnel far upstream, in the settling chamber; but at DNW this settling chamber is 50 m upstream of the test section and is 30 m wide and 18 m high. Since the flow is deflected as it passes across the rotor disc, adequate seeding of the vortex (which is always very difficult) requires control of the seeding point in the settling chamber; the seeding apparatus was installed on the DNW motorized transverse mechanisms and was remotely controlled.

The flow is periodic; so statistics are done for each point of the analyzed field at the same blade azimuth. Starting from a synchronization pulse delivered by the rotor at each turn (i.e. every 57 ms), data must be acquired within a short temporal window (typically 80µs) in order to freeze the phenomenon. Under these conditions the measurement probability is strongly reduced (by a factor one thousand compared to a continuous flow), and, even if the flow seeding provides a high data acquisition rate (continuous display of 50 kHz), a velocity map of a vortex may require several hours. A measurement strategy has been developed and is described in this paper in order to reduce this measurement time to less than half an hour.

3 Laser velocimeter description

3.1 Optical and mechanical setups

The aerodynamic department of ONERA currently uses a 3D laser velocimetry bench for measurements in research wind tunnels at Chalais-Meudon. The maximum displacements along the three axes XYZ in this apparatus are 600 mm. This setup has been the basis of the device used in DNW, but specific components have been added in order to extend its working distance to 5 m in the backscatter mode (the usual working distances being in the range of 1–2 m).

The Spectra-Physics 171 argon laser, emitting 10 W all lines, as well as the 2D beam dividing system creating 2 green beams (λ = 514.5 nm) and 2 blue beams (λ = 488 nm) which are coaxial, are fixed on the horizontal translation systems XY. The frequency shift which is induced on both green and blue components by a pair of acousto-optic modulators (Bragg cells) is fixed at 5 MHz (Boutier et al. 1984). These 4 beams are directed vertically by mirrors towards the emitting optics, composed of a Cassegrain beam expander (× 5) and a doublet (corrected for chromatism), 200 mm in diameter and having a 5 m focal length (Boutier et al. 1990). This optics axis makes an angle of 15° with the Y-axis of the velocimeter.

For the third (violet) component (λ = 476.5 nm), a fiber optic device has been added in order to minimize the weight that the Z vertical translation slide must hold. This translation slide also holds the heavy green-blue emitting device and the large Cassegrain telescope which receives light scattered by particles crossing the probe volume. The Spectra-Physics 2040 argon laser emitting 2 W on the violet line, as well as the rigid mechanical box enclosing optics which allow the division of the violet beam into two beams (separating plate, mirrors and two Bragg cells introducing also a 5 MHz frequency shift), are installed on the ground of the wind tunnel on a structure of Microcontrôle rails set on a stable wooden table. At the output of this box, two Dantec manipulators are used to couple the violet laser beams into two monomode, 20 m long, optical fibers. At its other end, each of these fibers is fitted with a beam expander (× 5) and focusing optics with a focal length adjustable between 2.5 and 5 m. These two ends, each having a cylindrical shape, are separated by 120 mm and are fixed on a beam rigidly linked to the Z slide; their mean line of sight makes an angle of 15° with the Y-axis, and is symmetrical to the green-blue axis with respect to the receiving telescope axis parallel to Y. Each of the violet emitting optics is equipped with fine adjustments (optics displacements with micrometer screws) in order to ensure the overlap of the violet beams inside the probe volume.

Light scattered by particles crossing the probe volume is gathered by a Cassegrain telescope, with a primary mirror 450 mm in diameter, which is placed 5 m from the sample...