1.5µM LIDAR FOR HELICOPTER BLADE TIP VORTEX DETECTION

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Abstract

The objective of Onera study in the AIM project 'Advanced In-flight Measurement Techniques' is to assess the capability of on board lidar technique to investigate in-flight tip vortices behaviour. This paper presents the design of a 1.5µm lidar sensor dedicated to tip vortex detection and tests on ground during a trials campaign on DLR helicopter in hover flight. The relevant information resulting from these trials is tip vortex velocity field but also vortex evolution according to time. The technical challenge here is to characterize a very small phenomenon at short range: vortex core radius with respect to age varies from typically 10 to 30 mm. Study result shows that lidar technique is promising for onboard measurement in real flight conditions. The velocity measurement is direct and absolute (not calibration needed) and its accuracy can be up to 0.25 m/s and commonly 1m.s^{-1}. However, seeding is necessary to realize a compact and reliable lidar system with components 'off the shelf': flight measurements within clouds could be a very good solution for efficient and powerful vortex lidar.

1. INTRODUCTION

Coherent detection lidars offer a practical and efficient tool to characterize and monitor wind fields and more specifically wake vortices [1], [2]. The technique measures the Doppler shift of light (from a laser source) scattered from atmospheric particles, and hence infers the line-of-sight flow velocity allowing a picture of vortex flow to be built up. Concerning helicopter, rotor vortex monitoring can be realized using an airborne lidar which appears to be a good candidate for airborne in-flight measurement systems due also to the use of 1.5µm technology. In fact, the rise in power of Erbium fiber lasers associated with the development of efficient fiber components for telecommunications has resulted in designing compact, reliable and eye-safe lidar sensor: recently, 1.5 µm fiber coherent Lidars have been successfully flown [3]. In this paper, we describe an innovating 1.5 µm lidar dedicated to tip vortex detection and present results of flight tests on DLR helicopter in hover flight. The aim of these field tests was to demonstrate the capability of laser anemometers for efficient, cost-effective in-flight testing for certification and in-flight research for aircraft and helicopter. In particular, one interesting and important outcome of this work isthe specification of a future 1.5µm lidar anemometer for helicopter in-flight research. The work performed and presented in this paper was part of the EC funded project AIM. In fact, AIM European project (Advanced In-flight Measurement Techniques) intends to test techniques such as BOS (Background Oriented Schlieren Method), IPCT (Image Pattern Correlation Technique), PIV (Particle Image Velocimetry) and Lidar technique which can be used for non-intrusive in-flight tests.

2. 1.5µM LIDAR DESIGN

The objective of this task consists in designing the 1.5µm lidar sensor suited to blade tip vortex detection in case of helicopter in hover flight. The helicopter used for tests, is latched to the ground in order to keep the rotor position constant with respect to the blade tip observation area. The relevant information resulting from these trials is tip vortex velocity field but also vortex evolution according to time. The technical challenge here is to characterize very small phenomena at short range: vortex core radius with respect to age varies typically from 10mm to 30 mm. Blade tip vortex is convicted and disturbed by the rotor inflow and its speed can reach a value of 50m/s.

The 1.5 µm lidar design, described on Figure 1 is split in several units to simplify the lidar installation and adjustments for the helicopter tests. It includes: a sensor head including a telescope and a scanning mirror which emits the laser beam, an electronic bay including laser source units and the fibered optical architecture, a data storage and real time visualization system including a computer and a display. The link between the sensor head and the electronic bays is carried out by an optical fiber. Therefore, it is easy to implement during field tests. The sensor head is placed on the ground beside the helicopter at a distance of 10 m. This position is a compromise between the optimization of the lidar Carrier to Noise Ratio and the perturbations from the helicopter rotor vibration and rotor flow turbulences. The laser power emitted by the sensor head is about 2 W, a figure compatible with the use of seeding particles which are available for tests: these wind tracers (having a very good backscattering coefficient) increase lidar sensitivity and therefore, allow the use of a laser source off the shelf. The field of view of the system is defined by a transverse length realized by the scanner and an axial length (along the optical axis) on which the lidar detection is effective (depth of focus). The transverse length (500mm) is chosen to be compatible with the helicopter stabilization and the vortex diameter. The depth of focus (300mm) is chosen considering the vortex phenomenon size and also the required detection sensitivity. The scanning mirror is made of ultra-light material (beryllium) to allow precise scanning in a very short time. Real time signal processing and real time visualization have been developed as well as a synchronization device between the lidar data and the scanner data.

3. 1.5µM LIDAR TESTS

Outdoors ground based lidar measurements have been performed on DLR’s MBB 105 helicopter in hover flight. Figure 2 illustrates the lidar installation on the trials site at DLR airport in Braunschweig. For these tests, it was planned to use olive oil droplets as rotor wind tracers and to implement the PIV seeding device. Unfortunately oil was suspected to damage the helicopter turbine, so as a substitute, smoke seeding produced by flares was used as illustrated on the Figure 2. During lidar tests, the difficulty was to obtain a high and uniform seeding density in the region of interest and especially when pulling the collective pitch for rotor thrust. It was not efficient in comparison with the oil seeding system initially planed which used air compressor to inject tracer particles in the vortex flow. Consequences are that lidar measurements were performed most of the time with helicopter running without rotor thrust.

Tests consisted in recording velocities lidar images of rotor wind fields at different vortex ages corresponding to observation planes 10°, 40° and 70° behind the trailing edge of the blade. A velocities lidar image is the power spectral density (color scale) for each frequency or radial velocity (vertical axis) as a function of line of sight or scan angle (horizontal axis) of the studied area.

Figure 3 illustrates lidar images of vortex velocity fields for 3.8° lidar scan angle and without helicopter rotor thrust. We observe that: the maximum velocity, vmax, decreases and the vortex core radius, rc, increases with the vortex age; a wind field component or a second vortex located near the blade tip vortex is also captured and measured by the lidar sensor.

4. INTERPRETATION OF WIND FIELD MEASURED BY LIDAR

The Doppler lidar measures the wind velocity projected along the laser line of sight, but the lidar velocity image can be translated in the radial vortex field distribution (or 2D vortex velocity) according to a vortex model. Previous Lidar wake vortex measurements had demonstrated that Hallock Burnham model best fitted the lidar measurements. Radial profile of tangential velocity $v_\theta(r)$ (where r is the distance from the vortex center) is given by the formula:

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r}\frac{r^2}{r^2 + r_c^2} \qquad (1)$$

The maximum tangential vortex velocity $v_\theta$max depends on root circulation Γ_0 and on core radius r_c:

$$v_\theta \max = \frac{\Gamma_0}{4\pi r_c} \qquad (2)$$

For data analysis, $v_\theta$max is adjusted to fit the maximum velocity and the slope near the vortex center, and Γ_0 to fit the envelope decrease of the vortex tangential velocity.

This vortex model can be used to fit the rotor wind field measured by the lidar sensor. The optimal set of vortex parameters values were found the same for all lidar images: this shows the consistency of the lidar measurement. As an example, in Figure 4, the vortex model (white curve) fits vortex lidar data for circulation parameter: Γ_0=2.8 m^2/s and for maximal speed: $v_\theta$max=29.m/s.

5. SPECIFICATION OF FUTURE 1.5 µM LIDAR ANEMOMETER FOR HELICOPTER IN-FLIGHT RESEARCH

The lidar design is derived from the 1.5 µm lidar performance model developed at ONERA and using results analysis from the lidar tests on hovering helicopter. The 1.5 µm lidar performance model is based on:

- vortex wind field model,

- instrumental model and

– signal processing simulation.

For the wind field model, PIV data which have been measured with an efficient oil seeding device and helicopter rotor thrust, are chosen because these data are most representative of real blade vortex and are obtained for representative helicopter flight conditions during Braunschweig tests.

For the instrumental model, lidar tests confirm the good choice of geometrical parameters of the lidar optical system such as spatial selectivity of the coherent lidar, emitted laser diameter on the telescope pupil, scanning mirror performance (scan angle, sweep time). On the other hand, the lidar laser power is an important parameter for instrumental model performance and is linked to the aerosol backscattering coefficient. In case of tests with seeding particles, the aerosol backscattering coefficient has a typical value of: $\beta=1.10^{-5}$ m-1.sr-1. Without seeding, the evolution of natural aerosol backscattered coefficient with altitude is given in TAB 1: the backscattering coefficient at low altitude (500 m) is already a 100 times weaker than the coefficient obtained with seeding and it decreases quickly with altitude.

H(m)	beta (m-1.sr-1)
500	1.26E-07
1000	2.01E-08
1500	5.58E-09
2000	2.69E-09
3000	1.39E-09
4000	8.92E-10
5000	5.94E-10
6000	3.86E-10

TAB 1. Aerosols backscattering coefficient versus altitude

The laser power was 2W for lidar tests with an assumed typical value of backscattering coefficient $\beta=10^{-5}$ $m^{-1}.sr^{-1}$. Therefore, without seeding, lidar measurements at low altitude would require a 100W CW laser: such laser is not realistic for an onboard sensor. Seeding is therefore necessary to measure blade tip vortex with a classical laser. Flight measurements in light clouds or fog could be a good solution since they would provide dense and homogenous seeding for efficient vortex detection. At altitudes lower than 5km, clouds are stratus or cumulus which are essentially water droplets with an average size of 8 µm. Calculation of absorption coefficient and backscattering coefficient for 1.5 µm wavelength was performed using MATISSE, a radiative transfer computation code developed at Onera (TAB 2). The atmospheric absorption coefficient (alpha) is very high but not penalizing for laser performance because the propagation range is very small. On the other hand, the backscattering coefficient (beta) of water droplets is very efficient.

cloud	alpha (m-1)	beta (m-1.sr-1)
Stracumulus	9.72E-04	1.35259E-05
stratus	1.39E-03	1.95785E-05
cumulus	1.72E-03	2.24733E-05

TAB 2. Absorption coefficient and backscattering coefficient of clouds for 1.5 µm wavelength

The impact of the laser power is illustrated in Figure 5 with a cloud atmospheric parameter of 1.10^{-5} $m^{-1}.sr^{-1}$. Performance calculations with a 2W and a 10W laser show that good lidar performances require a 10 W laser. This type of fiber laser is commercially available, is compact and its consumption is compatible with on board operation.

Concerning signal processing performance, it was designed so as to perform a lidar vortex image in 5ms: vortex evolution is considered to be stationary and remains small compared to the rotor period ($t_{blade}/10$). Signal processing parameters (spectrum number, scanning lines number, integrated spectrum number,…) have been optimized for this measurement time and a 1m/s speed accuracy. Therefore no meaningful improvement for a future 1.5µm lidar is necessary.

6. CONCLUSION

Experimental results of lidar tests prove the capability of the 1.5µm lidar technique to detect blade tip vortex velocities of hovering helicopter with a very good speed accuracy ($1m.s^{-1}$). The rotor main vortex was characterized in term of circulation using Hallock-Burnham vortex model. Study results and analysis show that lidar technique is promising for onboard measurement in real flight conditions. The lidar technique allows direct and absolute velocity measurement (no calibration is needed). Thanks to 1.5 µm technology, a compact probe can be realized using “off the shelf” components and integrated in helicopter. However, seeding is necessary. Flight tests within clouds could be a good solution for in flight helicopter blade vortex characterization using lidar.

7. ACKNOWLEDGMENTS

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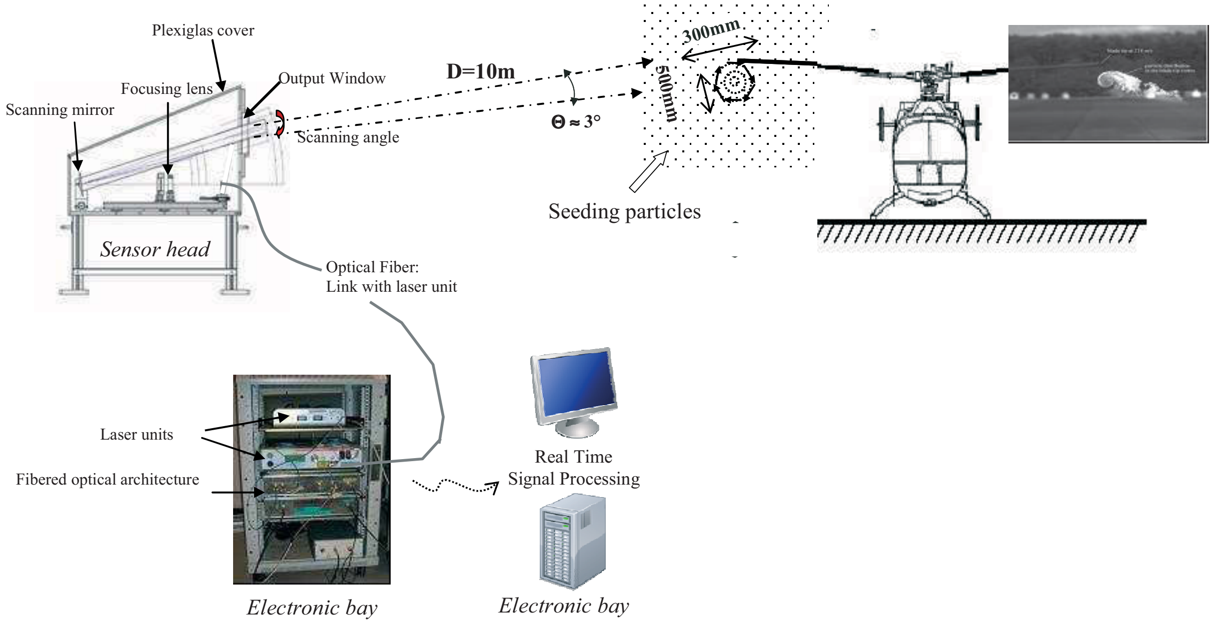


Figure 1. Description of the 1.5µm lidar for helicopter tests

Figure 2. 1.5µm lidar installation

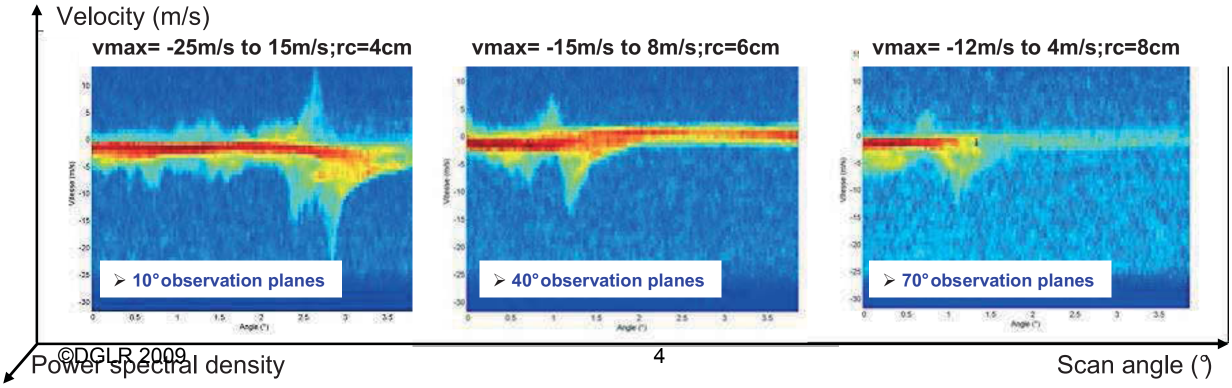


Figure 3. Lidar images of vortex velocity field

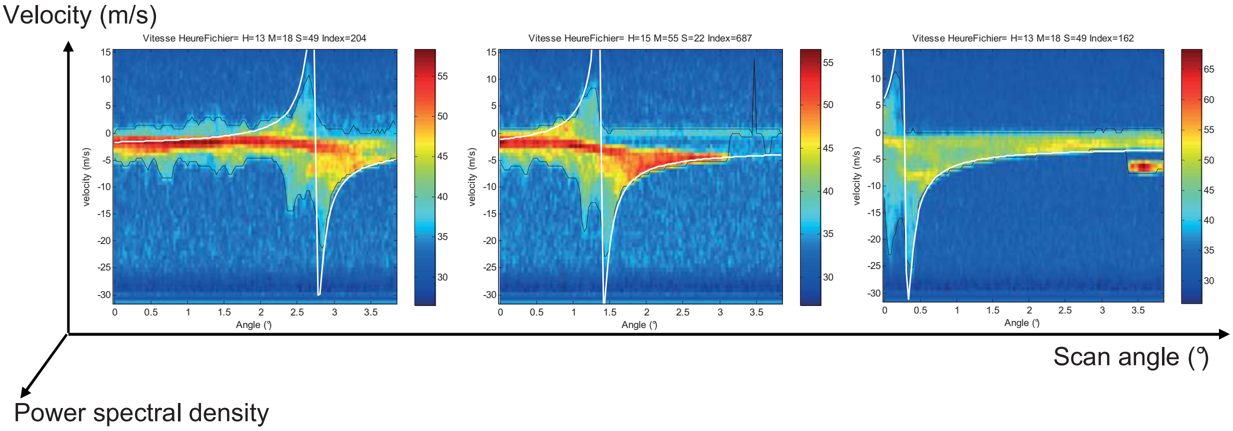
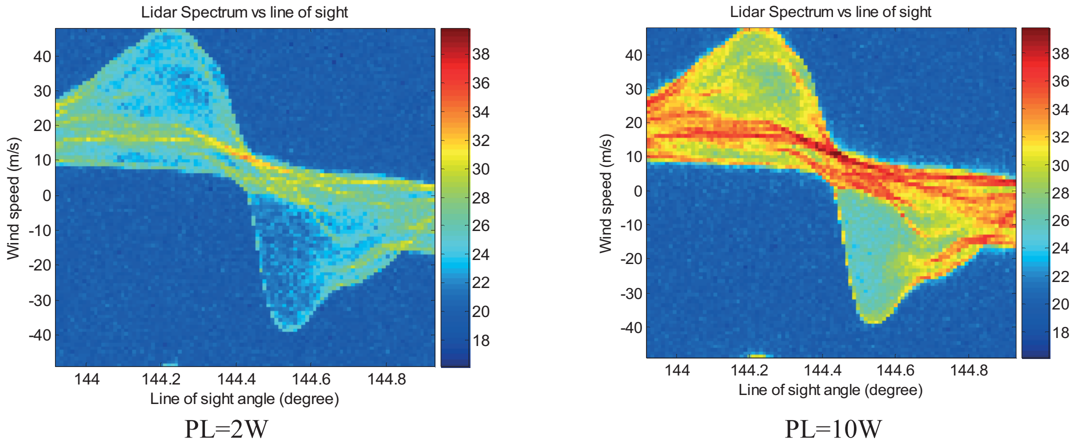


Figure 4. Comparison between vortex model (white curve) and lidar data (10° observation plane).



PL=2W PL=10W

Figure 5. Impact of laser power