DYNAMIC STALL INDUCED BY BLADE VORTEX INTERACTION IN HELICOPTER DESCENDING FLIGHT

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Abstract

In recent years studies have shown how blade-vortex interaction (BVI) can cause the onset of dynamic stall on helicopter rotors. In order to investigate this phenomenon wind tunnel tests were performed on a rotor model in descent flight conditions. The anaylsis of the rotor global performances indicated a defect of thrust for a particular value of collective pitch angle that can be explained as the occurrence of dynamic stall induced by a perpendicular vortex interaction. This conclusion is supported by evidence from both flapping angle measurements and by the results of numerical simulations performed using a code based on blade-element coupled with a vortex-particle wake model.

List of symbols

C_t	rotor thrust coefficient
$\alpha_{SH,u}$	rotor angle of attack, uncorrected
$\alpha_{SH,c}$	rotor angle of attack, corrected
β	blade flapping angle, mean removed
γ	rotor Lock number
μ	advance ratio
ψ	blade azimuth angle
σ	rotor solidity
θ_c	collective pitch angle
θ_s	longitudinal cyclic pitch angle

1 INTRODUCTION

The possibility of a collision between the helicopter rotor blade tip vortex and a following blade in descending flight is well known and it is, in general, associated with noise production. Indeed this is one of the main sources of helicopter noise and has been widely studied under this point of view. As a matter of fact, helicopter pilots try to avoid blade vortex interaction (BVI) conditions in order to reduce the noise propagation to the surrounding area. Nevertheless, this event can occur and a collateral effect that has not yet been widely investigated is the possible triggering of retreating blade dynamic stall.

As a matter of fact, a few years ago, a previous series of experiments carried out at Aerodynamic Laboratory of Politecnico di Milano on an oscillating 2D airfoil model demonstrated that a perpendicular vortex coming from upstream can induce dynamic stall [9;4]. In these experiments, the vortex issuing from the tip of the upstream airfoil (spanning just half test section) perpendiculrly impacted on the downstream oscillating airfoil inducing a local remarkable variation of the angle of attack and therefore facilitating the onset of dynamic stall. This observation led to the idea that a similar effect could happen on the real helicopter main rotor in BVI conditions. Indeed in the last years some other authors, Chaderjian in 2017 [1] and Richez in 2018 [8] found similar effects by means of CFD simulations on a complete helicopter rotor in BVI conditions. In particular, Chaderjian showed how a perpendicular BVI can induce dynamic stall on the retreating blade in the case of a four-bladed rotor at $\mu = 0.153$ and $C_t = 0.00657$, with a rotor angle of attack of 0.75°.

Thus a wind tunnel test activity on a rotor model was planned, in order to experimentally assess that this phenomenon is possible and to investigate its effect on rotor performances.

2 WIND TUNNEL TEST SETUP

The experimental tests were carried out in the GVPM (Large Wind Tunnel of Politecnico di Milano), using a four-bladed, fully articulated rotor model (see Figure 1).

The 4 m x 3.84 m test chamber was configurated in the open jet mode. The test rig was based on a whirl tower already extensively used in GVPM for previous researches [2;3]. This whirl-tower is powered by an hydraulic motor (maximum power 16 kW at 3000 RPM) and equipped with a strain gauge balance allowing to measure the thrust while the torque was measured by means of strain-gauges direclty fixed on the rotor-motor shaft. The whirl tower allowed to set the shaft angle of attack keeping the rotor head in the center of the testing area. The rotor was equipped with a

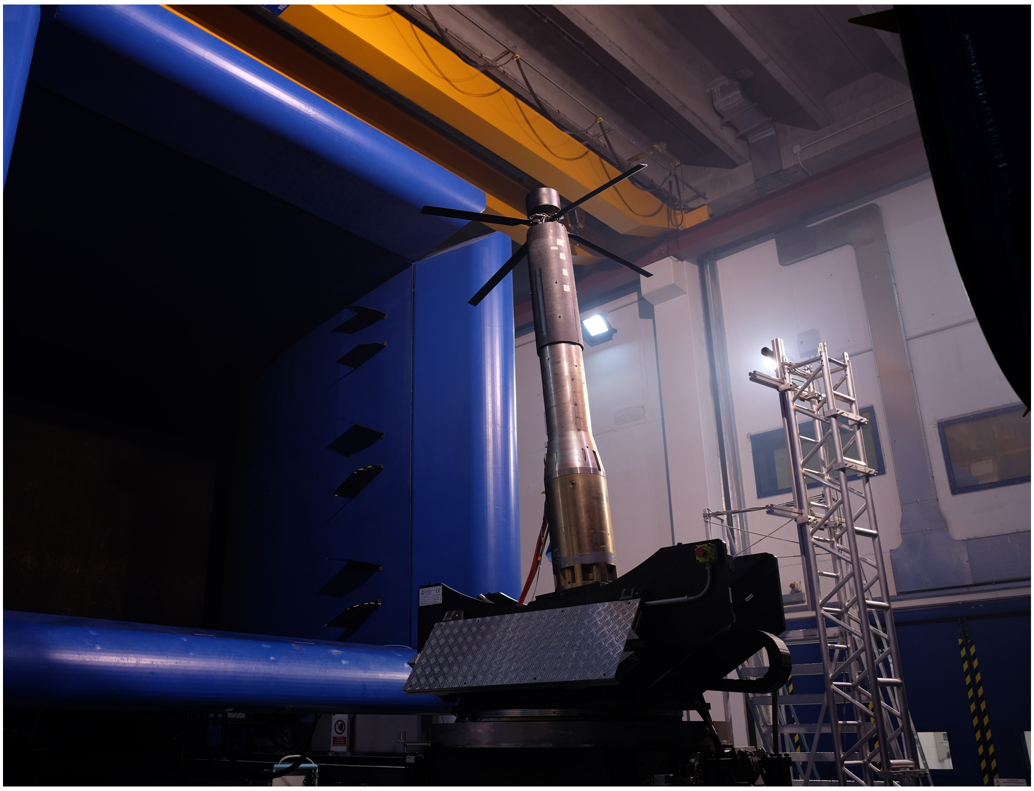

Figure 1: Test rig in place in the Large Wind Tunnel

set of four rectangular, untwisted carbon fiber blades, 0.6 m long and with a constant chord of 0.06 m. The blade section, constant along the span, was represented by a NACA 0012 airfoil. The rotor had a radius $R = 0.8$ m, a solidity of $\sigma = 0.0955$ and a Lock number $\gamma = 4.77$.

The rotor hub swashplate was actuated by three linear servo-motors connected to a control unit allowing for manual setting by means of three knobs.

The run-time measurement of pitch, flap and lag angles was made by means of Hall effect magnetic sensors. All the signals coming from the rotating part were connected to the DAQ system through a slip-ring. The rotor RPM too was measured by means of Hall effets sensor.

3 TEST PROCEDURE

3.1 Preliminary study

Before starting with the test activity, a preliminary study was conducted investigating the trajectory of the wake tip vortices in order to find suitable interesting test conditions. This analysis made use of a simple epicycloidal model[6] in order to find the possible blade-vortex intersections. In particular the case of $\mu = 0.13$ was analysed, close to the value of the test case of Chaderjian[1] and characterized by a rather large number of possible intersections.

Figure 2 shows the possible intersection points come out from this analysis and coloured on the base of the BVI typology, with black indicating perpendicular BVI, red indicating parallel BVI, and blue indicating oblique BVI.

The perpendicular interaction on the external retreating blade (indicated in the figure) was considered the most interesting for this study. Assuming a $C_t = 0.007$ (as in[1]) and making use of the Mangler-Squire[7] model for induced velocity, an angle of attack around $-2°$ was found for that BVI occurrence.

3.2 Test campaign

To produce the desired descent flight condition, the rotor shaft was inclined backwards resulting in a negative angle of attack. As the application of wind tunnel corrections would lead to a lower (in absolute value) angle of attack, the tests were carried out at two different shaft angle of attack ($\alpha_{SH,u} = 2°$ and $\alpha_{SH,u} = 4°$) that included the estimated angle for the interaction.

The tests consisted in a series of sweeps of collective pitch angle θ_c, ranging from 4° to 16°. For each test point the longitudinal cyclic pitch angle was manually adjusted to keep the flapping response as small as possible.

As a non negligible level of vibrations was expected (due to the possible onset of dynamic stall) the rotor angular velocity was kept relatively low (1200 RPM)

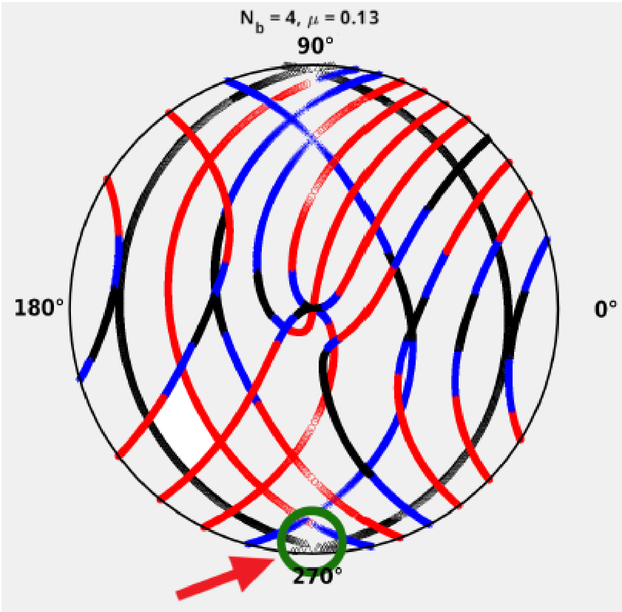

Figure 2: Possible BVI points in the disk plane evaluated by epicycloidal model (black for perpendicular, red for parallel and blue for oblique BVI)

leading to a tip velocity of 100 m s^{-1} ($M_{tip} = 0.2875$).

4 EXPERIMENTAL RESULTS

For both the considered angles of attack it was found that at a particular value of the collective pitch angle (not the same for the two cases) a defect of the rotor thrust coefficient was apparent: the thrust suddenly decreases then increases again showing a local valley in the C_t - θ_c graph as can be seen in Figure 3 and Figure 4. This effect could be explained as the effect of the dynamic stall triggered by the interaction with the vortex, although its occurrence was for a C_t higher than expected while the corrected angle of attack is close to what estimated.

In tables 1 and 2 the C_t obtained at high range of measured collective pitch angles are listed with the corrected value of incidence estimated by means of Heyson method[5].

θ_c	θ_s	C_t	$\alpha_{SH,c}$
11.1°	6.4°	0.0107	2.5°
12.0°	7.9°	0.0111	2.6°
12.9°	8.9°	0.0101	2.6°
14.0°	9.6°	0.0110	2.5°
15.1°	10.8°	0.0112	2.5°
16.0°	12.5°	0.0113	2.5°

Table 1: Test points for $\alpha_{SH,u} = 4°$

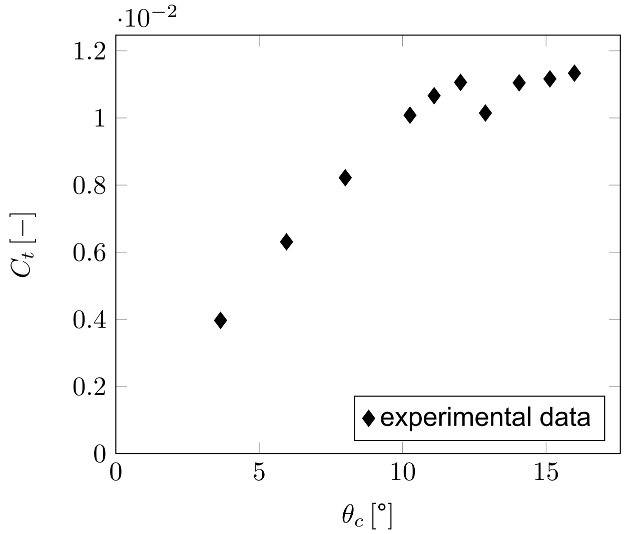

Figure 3: Thrust coefficient in function of collective pitch angle for $\alpha_{SH,u} = 4°$, $\mu = 0.13$

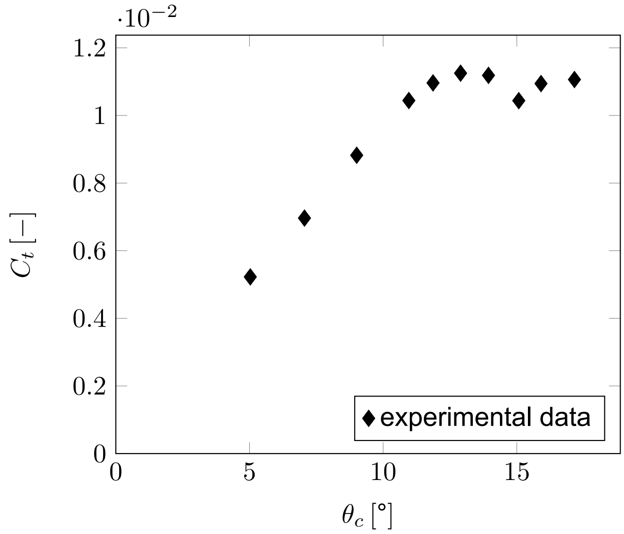

Figure 4: Thrust coefficient in function of collective pitch angle for $\alpha_{SH,u} = 2°$, $\mu = 0.13$

Figure 5 presents, for the case of $\alpha_{SH,u} = 4°$, the blade flapping behaviour in the condition where the C_t "'valley" ($\theta_c = 12.9°$) was found compared with the behaviour at previous and next collective pitch angles. It can be see that from $\theta_c = 12°$ to $\theta_c = 12.9°$ the flapping becomes much more irregular with apparent spikes occurring any two rotor revolutions. These spikes disappeared again for $\theta_c = 14°$. Although this observation is not a direct evidence of the BVI induced stall, it indicates that something of very particular is happening at that condition.

Further investigations by means of PIV technique and including more test conditions are forseen for the next year at GVPM.

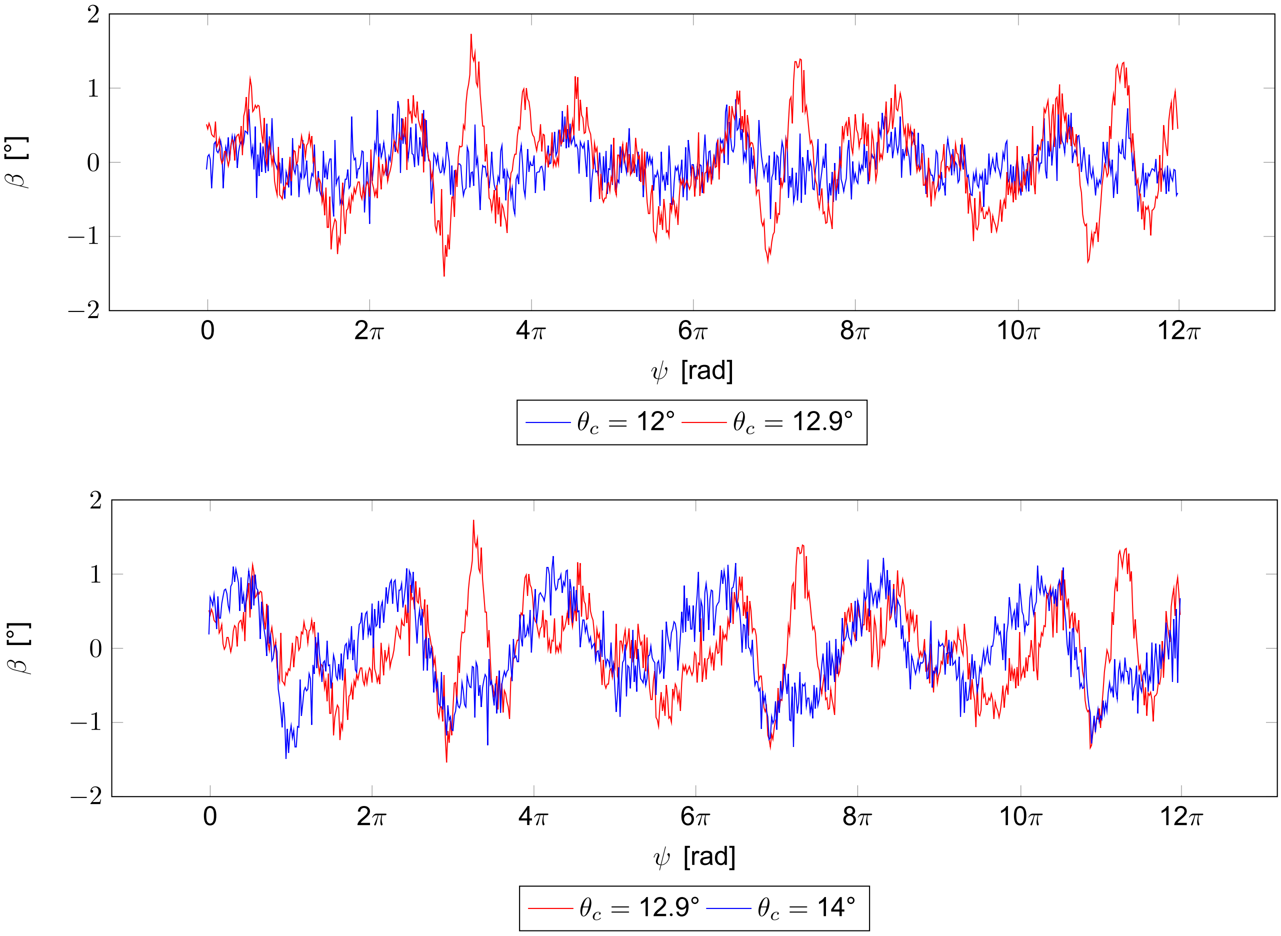

Figure 5: Blade flapping behaviour measured for $\alpha_{SH,u} = 4°$, $\mu = 0.13$

θ_c	θ_s	C_t	$\alpha_{SH,c}$
11.0°	7.7°	0.0104	0.6°
11.9°	7.9°	0.0110	0.5°
12.9°	9.3°	0.0113	0.5°
13.9°	10.7°	0.0112	0.5°
15.1°	12.9°	0.0104	0.6°
15.9°	14.2°	0.0109	0.5°
17.1°	16.2°	0.0111	0.5°

Table 2: Test points for $\alpha_{SH,u} = 2°$

5 NUMERICAL SIMULATION

In order to get a first confirmation of the experimental results a series of numerical simulations were carried out by means of an in-house code based on blade-element coupled with a vortex-particle wake model. The code did not include a dynamic model method and, furthermore, such a three-dimensional phenomenon is not expectable to be correctly reproduced by a quasi-2D approach as blade-element; nevertheless, this code can give an indication of the tip vortex trajectory.

The simulation were carried out for the corresponding free flight conditions (i.e. at the corrected values of the angle of attack), for $\alpha_{SH,u} = 4°$.

Figure 6 shows the tip vortex path, confirming the perpendicular BVI in correspondence of the collective pitch angle for which the C_t defect was observed.

6 CONCLUSIONS

An experimental wind tunnel activity carried out in possible BVI conditions showed a C_t defect for a particular value of collective pitch angle that can be explained as the onset of dynamic stall induced by a perpendicularly interacting vortex. This hypotesis seems to be confirmed by several observations and simplified analytical models; nevertheless, the phenomenon requires further investigation for a better physical insight. Furthermore, it is important to understand if similar behaviour can occour at lower values of thrust coefficient more characteristic of the flight envelope.

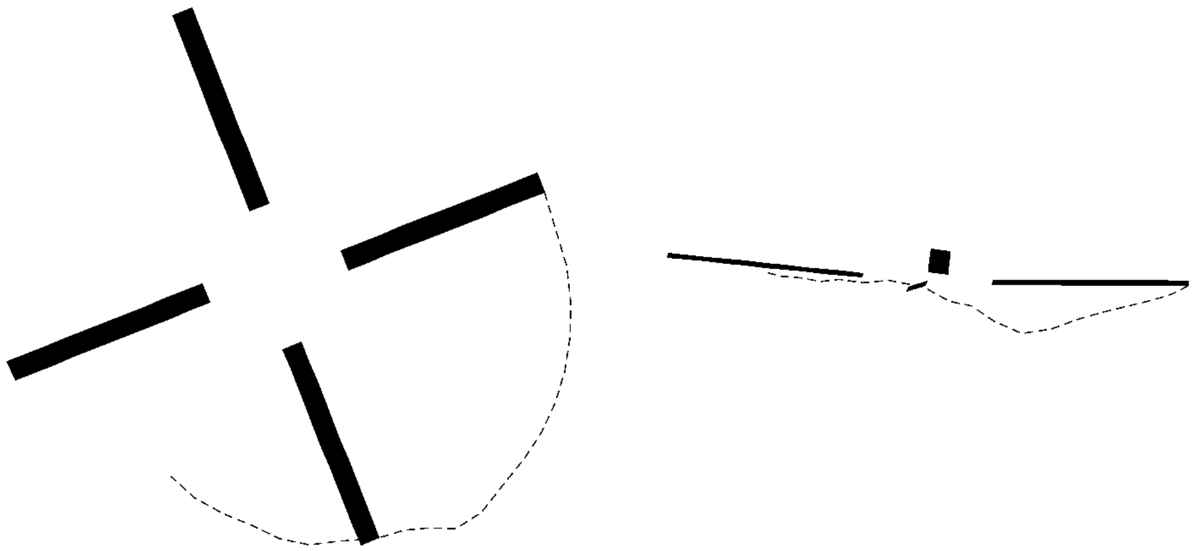

Figure 6: Tip vortex trajectory indicating blade-vortex interaction on the retreating blade, for the case of $\alpha_{SH,u} =$ 4°, $\mu = 0.13$ and $\theta_c = 12.9°$, top view (left) and lateral view (right); direction of flight is to the left, the interested blade is shown at $\psi = 284°$

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