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OSCILLATING AEROFOIL AND PERPENDICULAR VORTEX INTERACTION

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Abstract:

An experimental activity was conducted to investigate the aerodynamic effects of a stream-wise vortex impacting on a NACA 23012 oscillating aerofoil. The experimental set up allowed to study the effects of the blade pitching motion in the interaction with the vortex.
The impacting vortex was statistically qualified by means of a three-dimensional hot-wire anemometry, taking into account also the vortex wandering phenomenon. The flow developed on the aerofoil was investigated through Particle Image Velocimetry surveys carried out on different measurement planes along span-wise direction. The experimental study investigated both the light and the deep dynamic stall, representing typical helicopter flight conditions. In particular, in the tested light dynamic stall condition the phase averaged velocity fields showed that in downstroke the vortex impact triggers the flow separation on the aerofoil upper surface. Therefore, the vortex interaction can introduce detrimental effects on the blade performance. Moreover, the influence of the target aerofoil oscillating motion on the vortex trajectory was investigated.

Keywords: Vortex Interaction, Oscillating aerofoil, PIV, Hot-Wire Anemometry.

1 INTRODUCTION

The aerodynamic interaction between the helicopter rotor blades and the vortices produced by the blades themselves is a very important topic. This problem is particularly important for the effects on the rotor noise [1, 2], but it can also affect the rotor performances as well as produce blade vibrations and instability. This Blade Vortex Interaction (BVI) occurs mainly when the helicopter is slightly descending [3] so that the tip vortex wake remains in the region of the rotor disk. Depending on the direction of the vortex axis with respect to the blade span, three typical cases of BVI can be considered [4, 5]:

- (almost) parallel interactions

- (almost) perpendicular interactions
- oblique collision

A sketch of the three types of BVI is illustrated in Fig. 1.

Figure 1: Sketch of the three types of BVI.

When the vortex axis is parallel to the blade span, the resulting interaction is highly unsteady, substantially two-dimensional and distributed over a large spanwise portion of the blade. Conversely, perpendicular interactions are characterised by a strong three-dimensionality and moderate unsteadiness and they affect a small portion of the blade. The oblique interations combine the features of the previous two.

Besides the experiments reproducing the entire helicopter (or almost) [6, 7], experiments reproducing a singular phenomenon isolated in a partial model can be very useful to allow detailed observations. Moreover, these measurements can help both in physical insight and in the production of reference data for Computational Fluid Dynamics (CFD) validation. For example, experiments were conducted by Wittmer et al. [8, 9] to investigate the turbulent flow field due to the perpendicular interaction of a stream-wise vortex with a still blade section model in incidence. These experimental surveys showed an increase of the turbulent flow region extent. Moreover, an increase of its turbulent intensity was observed due to the interaction of the vortex with the wake of the still blade. In particular, it was found that these effects increase in magnitude reducing the vertical distance between the blade and the vortex.

The present paper describes the experiment carried out at Politecnico di Milano on an oscillating NACA23012 aerofoil struck by a stream-wise vortex (perpendicular interaction). The perpendicular interaction is characterised by a high degree of three-dimensionality as the vortex induces incidence angles anti-symmetrically with respect to its own axis. A narrow localisation essentially limited to the extension of the vortex section and a low degree of unsteadiness are other characteristics of the phenomenon. In fact, if the aerofoil moves perpendicularly to the vortex the flow does not change, unless the aerofoil velocity and/or incidence are changing. Of course, the real blade velocity and incidence cyclically vary in forward flight but the unsteadiness related to this variation is not so rapid as, for example, the effect of parallel BVI when the vortex rapidly travels over the aerofoil.

Due to its low unsteadiness, the noise effects of perpendicular BVI are less dramatic with respect to the parallel BVI, as it was shown by Glegg et al. [10] and Yu [2]. In case of parallel BVI the sudden pressure fluctuations induced by travelling vortices cause a radiation of strong impulsive noise (harmonic noise). On the other hand, subsequent perpendicular blade-vortex interactions cause a continuous noise (broadband noise) characterised by a much lower intensity with respect to the harmonic noise. Nevertheless, the locally induced incidences can trigger the retreating blade dynamic stall and produce rotor vibrations.

Many experiments published in the past [8, 9, 11, 12] using a blade section model struck by a perpendicular vortex do not include the target model oscillation missing that important contribution in the phenomenon. The novel set up employed in this experimental activity enabled to investigate the effects of blade pitching motion in the interaction with the vortex. Two kinds of anemometry systems were used for the present study. Triple hot-wire probe survey (3D-HW) was performed for the qualification of the stream-wise vortex with only the upstream model. On the other hand, Particle Image Velocimetry (PIV) was used to survey the interacting flow field around the oscillating aerofoil. The experimental investigation was carried out for a light and a deep dynamic stall condition [13] at some selected incidences. In fact, the scope of the present study was the investigation the interacting flow field for helicopter applications.

The stream-wise vortex characterisation was completed by the investigation of the vortex wandering. This phenomenon occurs typically in wind tunnel experiments and it affects particularly the fixed point measurements, as it was shown, for instance, in the past activities by Chigier and Corsiglia [14] and by Corsiglia et al. [15].

The aerodynamic loads were not evaluated during this test activity because the adopted test rig allows for unsteady pressure measurements only on the midspan section contour, while the investigated phenomenon is intrinsically three-dimensional. It has also to be considered that a quantitative load evaluation was not the target of the present study as the actual loads on a real blade in real operative conditions would be unavoidably different. In fact, the main focus of this study was to show how much the flow field around the blade can be changed by the vortex interaction.

This paper presents mainly qualitative reasoning and global results as they are more interesting on a general point of view. Nevertheless, all the acquired data are accessible by request to the authors to be useful for numerical validations.

2 EXPERIMENTAL SET UP

The tests were carried out in the 1 m × 1.5 m test section wind tunnel at the Aerodynamic Laboratory of the Dipartimento di Ingegneria Aerospaziale (DIA) of Politecnico di Milano. The maximum wind velocity is 55 m/s and the freestream turbulence level is less than 0.1%. Two 0.3 m chord models were used, both with NACA 23012 section. The upstream model (UM), spanning half the test section width, is still and just used to produce the vortex. The second one constitutes the target and is mechanically jointed to a driving system that makes it to oscillate in pitch. In particular, the model is pivoted around the axis at 25% of the aerofoil chord. The oscillating model driving system is composed by a brushless servomotor with a 12:1 gear drive. The model pitching motion is controlled by a proportional and a derivative action using an "in-house" developed interface software developed in Labview [16] ambient. More details about the description of the pitching aerofoil experimental rig can be found in Zanotti et al. paper [17] and in Zanotti's doctoral dissertation [18].

Figure 2 presents the test layout as well as the reference system used in the present activity, with the x-axis that lies on the test section central axis. The scheme in Fig. 3 shows the positions of the two aerofoil models inside the wind tunnel test section. As it can be observed, the leading edge of the oscillating model is positioned 3.5 c past the trailing edge of the upstream model.

Figure 2: Layout of the BVI test set up.

Figure 3: Scheme of the models set up inside the wind tunnel test section (top view).

The pitching cycles considered in the present study were sinusoidal pitching motion with mean angle of attack $\alpha_m = 5^\circ$ and 10°, a constant oscillation amplitude $\alpha_a = 10^\circ$ and reduced frequency $k = 0.1$. The reduced frequency is defined as $k = \pi f c/U_\infty$. The pitching conditions were tested at $U_\infty = 30$ m/s corresponding to a Reynolds number of $\mathrm{Re} = 6 \times 10^5$ and a Mach number of $\mathrm{Ma} = 0.09$. At the maximum angle of attack tested ($\alpha = 20^\circ$) the wind tunnel blockage due to the oscillating aerofoil model is 6%. The test conditions were selected as they reproduce typical flight conditions of helicopter rotor blades.

2.1 3D Hot-Wire set up

The adopted HW system was a Constant Temperature Anemometry (CTA) system Streamline 90N10 by Dantec Dynamics. The system was composed of one frame with three CTA modules. Every basic anemometer module contains three CTA bridges, a servo-loop with programmable gain, filters and cable compensation and a programmable signal conditioner. The programmable servo-loop allows to optimize the dynamic response and the bandwidth of the system. The signal conditioner provides amplification of the CTA signal before digitizing.

A tri-axial fiber-film probe Dantec 55R91 was used for the velocity surveys. The tri-axial sensor probe has three 70 μm diameter nickel-plated quartz fibres. The probe was calibrated in laboratory under monitored conditions, with respect to Reynolds number and velocity direction. The calibration method took into account the effects of temperature, pressure and humidity in order to extend the calibration itself to the wind tunnel ambient conditions [19]. The HW measurements were carried out with the upstream model at $\alpha = 10^\circ$ without the oscillating aerofoil. The Reynolds number related to the wind tunnel free-stream velocity and to the wing chord was kept equal to $6 \cdot 10^5$ during the test. The probe was moved in the y-z plane by means of a dual axis traversing system on a 100 mm × 100 mm measurement window centred on the reference system origin. The velocity time history for each grid point was measured for 15 s with a sampling frequency of 2 kHz.

Figure 4 shows a particular of the triple HW probe set up inside the test section.

Figure 4: Tri-axial HW probe set up inside the wind tunnel test section.

2.2 Particle Image Velocimetry set up

The PIV set up of the DIA Aerodynamics Laboratory allows for 2D flow field surveys on x-z plane windows at different positions around the oscillating model. The 2D PIV system employed for this activity was assembled with different components of different brands. A Dantec Dynamics Nd:Yag double pulsed laser with 200 mJ output energy and a wavelength of 532 nm was positioned on the top of the wind tunnel test section. A Pixelfly PCO double shutter CCD camera with a 12 bit, 1280 × 1024 pixel array was used to get the image pairs. The laser and the camera were attached to a single axis traversing system to move the laser sheet and the measurement window along the oscillating model span-wise direction (y-axis). The synchronization of the two laser pulses with the image pairs exposure was controlled by a 6 channels Quantum Composer pulse generator. A particle generator PIVpart30 by PIVTEC with Laskin atomizer nozzles was used for the seeding. The image pairs post-processing was carried out by PIVviev 2C software [20], developed by PIVTEC.

3 VORTEX WANDERING

The vortex wandering consists in a relatively slow oscillation of the vortex core tube and it represents a typical feature of the vortices generated in a wind tunnel [21]. Due to the wandering motion the time averaged measured vortex results to be more diffused than actually is [23]. In fact, the wandering is a slow motion that concerns all the vortex structure, so that it is completely separated in terms of frequency from the small scale turbulence inside the vortex itself.

The vortex wandering can be described through a bi-variate normal probability density function (*pdf*) [21, 22, 23]. The measured mean velocity components can be expressed as the convolution of the actual field with the bi-variate normal *pdf* that represents the wandering. The bi-variate normal *pdf* representing the wandering is characterised by two amplitude parameters (σ_y and σ_z for the y and z direction respectively), and an anisotropy parameter e. σ_y and σ_z are evaluated as the root mean square value of the v and w velocity components at the vortex centre divided by the tangential velocity gradient (this also measured at the mean vortex centre). The anisotropy parameter e is evaluated through the cross-correlation coefficient between v and w velocity components, measured at the mean vortex centre. The adopted bi-variate normal *pdf* is the following:

$$pdf(y_v, z_v) = \frac{1}{2\pi\sigma_y\sigma_z\sqrt{1-e^2}} \exp\left[-\frac{1}{2(1-e^2)}\left(\frac{y_v^2}{\sigma_y^2} + \frac{z_v^2}{\sigma_z^2} - \frac{2ey_vz_v}{\sigma_y\sigma_z}\right)\right]. \tag{3.1}$$

Once the parameters of the *pdf* are estimated, the real velocity field associated with the vortex can be recovered by a deconvolution process of the *pdf* with the averaged velocity field measured with the fixed probes. This process actually reverses the smoothing effects caused by wandering motion. In this work, two different deconvolution methods were adopted: *Richardson-Lucy* algorithm [24] and *blind deconvolution* algorithm [23, 25]. Both methods are based on Bayesian inference [24] that treats the deconvolution as a stochastic process. The first method estimates the most probable velocity field assuming the probability density function as assigned. The second one also updates that *pdf* on the base of the measured velocity field as input and of the obtained actual velocity field as output.

4 TEST RESULTS

4.1 3D Hot-Wire measurements of the isolated vortex

Figures 5 and 6 show the results of the 3D HW measurements carried out on the y-z plane with the upstream model at $\alpha = 10°$. In particular, Fig. 5 shows the velocity vector field of the isolated vortex. Figure 6 shows the contours of the x-component vorticity field calculated from the mean values of the measured y- and z-components velocity. The x-component vorticity field clearly shows the size of the vortex viscous core region and the position of the vortex core centre (y_v,z_v) corresponding to the position of the vorticity maximum. Once the position of the vortex core center is known, the tangential velocity field V_θ was computed from the average y- and z- velocity components by a change from Cartesian to polar coordinates. The vortex core radius r_v was evaluated as the radial distance from the vortex core center where the computed tangential velocity had its maximum value (V_{θ_v}).

Figure 5: HW velocity vector field of the isolated vortex; UM at $\alpha = 10°$.

Figure 6: x-component vorticity field of the isolated vortex; UM at $\alpha = 10°$.

The vortex characteristics and the amplitudes of the vortex wandering motion in span-wise and vertical directions were evaluated from the 3D-HW data and reported in Tab. 1.

α_{UM} [deg]	r_v [mm]	V_{θ_v} [m/s]	σ_y/r_v	σ_z/r_v	e
10	15.8	20	0.169	0.12	0.489

Table 1: Summary of the vortex characteristics ($\alpha_{UM} = 10°$)

The mean velocity profiles along the y- and z-axis are plotted in Fig. 7. The profiles are compared with the reconstructed actual velocity profiles obtained by removing the vortex wandering effects using the two deconvolution algorithms described in Sec. 3.

The velocity profiles reconstructed with the two deconvolution methods are very close to the measured mean velocity profiles, demonstrating that the vortex wandering introduces a small effect in both y- and z-directions, as also shown by the calculated σ_y and σ_z values. Moreover, the quite good agreement between the velocity profiles obtained with the two different algorithms suggests the reliability of the 3D-HW data post-processing.

Figure 7: Comparison of the vortex wandering reconstruction algorithms: (a) z-component velocity profile at z - $z_v = 0$; (b) y-component velocity profile at y - $y_v = 0$.

4.2 PIV measurements

The position of the upstream model tip was adjusted in order to get the required position of the vortex for each tested condition. In fact, a test condition corresponds to a particular incidence angle (in downstroke or in upstroke phase) for given values of the pitch oscillation cycle parameters. For each of these tested points, it was attempted to get the vortex core impact at the target model leading edge. This positioning was made progressively adjusting the upstream model z-position looking at the void particle region (corresponding to the vortex core) in the PIV pictures (see Fig. 8). Looking at a tenth of the pictures for each condition, in order to find out an average position, an estimation can be obtained with an overall approximation that can be quantified in the order of ±2 mm.

Figure 8: Particular of the void particle region in a PIV picture.

Before the tests on the oscillating aerofoil, a few PIV surveys were carried out without the target model to measure the vortex and to compare the measurements with the HW results. For these tests, the velocity flow fields were phase averaged over 100 image pairs. The PIV measurement planes were positioned between -25 mm $\leq$ y - y_v $\leq$ 25 mm. Figure 9 shows the comparison between the mean vertical velocity components profiles measured with PIV and HW anemometry at y - y_v = 0 mm. As it can be observed, the measurement techniques comparison presents a quite good agreement.

Figure 9: Comparison of the z-component velocity profile measured with HW and PIV at z - z_v = 0.

The main goal of the PIV measurements on the oscillating model was to investigate the interacting flow field on the upper surface of the pitching aerofoil in dynamic stall conditions. Figure 10 shows the $C_L - \alpha$ curves measured for the NACA 23012 aerofoil in the dynamic stall conditions investigated in the present study, compared to the static curve. The lift coefficient time histories were evaluated by the integration of the pressure measured on the aerofoil model midspan contour. A detailed description of the pressure measurement set up can be found in Zanotti and Gibertini [28]. The tested pitching cycle with $\alpha_m = 5^\circ$ represents the light dynamic stall regime according to the definition of McCroskey [13]. For this test condition the maximum angle of attack reached during the pitching cycle is near the aerofoil static stall angle of attack. This regime is characterised by minor flow separation as the flow is attached on the aerofoil upper surface during almost all the pitching cycle. Therefore, the airloads present a small amount of hysteresis during the pitching cycle, as it can be observed from Fig. 10 and according also to the experiments by Leishman [27].

The tested pitching cyle with $\alpha_m = 10^\circ$ represents the deep dynamic stall regime [13], in which a portion of the upstroke is extended beyond the static stall angle. In this test case, the flow is attached to the aerofoil surface for almost all the upstroke motion. As it can be observed from Fig. 10, lift grows linearly to a maximum value higher than the value obtained in static conditions. In fact, as it is well known [26], the flow separation is delayed due to a kinematic induced camber increase produced by the rapid positive pitching rate. This induced camber effect results in a decrease of the leading edge pressure and pressure gradients. During the downstroke motion, the flow presents a wide separation on the aerofoil upper surface and it is characterised by the fast passage of strong vortical structures, as it was shown by the PIV surveys in Zanotti and Gibertini's paper [28]. The asymmetric behaviour of the flow fields with respect to the motion of the aerofoil explains the large hysteresis of the airloads (see for instance the C_L loop in Fig. 10), representing a predominant feature of the deep dynamic stall regime.

Figure 10: $C_L - \alpha$ curves for the NACA 23012 aerofoil in static and dynamic stall conditions (Re = 6×10^5, Ma = 0.09) [28].

The tested conditions are identified by the parameters listed in the Tab. 2.

TN	α	k	α_m	α_a	Re	z_{UM}
1	10° Upstroke	0.1	5°	10°	$6 \cdot 10^5$	12 mm
2	15°	0.1	5°	10°	$6 \cdot 10^5$	-8 mm
3	10° Downstroke	0.1	5°	10°	$6 \cdot 10^5$	-8 mm
4	19° Upstroke	0.1	10°	10°	$6 \cdot 10^5$	-24 mm

Table 2: PIV test conditions with the oscillating aerofoil.

In order to get more resolution, the measurement area was composed by two measurement windows with a small overlapping band between them. The PIV surveys were carried out at $y - y_v = \pm 15$ mm, approximatively corresponding to the boundaries of the vortex viscous core. These measurement planes were selected because the maxima effects introduced by the vortex interaction are expected to be in correspondence to the upward and downward velocity component peaks induced by the vortex. For all these tests, the velocity flow fields were phase averaged over 40 image pairs.

Figures 11-14 present the results of the PIV surveys. Each figure shows the comparison between the clean condition (without the upstream model) and the interacting flow fields. The PIV results are illustrated by means of the velocity magnitude contours together with two-dimensional streamline patterns (i.e. the streamlines of the in-plane velocity). In order to better illustrate the aerodynamic features due to the vortex interaction, the velocity magnitude contours are plotted using colorbars with a different upper limit for the test cases at $\alpha = 10°$, $\alpha = 15°$ (light dynamic stall condition) and $\alpha = 19°$ (deep dynamic stall condition).

Figure 11: PIV results for the light dynamic stall condition at $\alpha = 10°$ in upstroke.

Figure 12: PIV results for the light dynamic stall condition at $\alpha = 15°$.

Figure 13: PIV results for the light dynamic stall condition at $\alpha = 10°$ in downstroke.

Figure 14: PIV results for the deep dynamic stall condition at $\alpha = 19°$ in upstroke.

At $\alpha = 10°$ in upstroke the flow on the aerofoil upper surface without vortex interaction is fully attached, as can be seen in Fig. 11a. In this test case, the main effect introduced by the vortex observed at y - y_v = -15 mm is a strong reduction of the local angle of attack, as it can be observed from the streamlines curvature at the leading edge region in Fig. 11b. In fact, the local incidence of the flow just upstream the leading edge results to be quite close to zero. This effect is due to the peak of downward velocity component induced by the vortex. In this case, the vortex interaction does not introduce significant modification to the overall flow behaviour with respect to the clean aerofoil configuration.

On the measurement plane at y - y_v = 15 mm, the maximum upward velocity component induced by the vortex introduces, on the contrary, a strong increase of the local angle of attack. In fact, as shown in Fig. 11c, the streamlines deflection at the leading edge region is conspicuously greater than the one observed for the clean configuration. Nevertheless, the streamline patterns on the aerofoil upper surface do not show a back-flow region.

At $\alpha = 15°$ (the maximum α of the pitching cycle) similar observations with respect to the previous case can be made for the flow field measured at y - y_v = -15 mm (see Fig. 12a and b). On the contrary, at y - y_v = 15 mm the flow is apparently distorted and the in-plane streamline patterns clearly indicate a strong three-dimensionality of the flow-field. The streamlines arising from the aerofoil surface observed in Fig. 12c are explainable with the presence of a remarkable span-wise velocity component. In fact, a predominant rotational flow in the y-z plane result in streamlines that, when projected on the x-z plane, are almost perpendicular to the aerofoil surface.

As expectable in this condition of light dynamic stall, the flow at $\alpha = 10°$ in downstroke is still characterised by a quite regular behaviour when the impinging vortex is not present. On the contrary, the case with the vortex shows the most interesting features about the interacting flow field. In fact, also at y - y_v = -15 mm the vortex produces a remarkable modification of the flow field behaviour. Coherently to the apparent effect of incidence reduction, the velocity is generally quite lower over all the aerofoil upper surface (see Fig. 13b). Nevertheless, the streamline patterns on the aerofoil upper surface do not present evident back-flow regions.

The PIV survey at y - y_v = 15 mm shows a wide back-flow area on the aerofoil upper surface that starts from the leading edge and it is characterised by a large vortical structure. The different behaviour of the interacting flow field observed at $\alpha = 10°$ in downstroke with respect to the test case at the same angle of attack in upstroke could be explained with a contributory kinematic effect induced by the rapid negative pitching rate of the aerofoil. This effect, producing a modification of the aerofoil camber, promotes in this phase of the pitching motion the onset of flow separation. A quantitative analysis of the influence of the pitching rate can be reasonably achieved under the assumptions of linearised aerodynamics theory. In particular, for the considered light dynamic stall condition the induced camber effect due to the pitching rate results, at $\alpha = 10^\circ$, in a modification of the ideal (Theodorsen) angle of attack $\Delta\alpha_{Th} = \pm 1.5^\circ$ [29]. In particular, the $\Delta\alpha_{Th}$ was calculated as follows:

$$\Delta\alpha_{Th} = \frac{1}{\pi}\int_0^1 \frac{dy_0/dx}{\sqrt{x(1-x)}}dx, \tag{4.1}$$

where $dy_0/dx = \dot{\alpha}\left(x + \frac{1}{4}\right)/U_\infty$ represents the modification of the aerofoil camber along the chord produced by the linear variation in normal perturbation velocity due to the pitching rate [26].

For the light stall cycle no significant effects were observed in upstroke phase. Consequently, for the case of deep dynanic stall cycle, only a quite high incidence was studied where the flow starts to be more unstable. On the other hand, the downstroke phase was not considered in this work because, for this conditions, it is already affected by a large and very unsteady separation [28]. Thus, the only case of $\alpha = 19^\circ$ in upstroke was considered for the deep dynamic stall condition.

As it can be seen in Fig. 14a, at $\alpha = 19^\circ$ in upstroke the onset of a trailing edge separation is observed also for the clean aerofoil configuration. The flow field measured at y - y_v = -15 mm shows that the vortex interaction tends to delay the flow separation at the trailing edge region, as it was shown by the streamlines patterns in Fig. 14b. This effect is coherent to the apparent effect of incidence reduction induced by the vortex on this measurement plane.

The PIV survey at y - y_v = 15 mm shows a separation bubble at the leading edge region. The upward velocity component induced by the vortex does not produce a wide back-flow region, as it can be expectable. This flow behaviour could be explained with a contributory camber increase effect induced by the positive rapid pitching rate.

Another aspect of the vortex interaction phenomenon was the investigation of the influence of the target aerofoil oscillation on the vortex motion. With this aim, PIV surveys were carried out for the light dynamic stall condition over a measurement window centered on the aerofoil leading edge. The tested conditions cover the whole pitching cycle with a constant step of 5° in angle of attack. For this test activity, the upstream model was positioned so that the vortex core impinges the leading edge of the target aerofoil at $\alpha = 5^\circ$ in upstroke. Figure 15 shows the contours of the computed divergence of the measured in-plane velocity components for each test condition. This operator represents, for incompressible flows, the variation of the span-wise velocity component in span-wise direction. The change in sign of the divergence operator highlights the vortex core attitude.

At $\alpha = -5^\circ$ the vortex centre-line passes under the aerofoil, as it can be observed in Fig. 15a. Then, it

Figure 15: Trajectory of the vortex for the light dynamic stall condition (contours of the divergence of the in-plane velocity components measured by PIV at z - $z_v = 0$).

arises and brushes the lower aerofoil surface at $\alpha = 0°$ in upstroke phase, getting the aerofoil leading edge at $\alpha = 5°$ (see Fig. 15 b and c). This upward motion is due to the induction of the aerofoil circulation associated to the lift and to the nose-up rotation about its quarter of chord. In the further upstroke motion, the vortex centre-line is deflected further upward. In fact, as it can be observed in Fig. 15d and e, increasing the angle of attack to $\alpha = 10°$ the vortex moves to brush against the upper surface and finally it is rather high over the aerofoil at the maximum incidence $\alpha = 15°$. At $\alpha = 10°$ and 5° in downstroke phase the vortex attitude presents a slightly higher upward deflection with respect to the upstroke phase and it starts to move downward (see Fig. 15f and g). At $\alpha = 0°$ in downstroke, the vortex is still on the upper side of the aerofoil (see Fig. 15h).

5 Conclusions

Experiments demonstrating the effects of a perpendicular vortex on an oscillating aerofoil in light and deep dynamic stall conditions were prepared, set up and executed. Thanks to the present experimental set up, the vortex interaction was investigated considering the effects of the blade pitching motion during a rotation cycle. This represents the main topic of the study. Moreover, the influence of the target aerofoil oscillating motion on the vortex trajectory was investigated in the present activity.

The vortex impacting on the oscillating aerofoil was previously qualified taking into account the phenomenon of vortex wandering. Appropriate statistical methods demonstrated that the vortex was characterised by a quite low degree of diffusion due to the wandering effect.

For the light dynamic stall condition, the effects of the vortex on the flow around the target aerofoil were apparent, especially in the case of downstroke motion. The strong modification of the flow topology observed in this test case demonstrates that the perpendicular vortex interaction can introduce also detrimental effects on the blade performance. In fact, the large flow separation induced by the vortex impact during downstroke motion can trigger the rotor blade stall and, thus, introduce rapid variations and large hysteresis of the airloads, as it occurs in the deep dynamic stall regime.

Moreover, the experimental data set produced in this activity through the two measurement techniques employed could be considered an interesting reference data base for the validation of numerical models. Indeed, the simulation of the complex unsteady aerodynamics related to the BVI phenomenon represents one of the most important goals of the CFD tools. With this purpose, all the experimental data are accessible by request to the authors.

APPENDIX

Nomenclature

BVI	Blade Vortex Interaction
c	blade section model chord [m]
C_L	lift coefficient
dy_0/dx	modification of the aerofoil camber due to the pitching rate [deg]
e	vortex anisotropy parameter
f	oscillation frequency [Hz]
HW	Hot-Wire
k	reduced frequency, $= \pi f c/U_\infty$
Ma	Mach number
pdf	probability density function
PIV	Particle Image Velocimetry
Re	Reynolds number, $\equiv cU_\infty/\nu$
r_v	vortex viscous core radius [mm]
TN	Test Number
U_∞	free-stream velocity [m/s]
u	stream-wise velocity component [m/s]
v	span-wise velocity component [m/s]
w	vertical velocity component [m/s]
V_{θ_v}	maximum vortex tangential velocity [m/s]
UM	Upstream Model
x	stream-wise coordinate [mm]
y	span-wise coordinate [mm]
z	vertical coordinate [mm]
y_v	vortex core centre span-wise coordinate [mm]
z_v	vortex core centre vertical coordinate [mm]
z_{UM}	vertical coordinate of the UM model quarter chord axis [mm]
α	angle of attack [deg]
α_m	mean angle of attack [deg]
α_a	pitching oscillation amplitude [deg]
$\Delta\alpha_{Th}$	modification of the ideal Theodorsen angle of attack [deg]
ν	cinematic viscosity of air [m^2/s]
σ_y	vortex wandering amplitude in span-wise direction [mm]
σ_z	vortex wandering amplitude in vertical direction [mm]

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