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Perpendicular blade–vortex-interaction over an oscillating airfoil in light dynamic stall

G. Droandi, G. Gibertini, A. Zanotti*

Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, Campus Bovisa, Via La Masa 34, 20156 Milano, Italy

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ABSTRACT

An experimental and numerical study was performed to investigate the effects of perpendicular blade vortex interactions on the aerodynamic performance of an oscillating airfoil. The selected test cases studied the aerodynamic interaction of a stream-wise vortex impacting on a NACA 23012 airfoil oscillating in light dynamic stall regime, representing a typical condition of the retreating blade of a helicopter in forward flight. The analysis of particle image velocimetry surveys and time-accurate simulation results enabled to point out the different effects due to the blade pitching motion on the interacting flow field. Thus, numerical results enabled to achieve a detailed insight about the aerodynamic loads acting on the oscillating airfoil in the interacting cases. In particular, the comparison with the clean airfoil case shows that a severe loss of performance is produced by the interaction of the vortex during the airfoil downstroke motion, as the vortex impact triggers the local stall of the blade section.

1. Introduction

The aerodynamic interactions between helicopter rotor blades and its own tip vortices represent an important topic of investigation in rotorcraft research field due to the adverse influence produced on rotor noise (Schmitz and Yu, 1983; Yu, 2000) and rotor performance. In fact, due to these interactions the resulting pressure fluctuations on the blade surface produce highly unsteady aerodynamic loads. Moreover, blade–vortex interactions (BVIs), occurring mainly when the helicopter is slightly descending (Shockey et al., 1997) and the tip vortex wake remains in the region of the rotor disk, are an important source of vibrations and instability. Literature distinguishes different classes of BVIs depending on the direction of the impacting vortex axis with respect to the blade span. In particular, parallel BVI occurs when the vortex and the blade axes are nominally parallel, perpendicular BVI when the axes are perpendicular and in parallel planes, orthogonal BVI when the axes are in orthogonal planes and finally oblique BVI when oblique collisions occur between the vortex and the blade. An extensive review on these interactions is given in Rockwell (1998) and Conlisk (2001).

An important effort was made in both experimental and numerical research fields to provide a better understanding of the physics involved in these aerodynamic interactions and their effects on rotor performance and handling qualities. In particular, in the past years different suitable computational models were developed to reproduce BVI in numerical simulations of rotor flow field. Among these studies, Rahier and Delrieux (1999) developed different vortex models with the capability to deform during close interactions. The suitability of these models to obtain a proper evaluation of noise and

* Corresponding author.
E-mail address: alex.zanotti@polimi.it (A. Zanotti).

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Nomenclature

Roman symbols

α	angle of attack (deg)
α_m	mean angle of attack (deg)
α_a	pitching oscillation amplitude (deg)
ρ	air density (kg/m^3)
ω	circular frequency (rad/s)
$\mathbf{\Omega}$	vorticity tensor
$\parallel \Omega \parallel$	vorticity magnitude (1/s)
Ω_x	stream-wise vorticity component (1/s)
Ω_y	span-wise vorticity component (1/s)
b	oscillating airfoil model span (m)
BVI	blade vortex interaction
c	blade section model chord (m)
CFD	computational fluid dynamics
C_{D^w}	drag coefficient$=D/\frac{1}{2}\rho U_\infty^2 cb$
C_L	sectional lift coefficient$=L/\frac{1}{2}\rho U_\infty^2 c$
C_{L^w}	lift coefficient$=L/\frac{1}{2}\rho U_\infty^2 cb$
C_M	sectional pitching moment coefficient about the airfoil quarter chord $M/\frac{1}{2}\rho U_\infty^2 c^2$
C_{M^w}	pitching moment coefficient about the airfoil quarter chord $M/\frac{1}{2}\rho U_\infty^2 c^2 b$
C_p	pressure coefficient $(p - p_\infty)/\frac{1}{2}\rho U_\infty^2$
d	distance along the normal to chord direction (m)
D	drag (N)
$\Delta\xi$	minimum stream-wise grid spacing on the oscillating airfoil surface
$\Delta\zeta$	minimum span-wise grid spacing on the oscillating airfoil surface
ΔX	minimum grid spacing in X direction for the vortex grid
ΔY	minimum grid spacing in Y direction for the vortex grid
ΔZ	minimum grid spacing in Z direction for the vortex grid
DAER	Dipartimento di Scienze e Tecnologie Aerospaziali
DSV	dynamic stall vortex
f	oscillation frequency (Hz)
k	reduced frequency$=\pi fc/U_\infty$
L	lift (N)
LE	leading edge
M	pitching moment coefficient about the airfoil quarter chord (Nm)
M_a	Mach number
N_{Tot}	total number of grid elements
N_ξ	number of grid elements along the oscillating airfoil section
N_ζ	number of grid elements along the oscillating airfoil span
N_η	number of layers in the oscillating airfoil boundary layer
N_X	number of grid elements in X direction for the vortex grid
N_Y	number of grid elements in Y direction for the vortex grid
N_Z	number of grid elements in Z direction for the vortex grid
OG	oscillating airfoil grid
p	pressure (Pa)
p_∞	free-stream pressure (Pa)
PIV	particle image velocimetry
Q	Q criterion$=1/2(\parallel \mathbf{\Omega} \parallel^2 - \parallel \mathbf{S} \parallel^2)$ (1/s^2)
R_e	Reynolds number
ROSITA	ROtorcraft Software ITAly
$\mathbf{S}$	strain–rate tensor
TE	trailing edge
TS	time steps
u	chord-wise velocity (m/s)
v	span-wise velocity component (m/s)
w	vertical velocity component (m/s)
$\lvert U \rvert$	velocity magnitude (m/s)
U_∞	free-stream velocity (m/s)
VG	vortex generator airfoil grid
x	stream-wise coordinate axis
X	chord-wise coordinate axis
Y	span-wise coordinate axis
Z	vertical coordinate axis

loads was verified by comparison with experimental data. More recently, Zioutis et al. (2004) investigated the influences of numerical simulation of different BVI cases on the computational results of rotor blade downwash distribution and aerodynamic loading. A high-fidelity, implicit large-eddy simulation was used by Garmann and Visbal (2015) to investigate the unsteady interactions resulting from a stream-wise vortex impinging upon a finite plate at different span-wise positions.

A complete analysis including numerical modelling and wind tunnel data for the evaluation of the effects of BVIs on rotor noise was given in Glegg et al. (1999) and Yu (2000), showing that, due to its low unsteadiness, the noise effects of perpendicular BVI are less significant with respect to parallel BVI. Indeed, the sudden pressure fluctuations induced by travelling vortices in parallel BVI result in the propagation of strong impulsive (harmonic) noise, while subsequent perpendicular BVIs produce a continuous (broadband) noise characterised by a much lower intensity compared to the harmonic noise. Nevertheless, the locally induced angles of incidence produced by perpendicular interactions can trigger dynamic stall in the retreating blade and produce rotor vibrations.

Among the experimental activities, Wittmer and Devenport (1999a,b) investigated the turbulent flow field produced by a perpendicular interaction of a stream-wise vortex with a still blade section model, showing that the extent of the turbulent flow region and the turbulent intensity increase due to the interaction of the vortex with the blade section wake. In the past years the use of particle image velocimetry (PIV) provided quantified visualisations of the flow generated during BVIs (Horner et al., 1996; Green et al., 2000). Thanks to the development of stereoscopic PIV set up, a more detailed insight into the three-dimensional nature of the interacting flow field was gained, as done by Green et al. (2006) for the investigation of