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Assessment of 2D/3D numerical modeling for deep dynamic stall experiments

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ABSTRACT

The results of computational fluid dynamics (CFD) simulations in two and three spatial dimensions are compared to pressure measurements and particle image velocimetry (PIV) flow surveys to assess the suitability of numerical models for the simulation of deep dynamic stall experiments carried out on a pitching NACA 23012 airfoil. A sinusoidal pitching motion with a 10° amplitude and a reduced frequency of 0.1 is imposed around two different mean angles of attack of 10° and 15°. The comparison of the airloads curves and of the pressure distribution over the airfoil surface shows that a three-dimensional numerical model can better reproduce the flow structures and the airfoil performance for the deep dynamic stall regime. Also, the vortical structures observed by PIV in the flow field are better captured by the three-dimensional model. This feature highlighted the relevance of three-dimensional effects on the flow field in deep dynamic stall.

1. Introduction

Several rotary-wing aircraft designs currently in advanced or preliminary development stage, such as the tiltrotor, like Bell Boeing V-22, AgustaWestland AW609 (Barbour, 2000) and ERICA concept (Gibertini et al., 2011), or the compound like Sikorsky X2, or the Eurocopter X3, are indeed revolutionary configurations which introduce significant changes with respect to standard helicopter designs. These new configurations were introduced to increase the maximum forward speed of the aircraft, which is currently limited by the occurrence of the dynamic stall on the retreating blade (McCroskey, 1981; Leishman, 2007).

The prediction of the onset and evolution of dynamic stall is a very challenging task. The research on dynamic stall is now focusing on the evaluation of reliable numerical tools for the simulation of this nonlinear, highly unsteady phenomenon, characterised by the rapid formation, migration and shedding of strong vortices (Visbal, 2011). In particular, three-dimensional effects in dynamic stall were recently studied by comparing two- and three-dimensional simulations (see for instance Spentzos et al., 2005; Martinat et al., 2008; Costes and Richez, ; Wang et al., 2012; Klein et al., 2012).

The verification of the numerical models requires thorough comparison between the simulations results and a comprehensive experimental data base (Coton and Galbraith, 1999; Raffel et al., 2011), in particular for the deep dynamic stall conditions. With this aim, a new experimental-numerical activity started at Politecnico di Milano. Wind tunnel tests were carried out on a pitching NACA 23012 blade section. The airfoil was selected since, being a typical helicopter blade airfoil, it was already employed by other researchers in experimental activities about the dynamic stall on pitching blade

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Nomenclature

α	angle of attack (deg)
α_m	mean angle of attack (deg)
α_a	pitching oscillation amplitude (deg)
Δx_{LE}	minimum streamwise grid spacing along airfoil at leading edge
Δx_{TE}	minimum streamwise grid spacing along airfoil at trailing edge
Δx_s	maximum streamwise grid spacing along airfoil
Δz	spanwise grid spacing along blade section model
ω	circular frequency (rad/s)
b	blade section model span (m)
c	blade section model chord (m)
C_L	lift coefficient
C_M	pitching moment coefficient about the airfoil quarter chord
C_p	pressure coefficient
d	distance along the normal to chord direction (m)
DSTA	Dipartimento di Scienze e Tecnologie Aerospaziali
DSV	Dynamic Stall vortex
f	oscillation frequency (Hz)
k	reduced frequency $=\pi fc/U_\infty$
M	Mach number
N	number of grid points
N_{tot}	total number of grid points
N_x	number of grid points along the airfoil surface
N_y	number of grid points in the direction normal to the airfoil surface
N_L	number of layers in boundary layer
PIV	Particle image velocimetry
Re	Reynolds number
TS	Time steps
u	streamwise velocity (m/s)
$\|U\|$	velocity magnitude (m/s)
U_∞	free-stream velocity (m/s)
x	chordwise coordinate axis
y	normal coordinate axis
z	spanwise coordinate axis

sections(Leishman, 1990; Raffel et al., 1995a). The experimental rig was designed to reproduce the deep dynamic stall condition for a full-scale helicopter rotor blade section. The experimental setup is suitable for different measurement techniques including unsteady pressure measurements, obtained from miniaturized pressure transducers installed on the midspan airfoil contour, and particle image velocimetry (PIV), which makes it possible to completely characterise the time-dependent flow field to achieve a detailed insight of the different stages of the dynamic stall process. The main goal of the research effort currently ongoing at Politecnico di Milano is to obtain reliable numerical models to be used in the development and sizing of new control devices for dynamic stall effect mitigation, to be tested in the same rig.

The wind tunnel tests of airfoils are affected by sidewall interference. In particular, when airfoil stall occurs, the flow rapidly becomes three-dimensional (Leishman, 1990), even in the case of a model spanning from wall to wall (Nishino and Shariff, 2010). A possible mitigation of this effect is the wall boundary layer suction (Catalano, 2004) but its implementation together with an oscillating airfoil system, although not impossible in principle, would be quite complex and, actually, the known reference experiments on airfoil dynamic stall (see for instance Gardner et al., 2011; Leishman, 1990; Carr et al., 1978; Raffel et al., 1995b) were carried out without suction.

In the present activity, both two and three-dimensional CFD models were created using EDGE (Eliasson, 2002), a compressible Navier–Stokes solver developed at FOI, the Swedish Defense Research Agency. Two- and three-dimensional numerical results were compared to the experimental ones to expose the suitability of the models to reproduce the performance and the flow physics involved in the deep dynamic stall regime.

In Section 2, the experimental setup is outlined. In Section 3, the EDGE code is briefly described and the two- and three-dimensional CFD models are detailed. Section 4 reports the comparison of two- and three-dimensional simulation against experimental results. Final considerations and comments are given in Section 5.

2. Experimental setup

Experimental activities were conducted at Politecnico di Milano in the low-speed closed-return wind tunnel of the Aerodynamics Laboratory of the DSTA. The wind tunnel has a rectangular test section with 1.5 m height and 1 m width. The maximum wind velocity is 55 m/s and the free stream turbulence level is less than 0.1%.

The airfoil model was manufactured in aluminum, with chord $c=0.3$ m and span $b=3.1$ c. The aspect ratio of the blade section model is close to that used for the models employed in the known reference experiments on dynamic stall (see for instance Gardner et al., 2011; Leishman, 1990). The model has an interchangeable midspan section for the different measurements techniques employed, one for PIV flow surveys and a second one for unsteady pressure measurement equipped with pressure taps positioned along the midspan chord line. The model is pivoted around two external steel shafts corresponding to the 25% of the airfoil chord.

The layout of the experimental rig designed for testing pitching airfoils is presented in Fig. 1. The model pitching motion is provided by a brushless servomotor with a 12:1 gear drive. Two different encoders mounted on the model external shaft mechanically decoupled from the motorized strut were used for feedback control and to get the instantaneous position of