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Experimental assessment of an active L-shaped tab for dynamic stall control

A. Zanotti *, G. Gibertini

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 activity was performed on a NACA 23012 pitching airfoil to investigate the effectiveness of an active trailing edge L-shaped tab for deep dynamic stall control. The active control system, based on the use of micro pneumatic actuators, was designed to control the deployment and retraction of the tab along the oscillating cycle. In particular, the tab was designed to behave as a Gurney flap when deployed as its end prong protrudes at the airfoil trailing edge, while in retracted position the tab behaves as a trailing edge flap. The L-shaped tab design presents interesting features to be employed on rotor blades, due to an easier integration at the trailing edge with respect to a deployable Gurney flap. Wind tunnel tests were carried out considering two pitching cycles producing deep dynamic stall regime. Unsteady pressure measurements were performed at the model midspan section to obtain the phase-averaged aerodynamic loads curves. The tests results showed that the deployment of the tab during the upstroke produces a conspicuous increase of lift with respect to the clean airfoil case, corresponding to a higher level of available thrust on the retreating blade. The retraction of the tab before stall onset does not introduce a valuable effect in terms of pitching moment peak reduction with respect to clean airfoil. Moreover, the active control system produces a conspicuous reduction of the negatively-damped portions of the pitching cycles and of the negative aerodynamic damping peak that could account for stall flutter divergence.

1. Introduction

In recent years, the strong demand for faster helicopters spurred rotorcraft research activity into retreating blade dynamic stall (McCroskey, 1981) which is one of the main aerodynamic phenomenon responsible for limitation of the performance of classical helicopter rotor configurations. Dynamic stall produces, in fact, several adverse effects on helicopter performance as the limitation of the forward speed and thrust, high control system loads and a high level of vibrations affecting the helicopter dynamic performance in terms of maneuver capability and handling qualities. Moreover, an important issue related to dynamic stall process is the occurrence of *stall flutter* (Carta, 1967), a single degree of freedom limit cycle oscillation causing blade structural damage and excessive cabin vibration.

The attention of rotorcraft research was therefore addressed to the design of active blades aimed to alleviate the principal detrimental effects induced by dynamic stall in order to expand the helicopter flight envelope, the vehicle utility and preserve the structural integrity of the rotor blades. Of course, the evaluation of an effective active device to be used on a rotor represents a very challenging activity, taking into account the severe requirements related to its integration on a helicopter

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

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Nomenclature

α	angle of attack [deg]
α_m	mean angle of attack [deg]
α_a	pitching oscillation amplitude [deg]
$\Xi(t)$	time-resolved aerodynamic damping coefficient
Ξ_{cycle}	cycle-integrated aerodynamic damping coefficient
ω	circular frequency [rad/s]
$A_{C_M}(t)$	time-resolved aerodynamic damping amplitude = $\sqrt{C_M^2 + \tilde{C_M}^2}$
b	airfoil section model span [m]
c	airfoil section model chord [m]
C_L	lift coefficient
C_M	pitching moment coefficient about the airfoil quarter chord
C_p	pressure coefficient
DSV	Dynamic Stall vortex
f	oscillation frequency [Hz]
h	height of the deployed L-tab end prong below the trailing edge [m]
HES	Hall Effect Sensor
k	reduced frequency $= \pi f c / U_\infty$
M	Mach number
Re	Reynolds number
t	time [s]
U_∞	free-stream velocity [m/s]
x	chord-wise coordinate axis

Superscripts

$\tilde{}$	Hilbert transformed data-series

blade and the severe operative conditions. Many attractive solutions were investigated in the recent literature. The most of these experimental activities were carried out on oscillating airfoils. This test case presents, in fact, the characteristics of being a simple effective tool to evaluate the potential capabilities of the investigated device before a definite experimental assessment in the real operative conditions of a helicopter rotor blade. In the following a brief analysis of the most interesting activities in this field is given.

Improvements in dynamic stall control were investigated by means of the optimization of the blade airfoil shape during the pitching cycle. For instance, Chandrasekhara et al. (2004) studied the effect of the drooping on the leading portion of an oscillating airfoil. Tests results showed that the leading edge droop reduces the strength of the dynamic stall vortex (DSV) and consequently produces a reduction of the negative peak pitching-moment together with a net positive aerodynamic damping of the airfoil. Similar results were found in the numerical study by Feszty et al. (2004) investigating the effect of a classical trailing edge flap for dynamic stall alleviation over a pitching airfoil. In particular, the upward deflection of the flap for the duration of about $\frac{1}{3}$ of the airfoil motion period produces a weakening of the DSV responsible for the large negative pitching moments and associated to negative aerodynamic damping. Nevertheless, both the described solutions produced a reduction of the available lift force with respect to the clean airfoil configuration. Moreover, the use of such devices would require a complex mechanical system for the actuation that would introduce an apparent increase of weight to be avoided on a rotor blade subject to high centrifugal forces. On the other hand, a quite simple and effective solution in terms of device integration and actuation system was recently explored by Gardner et al. (2017) that obtained interesting results in terms of dynamic stall hysteresis reduction and pitching moment peak decrease by means of a back-flow flap attached to the suction side of an airfoil with a solid-state hinge and guided by a magnetic actuator.

Similar results were found by Le Pape et al. (2012) and Mai et al. (2008) that investigated the use of a row of deployable vortex generators implemented at the leading edge of an airfoil in both static and dynamic stall conditions. Indeed, the experiments showed that the deployment of vortex generators during the retreating blade side of the rotor disk produces the reduction of the pitching moment peak and the area of the negative damping hysteresis loop, but introduces a not negligible penalty on the lift force. Nevertheless, different compromises on the effect on lift and pitching moment can be achieved by varying the heights and the phase of actuation of the vortex generators.

Blowing devices typically used to delay the static stall were also studied for dynamic stall alleviation. For instance, Singh et al. (2006) investigated the use of air-jet vortex generators. In this test case, the air blown tangentially at the leading edge of the airfoil produces a delay of the flow separation and of the DSV formation. The DSV was also weakened by the air-jet interaction with a consequent reduction of the pitching moment peak. The air-jet blowing also promotes the reattachment of