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High-resolution computational fluid dynamics predictions for the static and dynamic stall of a finite-span OA209 wing[☆]

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ABSTRACT

High-resolution computational fluid dynamics (CFD) predictions of static and dynamic stall of a finite-span ONERA OA209 wing were validated against the wind tunnel test measurements. The freestream Mach number was 0.16 and the Reynold number was 1 million. For the dynamic stall study, a sinusoidal pitching motion was prescribed. The CFD modeling approaches employed were — Delayed Detached Eddy Simulation (DDES) modeling using the NASA OVERFLOW flow solver, Unsteady Reynolds-averaged Navier–Stokes (URANS) modeling using the ONERA elsA flow solver, and DDES modeling using the NASA FUN3D flow solver. The flow was modeled as both fully turbulent and transitional. A comparative study between predictions and the wind-tunnel test data for pre- and post-stall measurements was carried out that included wing section lift and moment, surface pressure, and velocity field at chordwise and spanwise planes. The high spatial and temporal resolutions employed resulted in good correlations with the test data, in particular with the inclusion of DDES modeling along with a turbulence transition model. The CFD modeling parameters thus establish were applied to a deep and a light stall cases, and were found to accurately capture the wing section loads, demonstrating its generalizability in capturing the stall dynamics.

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1. Introduction

Helicopter rotor blades encounter a wide range of aerodynamic conditions during forward flight, varying from transonic flow with limited angles of attack on advancing blade side to low subsonic flow with large angles of attack on retreating blade. Under high blade loading, encountered in severe maneuvers and high thrust conditions, angles of attack above the static stall angle are reached on the retreating blade. The cyclic pitching motion of the blade then leads to unsteady flow separation on the retreating side blade, referred to as dynamic stall.

Dynamic stall, in general, is characterized by three distinct mechanisms, or a combination thereof: leading-edge separation, trailing-edge separation, and shock-induced separation. The leading-edge stall, of the three, is commonly encountered on helicopter rotor blades. It encompasses a number of complex fluid mechanics phenomena such as formation of laminar

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Nomenclature

C	wing chord, m
C_l	section lift coefficient, $\frac{l}{1/2\rho_\infty V_\infty^2 C}$
C_m	section moment coefficient, $\frac{m}{1/2\rho_\infty V_\infty^2 C^2}$
c	speed of sound, m/s
d	distance to the wall, m
K	reduced frequency, $\Omega C/(2V_\infty)$
k	turbulent kinetic energy, m^2/s^2
l	section lift per unit span, N/m
m	section moment per unit span, Nm/m
M	freestream Mach number, V_∞/c_∞
N	number of grid points
R	wing span, m
r	wing span location, m
Re	freestream Reynolds number, $V_\infty C/\nu_\infty$
t	time, s
T	pitching period, $2\pi/\Omega$
TI	turbulence intensity, $\sqrt{2/3k/V_\infty^2}$
u^*	friction velocity, $\sqrt{\tau_w/\rho}$, m/s
V_x	streamwise velocity, m/s
V_y	vertical velocity, m/s
V_z	spanwise velocity, m/s
V	speed, m/s
y^+	u^*d/ν
δ	grid spacing, m
ρ	density, kg/m^3
θ	wing pitch angle, deg
θ_A	amplitude of sinusoidal pitching, deg
θ_M	mean of sinusoidal pitching, deg
ϕ	phase of sinusoidal pitching, deg
ν	kinematic viscosity, μ/ρ, m^2/s
μ	molecular viscosity, kg/m/s
μ_t	turbulent (eddy) viscosity, kg/m/s
ω	specific turbulent dissipation rate, 1/s
Ω	pitching rotational rate, rad/s
τ_w	wall shear stress, N/m^2

Subscript

∞	freestream value

Abbreviations

2-D	Two-dimensional
3-D	Three-dimensional
CFD	Computational Fluid Dynamics
DDES	Delayed Detached Eddy Simulation
LDV	Laser Doppler Velocimetry
PIV	Particle Image Velocimetry
LM	Langtry–Menter γ-$Re_{\theta t}$ transition model
SA	Spalart–Allmaras
SST	Shear Stress Transport
URANS	Unsteady Reynolds-Averaged Navier–Stokes

separation bubble(s), transition of flow from laminar to turbulent, formation of a leading-edge vortex, interaction of the vortex with the viscous shear layer, and flow reattachment. During upstroke, the flow unsteadiness causes the stall to be delayed to angles much higher than the static stall angle. Upon separation, a leading-edge vortex is formed which enhances