Modelling Rotor Wakes in Ground Effect


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Numerical prediction of the geometry of the rotor wake and its effect on the performance of the helicopter, when in ground effect, remains a challenge. This is because certain experimentally observed features of the rotor flow field, such as the formation of the characteristic "ground vortex" and the dynamics of its interaction with the remainder of the rotor flow, require extremely long-term calculations, in computational terms, to capture. The development of the rotor flow field in ground effect is studied using a computational model which, through its vorticity conserving properties, is ideally suited to capturing vortical features in the flow that take a large number of rotor revolutions to develop. Computations confirm experimental observations that the geometry of the rotor wake undergoes a transition through a set of qualitatively different flow states as the helicopter's forward speed is increased. Transition between states is mediated by what appears to be a convective instability of the vortex sheet generated on the ground plane by the rotor. Certain characteristic features in the rotor thrust and power, and in the variation of control angles with forward speed, can be traced back to the dynamics of the vortical structures produced by the growth of this instability.

Nomenclature

A	rotor disc area, πR^2
a	aerofoil lift-curve slope
C_L	blade section lift coefficient
C_T	rotor thrust, scaled by $\rho A(\Omega R)^2$
c	blade chord, scaled by R
h	height above the ground, scaled by R
I_β	blade flapping inertia, scaled by $\rho A R^3$
N	number of rotor blades
P	induced power
R	rotor radius
r	radial coordinate, scaled by R
v	flow velocity, scaled by ΩR
γ_β	rotor Lock number, $ac/\pi I_\beta$
θ	blade pitch: $\theta = \theta_0 + \theta_{1s} \sin\psi + \theta_{1c} \cos\psi$
θ_0	collective pitch control angle
θ_{1c}	lateral cyclic control angle
θ_{1s}	longitudinal cyclic control angle
μ	advance ratio (rotor forward speed, scaled by ΩR)
μ^*	thrust-weighted advance ratio (rotor forward speed, scaled by $\Omega R\sqrt{C_T/2}$)
ρ	air density
σ	rotor solidity, Nc/π
ψ	rotor azimuth
ω	flow vorticity, scaled by ΩR^2
Ω	rotor rotational speed

Abbreviations

IGE	In Ground Effect
OGE	Out of Ground Effect (i.e. in free air)
VTM	Vorticity Transport Model

Introduction

It is well known that when a helicopter operates at heights above the ground that are less than roughly the diameter of its rotor, such as during takeoff and landing, the proximity of the ground modifies the geometry of the rotor wake and hence the performance of the helicopter.

The geometry of the wake of a rotor hovering in ground effect, and the effects of the geometry of the wake on the rotor's performance, have been studied in great detail both experimentally and numerically (Refs. 1–8). In simple terms, as the rotor wake approaches the ground it is forced to spread out, rather than contracting as it would in free air. The associated reduction of the inflow through the rotor that accompanies this expansion in the wake alters the load distribution on the rotor disc in such a way that, for a given thrust, the power required by the rotor decreases as the height of the rotor above the ground is reduced (Ref. 2).

Transition from hover to forward flight breaks the circular symmetry of the rotor-induced flow on the ground plane. Along a horseshoe-shaped stagnation locus some distance upstream of the rotor, the velocity of the rotor-induced flow moving forward ahead of the helicopter is balanced by the velocity of the free stream (Ref. 9). This causes the flow to separate from the ground plane, and the wake of the rotor is observed to roll up to form a concentrated "ground vortex" just above this separation line. As the forward speed of the rotor is increased, this vortex moves downstream towards the leading edge of the rotor, and, in contrast to the situation out of ground effect where the power required reduces considerably, the power required by the rotor in ground effect remains effectively constant or even increases because of the downwash induced by this vortex (Ref. 10). The

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