JOURNAL OF AIRCRAFT
Vol. 46, No. 5, September–October 2009

Numerical Simulation of Autorotation in Forward Flight

Hak Yoon Kim*
Korea Aerospace University, Goyang 412-791, Republic of Korea
Dong Jin Sheen†
Hanseo University, Seosan 360-706, Republic of Korea
and
Seung O. Park‡
Korea Advanced Institute of Science and Technology, Daejeon 305-701, Republic of Korea

DOI: 10.2514/1.42209

Autorotation in forward flight is an important subject for gyroplanes or compound helicopters. By integrating the flapping and rotational equations of motion, we investigate in this work the steady-state autorotation of a three-bladed rotor for a given set of three independent variables: forward velocity, collective pitch angle, and shaft angle. Two-dimensional aerodynamic coefficients as functions of the angle of attack and the Reynolds number from the Navier–Stokes simulation and Pitt/Peters inflow model to determine induced flowfield are adopted to implement the simulation. Transient behavior of the solution from arbitrary initial conditions to a steady-state periodic solution is described. Variations of rotor speed and flapping angle of autorotation with the shaft angle and the collective pitch angle for a given forward velocity are presented and discussed in detail. Drastic changes in the region of autorotation near a specific shaft angle is found to exist, below which the range of collective pitch angle for stable autorotation becomes very limited and the flapping angle changes abruptly with the pitch angle.

Nomenclature

B = tip-loss factor
b = number of rotor blades
$C_L(\psi)$, $C_M(\psi)$ = rolling and pitching moment coefficients of the rotor
$C_T(\psi)$ = thrust coefficient of the rotor
c = blade section chord, m
c_l, c_d = lift and drag coefficients of the airfoil section
d_{CM} = distance from the flapping hinge to the blade center of mass, m
e = flapping hinge offset, m
g = acceleration due to gravity, $\mathrm{m/s^2}$
I_h = flapping moment of inertia of one rotor blade, $\mathrm{kg \cdot m^2}$
I_p = polar moment of inertia of complete rotor system, $\mathrm{kg \cdot m^2}$
n = index used in the summation of the number of rotor blades
R = rotor blade radius, m
r = distance measured along the blade, from the axis of rotation to the blade element, m
V = velocity along the flight path, m/s
$v_i(r, \psi)$ = induced-velocity distribution; negative in the downwash sense, m/s
v_{im} = momentum-induced velocity at the rotor; negative in the downwash sense, m/s
v_0, v_s, v_c = induced-velocity harmonics, m/s
W = rotor blade weight, N
x = ratio of the blade element radius to the rotor blade radius, r/R
x_c = nondimensional cutout radius, r_c/R
α_s = rotor shaft angle (angle of attack of the disk plane), deg
β = rotor blade flapping angle with respect to the hub plane, rad, deg
$\beta_{\max}$, $\beta_{\min}$ = maximum and minimum flapping angles, deg
$\dot{\beta}$, $\ddot{\beta}$ = first and second derivatives of β with respect to time, rad/s, $\mathrm{rad/s^2}$
λ_S = inflow ratio, $(V \sin \alpha_s - v_i)/\Omega R$
μ_S = advance ratio, $V \cos \alpha_s / \Omega R$
ξ = nondimensional hinge offset distance, e/R
ρ = mass density of air, $\mathrm{kg/m^3}$
ψ = blade azimuth angle measured from a downwind position in the direction of rotation, deg
Ω, $\dot{\Omega}$ = rotor angular velocity and acceleration, rad/s, $\mathrm{rad/s^2}$

I. Introduction

AUTOROTATION in rotorcrafts is a parametrically well-defined phenomenon, as reviewed by Lugt [1]. The governing equations for the flapping and rotational motions of rotors are well established, as can be found in Johnson [2] and other references. These equations involve various dynamic properties of the rotors, complicated aerodynamics, pitch–flap coupling, hinge offset, etc. For the analysis of autorotation, these equations have often been applied so far to determine collective pitch angles iteratively under the condition that the aerodynamic torque on the rotor is zero.

Vertical autorotation is of main interest in helicopters. In a recent study [3], blade element momentum theory and a modified Froude–Finsterwalder equation for the inflow were applied for the analysis of autorotation. The flapping equation (with a flap frequency) and the inflow equation were used to design an autorotative payload delivery system in [4]. Gyroplanes and compound helicopters use autorotation during vertical and high-speed forward flights. To deal with this wide spectrum of flight conditions, cases of various advance ratios along with nonlinear and unsteady aerodynamics must be considered. McCormick [5] adopted a simplified flapping equation with a first harmonic nonuniform inflow model in his numerical study. Floros and Johnson [6] performed a numerical

---

Received 16 November 2008; accepted for publication 20 March 2009.

*Lecturer, Department of Aircraft Maintenance Institute, 200-1 Hwajeon-dong, Deogyang-gu; also Ph.D. Student, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Republic of Korea. Member AIAA.

†Associate Professor, Department of Aeromechanical Engineering, 360 Daegok-ri, Haemi-myun.

‡Professor, Department of Aerospace Engineering, 373-1 Kusong-dong, Yuseong-gu. Senior Member AIAA.