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Effect of Rotation Kinematics and Angle of Attack on Flapping Flight

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Unsteady aerodynamics of a rigid flapping wing at a Reynolds number of 10,000 for forward flight with an advance ratio of 0.5 is analyzed. A spiral leading-edge vortex with a strong spanwise flow along its core is formed during the downstroke, resulting in a peak lift and thrust. A negative spanwise flow formed due to the tip vortex prevents the removal of vorticity from the leading-edge vortex, leading to instability and separation of the leading-edge vortex. Analysis of different rotation timings shows that supination results in the leading-edge vortex formation near the base and its strength depends on the flapping velocity. A stronger vortex is formed for advanced rotation and it generates high lift. Delayed rotation affects thrust production during translation and results in low propulsive efficiency. Analysis of rotation duration shows that shorter rotation results in high instantaneous lift values, whereas continuous long-duration rotation results in high thrust and propulsive efficiency. Analysis of different angles of attack show that a moderate angle of attack, which results in a high thrust-to-lift ratio and complete shedding of the leading-edge vortex at the end of translation, is required for high propulsive efficiency.

Nomenclature

$\mathbf{a}^i$ = contravariant basis vectors
C = midspan chord length
C_L = coefficient of lift
C_T = coefficient of thrust
F = force acting on the wing
f = frequency of flapping
$\sqrt{g}$ = Jacobian of the transformation
g^{ij} = contravariant metric tensor
$\sqrt{g}U^j$ = contravariant flux vector
$\sqrt{g}U_g^j$ = contravariant flux due to grid movement
J = advance ratio (U_∞/U_f), ratio of the flight velocity to the flapping velocity
P = power
p = pressure
R = semiwingspan
Re = Reynolds number ($U_f c/\nu$)
Re_t = inverse of the turbulent viscosity
Uf = flapping velocity; $2\Phi f R$
U_∞ = freestream velocity, forward-flight velocity
u_i = Cartesian velocity vector
u_i^g = Cartesian grid velocity vector
$\mathbf{x}$ = physical space coordinate
α = angle of attack
β = stroke plane angle
η_{prop} = propulsive efficiency
ν = kinematic viscosity
$\boldsymbol{\xi}$ = computational space coordinate
ρ = torsional angle
τ = shear stress on the surface of the wing
Φ = total flapping amplitude (maximum to minimum)
ϕ = flapping amplitude
Ω = angular velocity
ω = vorticity

Subscripts

d = downstroke
eff = effective
u = upstroke
x, y, z = fixed reference frame
ξ, η, ζ = rotating reference frame

I. Introduction

Micro air vehicles (MAVs) typically have dimensions of less than 15–20 cm with gross takeoff weights of around 100 to 200 g and flight speeds of around 10–15 m/s, which corresponds to a Reynolds number range between 10,000 and 100,000. At these low Reynolds numbers, the aerodynamic efficiency (lift-to-drag ratio) of conventional fixed airfoils rapidly deteriorates [1]. The chief reason for the deterioration in performance is that at low Reynolds numbers, the boundary layer remains laminar downstream of the location of minimum pressure on the airfoil, making it very susceptible to flow separation as the angle of attack increases, resulting in an early onset of stall (Carmichael [2]). In addition, because of the low-aspect-ratio wings used in MAVs, the tip vortex covers a major part of the wing and the aerodynamic performance is greatly affected by the shedding of the tip vortices (Pelletier and Mueller [3]). On the other hand, birds and insects for which the flight regime coincides with that of MAVs use flapping wings to provide both lift and thrust efficiently. They do this by taking advantage of unsteady flow mechanisms using wing kinematics evolved over millions of years. The kinematics involved in normal flapping flight are divided into two translation motions corresponding to up- and downstrokes and two rotational motions (pronation and supination) corresponding to stroke reversals. Pronation is achieved before the downstroke and supination is achieved before the upstroke. Figure 1 shows the critical kinematic parameters of flapping flight, with their definitions given in Table. 1.

A number of unsteady aerodynamic mechanisms such as clap and fling [4], delayed stall [5,6], wake capturing [7], and rotational circulation [7] have been proposed to explain the generation of lift in birds and insects. Among these, the delayed-stall mechanism involves the formation of a stable leading-edge vortex (LEV) and is the primary mechanism used by most birds and insects for production of lift and thrust during the translational period. During the downstroke, air swirls around the leading edge and forms a LEV. This LEV increases the bound vortex circulation and hence the lift. In a fixed airfoil, the formation of the LEV leads to dynamic stall within

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