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Effects of deformation on lift and power efficiency in a hovering motion of a chord-wise flexible wing

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ABSTRACT

To understand the effects of flexibility on aerodynamic force, the lattice Boltzmann flexible particle method (LBFPM) is employed to simulate deformation and its relationship with inertial and elastic forces in a flapping motion of a chord-wise flexible wing in a three-dimensional space at a hovering Reynolds number of Re = 136. The rigidity *EI* and effective inertia Π_0 are systematically varied, and lift, drag, deformation and power efficiency are computed and compared. It is found that both the rotational and translational inertia contribute to the deflection limited by flexural rigidity and result in a large angular and translation velocities, which generate a large intensity of vorticity and benefit lift and power efficiency. It is revealed that a “mirrored S” or “S” shaped deflection due to the rotational inertia plays a more positive role than the deflection caused by the translational inertia.

1. Introduction

Some natural fliers, such as insects and birds, may fly with flexible wings flapping due to the lack of wheels in nature, while most modern aircrafts use either fixed or rotational wings. It is well known that the forces on flexible wings are determined not only by wing-flapping kinematics, but also by the motion of the surrounding fluid. Interactions between deformation and unsteady fluid flow may alter the fluid field and change hydrodynamic forces on the wings. Therefore, it is important to understand the sophisticated interacting relationships between the deformation and the structure of fluid response.

The deformation is determined not only by the forces exacted on the wing, but also by its elastic properties. The values of elastic flexural rigidity in span-wise or chord-wise directions depend on wing materials and structure, such as vein arrangement, folding lines, and flexion lines. In general, flying vertebrates, such as birds and bats, can actively control the degree of wing bending and twisting by using muscular contraction or expansion and by bone movement. However, insects can use only their base to actively drive wing flapping and transmit the motion outward to wing tips. They cannot actively control their deformation due to the lack of muscles over the wing chord and span since muscles are limited to the wing base area. The insects mainly experience passive deformation, bending or twisting, responding to aerodynamic forces, inertial motion of the wings, and asymmetrical flexural rigidity in chord and span directions. Deformations, including span

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Nomenlature

κ	reduced frequency
Re	Reynolds number
p	pressure
f	flapping frequency
ω	flapping angular velocity
U_0	reference velocity
ν	kinematic viscosity
H	amplitude of the plunge
l	coordinate variable along the chord direction
Π_0	effective inertia
ρ_s	wing density
ρ_f	fluid density
h	wing thickness
EI_l	bending flexural rigidity
E	Young's modulus
I_l	second moment of area
c	chord length
s	span length
F_f	non-dimensional hydrodynamic force per unit chord length
$f_\sigma(\vec{x},t)$	fluid particle distribution function
$\vec{e}_\sigma$	particles discrete velocity
$f_\sigma^{eq}(\vec{x},t)$	equilibrium distribution function
δt	length of time step
τ	single relaxation time
σ	direction number of the particle discrete velocity
$\vec{u}$	fluid velocity
ω_σ	weight coefficient
ϵ	Knudsen number
t_0	short time scale
t_1	long time scale
t_+	time after fluid particle collision
$\vec{\Omega}$	angular velocity of the solid segment
$\vec{U}_b$	boundary velocity of the solid segment
$\vec{U}_c$	velocity of the mass center of solid segment
$\vec{R}_i$	position vector of the mass center of solid segment i
$\vec{x}_b$	position vector of the solid boundary node
$\vec{x}$	position vector of the fluid boundary node
$\vec{F}$	hydrodynamic force
$\vec{F}^h$	total hydrodynamic force on solid particle i
$\vec{T}^h$	total hydrodynamic torque on solid particle i
$\vec{C}^{i+}_i$	vector from the mass center of the segment i to the joint
$\vec{c}^{\,+}_i$	semi-axis vector of the wing segment in the body-fixed coordinate system
N	number of the segment
a_3	length of the semi-axis of the wing segment along the chord
Θ_i	bending angle between the ith and $(i+1)$th segment
$\vec{F}_{ih}$	total force on segment i
$\vec{F}_i$	total hydrodynamic force on segment i
$\mathbf{I}$	inertial moment
M	mass of segment
$\vec{G}_{ti}$	total constraint force on the ith segment
$\vec{T}^b$	total bending torque
$\vec{T}^{G}_{ti}$	total torque due to the constraint force
$\vec{G}_i$	constraint force on joint i
ω_0	nature frequency
ω^*	normalized frequency
C_l	lift coefficient
F_y	total hydrodynamic force in the Y-direction
C_d	drag coefficient
F_z	total hydrodynamic force in the Z-direction
P	power input coefficient
f_P	power efficiency
θ	pitch angle
α_0	initial pitch angle
α_1	amplitude of pitch motion
α_2	phase angle
O'_z	pitch angular velocity
U_r	angular velocity amplitude
θ_L	leading edge angle
θ_T	trailing edge angle
$\Delta\theta_L$	leading edge deflection angle
$\Delta\theta_B$	trailing edge deflection angle

deflection and chord camber due to flexion lines, have been observed (Wootton, 1981, 1990), in particular, at stroke reversal points where acceleration and deceleration occur.

To understand how the wing deforms due to flapping, Heathcote et al. (2004) conducted experiments to investigate the flexibility of a wing in chordwise (Heathcote and Gursul, 2007) and spanwise (Heathcote et al., 2008) directions on the thrust, lift, and power efficiency. They found that at high plunge frequencies the thrust coefficient of the airfoil with intermediate stiffness was greatest. Recently, Chimakurthi et al. (2009) presented a computational aero-elasticity framework for analyzing a flapping wing in a three-dimensional space. Their computational results for flexibility in the spanwise direction of a wing plunging were consistent with the experimental results of Heathcote (Shyy et al., 1999, 2010). The simulations of Visbal et al. (2009) and Gordnier et al. (2010) have shown that flexibility may delay stall and enhance thrust forces. Many other authors have closely related natural resonance to flight performance. Masoud and Alexeev (2010) showed that at the ratio of the flapping to natural frequency of 0.95 the maximal propulsive force was obtained. Spagnolie et al. (2010) had forward velocity peaks when the flapping frequency is near the resonance frequency. Michelin and Llewellyn Smith (2009), Thiria and Godoy-Diana (2010), Gogulapati and Friedmann (2011), and Wu et al. (2010) have had a similar conclusion. This is that when flapping frequency is close to the natural frequency, the resonance phenomenon induces a large lift or propulsive force and maximizes the efficiency.

However, Sunada et al. (1998) measured the natural frequency and the wing-beating frequency of four different dragonflies. They found that the wing-beat frequency ratios were in the range 0.3–0.46 while Chen et al.'s (2008)

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