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Effects of mass and chordwise flexibility on 2D self-propelled flapping wings

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ABSTRACT

A self-propelled flexible flapping wing 2D numerical model undergoing a combined pitching and heaving motion is presented. Since such freely moving foil experiences zero net thrust, a definition of efficiency for this kind of problem is proposed and discussed against other formulations found in the literature. It is also shown that the deviation motion of wings such as that found in natural flyers is likely a consequence of the fluid–structure dynamics of the wings. The passive deviation motion observed in numerical simulations is either a consequence of a feathering mechanism referred to as rigid feathering or of the inertial displacement caused by the wing deformation. The effects of flexibility on the performance of the wing are also presented. It is found that flexibility may significantly enhance the efficiency in pressure-driven deformation cases. The rigid feathering mechanism is found to have an effect similar to that of the feathering caused by wing flexibility on the performances of pressure-driven deformation cases.

1. Introduction

While most studies of oscillating wing are performed in an imposed upstream flow, the motion of flying animals or man-made flying devices is not constrained; it is a consequence of the propulsive force. In the case of flapping wings, the resulting velocity is most likely to fluctuate since the propulsive mechanism is unsteady. This remains true unless the mass of the body on which the wings are attached, is much larger than the wing themselves. Recently, the study of self-propelled flapping wings seems to have gained prevalence over "clamped" flapping wings (Zhang et al., 2009, 2010; Spagnolie et al., 2010; Thiria and Godoy-Diana, 2010; Ramananarivo et al., 2011; Alben et al., 2012; Hua et al., 2013; Lee and Lee, 2013; Yeh and Alexeev, 2014; Zhu et al., 2014a, 2014b).

Letting the wing free to move in the direction transverse to the strokes inherently introduces some passive mechanisms on the wing. Yet, passive mechanisms are known to be used by flying and swimming animals to minimize their energy consumption. For example, some insects, such as dragonflies, benefit from fluid torque to achieve effortless wing rotation during the pronation (see Wang, 2005). As another example, fishes that swim upstream behind an obstacle not only do benefit from a low velocity wake region that reduces the effort needed to stay put, but actually experience thrust. Indeed, Beal et al. (2006) demonstrated that even a dead fish can experience thrust when its body resonates with the vortices in the wake of a bluff body. Further experiments showed that it is also possible to apply this principle to a high-aspect-ratio foil

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Nomenclature

$\mathbf{c}$	relative convective velocity
c	chord length
C_P	power coefficient
C_p	pressure coefficient
C_T	thrust coefficient
(d_x, d_y)	displacement vector field
E	Young modulus
e	wing thickness
$\tilde{e}$	Green–Lagrange strain
$\mathbf{F}'$	force vector per unit span
f	frequency
f^*	reduced frequency
h	heaving displacement
h^*	normalized heaving amplitude
h_0	heaving amplitude
I'	beam cross-section area moment of inertia per unit span
M'	internal bending moment in a beam per unit span, moment per unit span
N'	internal normal force in a beam per unit span
$\hat{\mathbf{n}}$	unit surface normal vector
P	power
p	pressure field
Re	Reynolds number
S	surface
St	Strouhal number
T	thrust force
t	time
U^*	normalized velocity
V	volume
$\mathbf{v}$	velocity vector field
$\hat{\mathbf{v}}$	control surface velocity
α	angle of attack
α_{Eff}	effective angle of attack
$\tilde{\chi}$	curvature of the deformed beam
δ_P^*	normalized flexibility
η	efficiency
μ	dynamic viscosity
ν	kinematic viscosity
ω	vorticity field (z-component)
$\tilde{\phi}$	phase shift
ρ	density
Σ	pressure-to-inertia ratio
τ	shear load
θ	pitching angle
θ_0	pitching amplitude
θ_{Eff}	effective pitching angle

behind a long D-cylinder. A similar study was also performed by Eldredge and Pisani (2008) using a viscous vortex particles method to model three rigid bodies connected with hinges. It was found, surprisingly, that the mechanism works equally well on multi-elements rigid bodies whether the hinges are linked with torsional springs or locked.

Using the same numerical method, Wilson and Eldredge (2011) studied the physics of bodies. These bodies were either actively or passively controlled. In the case of passively controlled bodies, the motion was specified on certain hinges while the other hinges were linked with torsional springs. On the other hand, actively controlled bodies used prescribed kinematics on all hinges. It was found that some configurations with passively controlled bodies provide optimal swimming speed and efficiency.

On a more fundamental perspective, von Ellenrieder et al. (2008) suggested that the choice of wing frequency in swimming and flying animals may be the result of a limit cycle process. That is, the flapping wing dynamics of such species would rely significantly on passive mechanisms. In that context, a device that propels itself using a specific flapping wing configuration (geometry and kinematics) without active control should be designed so that it naturally reaches a limit cycle that corresponds to an optimal regime.

In this paper, mass and chordwise flexibility effects on self-propelled 2D flapping wings performances are investigated with respect to a formal dimensionless parametric space previously introduced (Olivier and Dumas, 2016). The imposed kinematics consists of a combined pitching and heaving motion while the wing is let free to move in the horizontal direction. The imposed pitching motion forces the wing to travel in a specific direction (a zero pitching amplitude can produce a hysteretic regime involving either forward or backward motion, see Zhang et al. (2009, 2010) and Spagnolie et al. (2010)). In cases of strong fluid–structure interactions (i.e., light wings with respect to fluid), it will be shown that two feathering mechanisms act simultaneously and strongly affect the dynamics of the wing and of the flow. On the other hand, when weak fluid–structure interactions occur (i.e., heavy wings with respect to fluid), the rigid wing acts mostly as if it was moving at constant velocity in the x-direction while the flexible ones exhibit a small deviation motion. Moreover, while self-propelled wings reach a terminal average velocity from which a reduced frequency can be computed, the circumstances under which the optimal reduced frequency of the corresponding constrained scenario is reached will be discussed. Section 2 introduces the proposed flexible flapping wing problem definition and the corresponding performance metrics. Section 3 presents the mathematical model that describes the incompressible flow and the elastic wing section as well as the numerical methods used to solve the fluid–structure coupled problem. Section 4 presents numerical verifications and discusses the validity of the numerical method. Finally, Section 5 reports the results and discussions of 2D self-propelled rigid and flexible flapping wings.