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Numerical study of the effect of motion parameters on propulsive efficiency for an oscillating airfoil

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ABSTRACT

A numerical study on an airfoil undergoing combined heaving and pitching motion in cruise condition to assess the effect of a range of kinematic parameters on the propulsive efficiency is presented. The study assesses the effect of parameters like oscillation frequency, pitch amplitude, and non-dimensional heaving amplitude on the propulsive efficiency of the airfoil and uses an in-house computational fluid dynamics code. The propulsive efficiencies of the foil in the frequency range of 1–30 Hz, pitch amplitude range of 3–19º, and non-dimensional heave amplitude range of 0.1–0.9 were computed and compared in order to explore the relationship between kinematic parameters and propulsive efficiency. Results indicate that at smaller pitch amplitudes low efficiencies occur at lower frequencies and high efficiencies occur when frequencies and heave amplitudes are on higher side. The low propulsive efficiency regions disappear with increasing pitch amplitude and larger regions at higher frequencies and heave amplitudes show high efficiencies. When both heave amplitude and frequency are small, propulsive efficiency is less than 0.5; when heave amplitude range is from 0.2 to 0.7, high efficiency occurs at high frequencies, however, with increasing heave amplitudes, these high efficiencies occur at lower frequencies. When the range of frequency is from 8 Hz to 30 Hz, the size of high efficiency area first increases, then decreases. And we explore the reasons why the oscillation frequency, pitch amplitude, and non-dimensional heaving amplitude can affect the propulsive efficiency. Combinations of kinematic parameters for optimal propulsive efficiency have been identified.

1. Introduction

Flapping-wing Micro Air Vehicle (FMAV) is an integrated system that can combine propulsion and lift at a wide range of speeds. Due to its high propulsive efficiency and stealth capability, FMAV continues to be a growing field, with ongoing research into unsteady, low Reynolds number aerodynamics, micro-fabrication, fluid-structure interaction etc. A significant performance index for FMAVs is the propulsive efficiency of their flapping wings which affects flight speed, range, and endurance. Therefore, an in-depth study is necessary to improve current understanding of the effects of kinematic parameters of the flapping wings on the propulsive efficiency of a FMAV. There are four forces that act on a FMAV in flight: lift, weight, thrust, and drag. If the magnitude and direction of the forces acting on the FMAV are exactly balanced, then there is no net force acting on the FMAV and a steady-cruise condition is

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Nomenclature

a	speed of sound
c	chord length
C_d	drag coefficient
C_l	lift coefficient
C_m	torque coefficient
C_x	instantaneous horizontal force coefficient
C_y	instantaneous vertical force coefficient
C_{pm}	pitch power coefficient
C_{pt}	uniform motion power coefficient
C_{py}	heave power coefficient
$\overline{C}_p$	time-average total power
$\overline{C}_{pt}$	time-average thrust power
d	distance to closet wall
$D(t)$	instantaneous drag
D_p	contribution of pressure force to drag
D_υ	contribution of viscous force to drag
e	total energy per unit volume
$F_y(t)$	vertical instantaneous force
f	frequency of oscillations
h_0	the max displacement of heaving motion
h_0/c	dimensionless heave amplitude
H	total enthalpy
J	transformation Jacobian
L	characteristic length , for airfoil $L = c$
M	torque about the pitch axis
Ma_∞	U_∞/a
n	direction normal to the wall
n_3	the positive x_3 direction
n_{ts}	time steps for one cycle $(t/\Delta t)$
p	static pressure
Pr	Prandtl number
P_y	heaving power
P_t	uniform motion power
P_θ	pitching power
Re	UL/υ
t	time
T_p	contribution of pressure force to thrust
T_υ	contribution of viscous force to thrust
T	horizontal thrust; period
V_x	forward velocity of the airfoil
V_y	the heaving velocity
U_∞	cruise velocity of airfoil
θ_0	pitch amplitude
x, y, z	Cartesian coordinates
ξ, η, ζ	general curvilinear coordinates
U	constant cruising speed
U_{ref}	limiting velocity for preconditioning
U, V, W	contravariant velocity components in Section 3.2
x_p	pitching axis
ω	pitching angular velocity
$\tau_{x_i x_j}$	shear stress
ρ	density
ρ_p	$\frac{\partial\rho}{\partial p}$
ρ_h	$\frac{\partial\rho}{\partial h}$
γ	ratio of specific heat
Ω	magnitude of vorticity
μ	molecular viscosity coefficient
ν	kinematic viscosity
$\hat{\nu}$	field equation variable in Spalart-Allmaras turbulence model
Γ	The preconditioning matrix
η	propulsive efficiency
Δt	time step
$\hat{q}$	$\hat{q}=\boldsymbol{q}/J$
$\boldsymbol{q}$	primitive variables
$\dot{q}_{x_i}$	hear flux terms
A, B, C, D	area sign in Figs. 15 and 5
a, b, c, d	point sign in Figs. 8 and 12
St	fL/U

Vectors in in Cartesian coordinate (x, y, z)

u, v, w	Cartesian velocities in x, y, z directions
$\boldsymbol{Q}$	conserved terms
$\boldsymbol{G}, \boldsymbol{F}, \boldsymbol{H}$	inviscid flux terms
$\boldsymbol{G_\upsilon}, \boldsymbol{H_\upsilon}, \boldsymbol{F_\upsilon}$	viscid flux terms

Vectors in generalized coordinate (ξ, ζ, η)

$\hat{\mathbf{Q}}$	conserved terms
$\hat{\boldsymbol{G}}, \hat{\boldsymbol{F}}, \hat{\boldsymbol{H}}$	inviscid flux terms
$\hat{\boldsymbol{G}}_\upsilon, \hat{\boldsymbol{H}}_\upsilon, \hat{\boldsymbol{F}}_\upsilon$	viscid flux terms

reached. Consequently, the FMAV maintains a constant airspeed called the cruise velocity.

Researchers are always eager to explore new emerging grounds in the field, so the fluid-force-induced oscillations became one of the most popular research topics in fluid dynamics. For Micro Aerial Vehicles operated at the low Reynolds number regime, flapping and fixed wings are employed in various ways to create aerodynamic forces. However, the mechanism of flapping wing is completely different from traditional fixed-wing and rotary-wing, and its lift generation, which is determined by the unsteady flow physics, interacting with wing kinematics and shape, is thus more complex. Many studies have focused on the physical mechanisms of force production in flapping foils with an attempt to find the optimum wing flapping motion by the use of appropriate kinematic parameters. In addition, it is also found that dynamic stall (Ellington et al., 1996), rotational movement and fast pitch-up (Freymuth, 1988), wake-capturing (Dickinson et al., 1999), and Weis-Fogh's clap and fling mechanism (Weis-Fogh, 1973) all can provide sustainable forces for a stable hovering motion. Recently there has been increased research interest in flapping wing propulsion. Its kinematics, aerodynamics and flow characteristics have been investigated through experimental and numerical studies on insects (Walker et al., 2008; Shkarayev and Kumar, 2015; Wang et al., 2003) as well as oscillating airfoils modeling flapping wings in various conditions (Rege et al., 2013, 2015; Platzer et al., 2008). Anderson et al. (1998) observed that the phase angle between plunge and pitch oscillations plays a significant role in maximizing the propulsive efficiency of oscillating foils. Nagai et al. (2009) investigated the significance of dynamics stall, wake-capturing and rotational effect on flapping insect wings. They found that the lift is generated during downstroke while a high thrust is achieved during upstroke. Jones et al. (1998) conducted numerical simulations for the flow