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Efficiency of an auto-propelled flapping airfoil

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ABSTRACT

The present study deals with an investigation of the flow aerodynamic characteristics and the propulsive velocity of a system equipped with a nature inspired propulsion system. In particular, the study is aimed at studying the effect of the flapping frequency on the flow behavior. We consider a NACA0014 airfoil undergoing a vertical sinusoidal flapping motion. In contrast to nearly all previous studies in the literature, the present work does not impose any velocity on the inlet flow. During each iteration the outer flow velocity is computed after having determined the forces exerted on the airfoil. Forward motion may only be produced by flapping motion of the airfoil. This is more consistent with the physical phenomenon. The non-stationary viscous flow around the flapping airfoil is simulated using Ansys-Fluent 12.0.7. The airfoil movement is achieved using the deformable mesh technique and an in-house developed User Define Function (UDF). Our results show the influence of flapping frequency and amplitude on both the airfoil velocity and the propulsive efficiency. The resulting motion is contrasts to the applied forces. In the present study, the frequency ranges from 0.1 to 20 Hz while the airfoil amplitude values considered are: 10%, 17.5%, 25% and 40%.

1. Introduction

Flying and swimming animals use their body and member movements as a means of displacement in the air and water, respectively. What allows for this extraordinary mobility has been subject of many studies during the past years, but understanding the mechanisms involved and controlling them still remains a complicated tasks. Experiments are hard to set up owing to the fact that equipping an animal with measurement probes often disturbs the animals' behavior.

The first tentative explanations concerning the mechanisms of lift and propulsion by flapping were proposed in 1909 (Knoller, 1909) and 1912 (Betz, 1912). The Knoller–Betz effect stipulates that insects produce a propulsion force by achieving a sinusoidal distribution of the angle of attack during the flapping movement. The main property of the flow associated with an oscillating movement is the existence of a pair of asymmetric vortices, which are located in the vicinity of the leading edge on both the extrados and the intrados. During the flapping movement, the vortices are pushed towards the trailing edge where they are ejected, thus, initiating the formation of a vortex street.

While a steady swimming fish moves its body or fins in the water, muscle contraction, nervous system control along with interaction between the body tissues and the surrounding fluid contribute to the efficient and agile motion (Yu et al., 2008). Among the fish swimming, the carangiform swimmer has the ability of maintaining high-speed swimming in calm waters, whereas the anguilliform swimmer exhibits remarkable maneuverability in cluttered environments (Sfakiotakis et al., 1999).

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Nomenclature

c	airfoil chord
C_{Dp}	drag coefficient
C_L	lift coefficient
C_p	period-averaged consumption power rate coefficient
C_t	period-averaged thrust power
Δt	time step
$\vec{V}$	center of mass velocity
$\vec{F}$	global force per unit span
f	flapping frequency
F_x	longitudinal projection of the global force
F_{xp}	generated pressure force in the x-direction (longitudinal)
F_y	transversal projection of the global force
F_y	instantaneous generated force component in the normal-direction (transversal)
H	near wall cell height
h	instantaneous airfoil position
h_0	non-dimensional maximal amplitude of the flapping movement
H_{ideal}	near wall ideal cell height
$H_{\min}$	near wall minimum cell height
k_G	Garrick reduced frequency ($\pi f/u$)
m	mass of the body
Re	Reynolds number (based on constant imposed inlet velocity) ($\rho U_e c/\mu$)
Re_x	Reynolds number (based on airfoil velocity) ($\rho uc/\mu$)
Re_{xm}	steady-state Reynolds number (based on airfoil velocity)
t	time
u	longitudinal projection of the center of mass velocity
U	longitudinal velocity of body center of mass
U_e	constant imposed inlet velocity
v	transversal projection of the center of mass velocity
x	streamwise direction (longitudinal)
y	vertical direction (normal)
α_s	layer split factor
η	propulsive efficiency
ρ	density
μ	viscosity
σ	reduced frequency ($2\pi f/U$)

Fish and Lauder (2006) were interested in fish as well as biological control mechanisms of aquatic mammals flow. This is an area having a long history and lots of results reflecting the increasing interest of researchers towards understanding how organisms control the flow around their bodies and their tubercles. Fish and Lauder (2006) identified research area useful to understanding of the non-stationary nature of the movement.

Prangemeier et al. (2010) investigated using particle image velocimetry (PIV) the manipulation of trailing-edge vortex for an airfoil undergoing harmonic plunging superimposed with a pitching motion near the bottom of the stroke (the so-called quick-pitch motion). It has been shown that the trailing-edge vortex circulation can be reduced by more than 60% for all quick-pitch cases compared with a benchmark pure-sinusoidal plunge motion.

A comprehensive review of the biological and hydrodynamic literature of the aspects of aquatic locomotion was provided in Bandyopadhyay (2004), Fish (2004), Lauder (2005) Lauder and Drucker (2004), Triantafyllou et al. (2000, 2004), Webb (1998) and Wilga and Lauder (2004).

Postlethwaite et al. (2008) studied a model for the optimal movement of an electric fish searching for a prey. The model has six degrees of freedom, which allows for movements that the real fish cannot execute. However, the results have shown that the optimized trajectories are those made by the real fish.

In the flying area Hoa et al. (2003) reviewed the laws and the instationary modes for aerial biological and synthetic vehicles. Hoa et al. (2003) present an explanation for the aerodynamic gain of the flexible wings compared to the rigid wings. They also develop a three-dimensional non-stationary CFD code with an integrated distributed algorithm. The results of their model show that the flexible membranes improve both lift and thrust not by maximizing the force positive peaks, but rather by reducing the negative minima.

Lin et al. (2006) carried out wind tunnel tests to measure the lift and the thrust of a membrane wing flapping mechanically with various frequency, velocity and angle of attack values. They observe that the wing structure flexibility affects the thrust and the lift due to its deformation for high flapping frequencies. For a constant speed, the lift force increases with flapping frequency. For a constant flapping frequency, the flight velocity can be increased by decreasing angle of attack while losing slightly on the lift force. Mazaheri and Ebrahimi (2010) use an experimental apparatus to investigate the effects of a wing's twisting stiffness on the generated thrust force and the power required at different flapping frequencies. The results show the manner in which the elastic deformation and inertial flapping forces affect the dynamical behavior of the wing.

Some prototypes using fish-like propulsion are now available. Among others, we mention the work of Yu et al. (2009), which addresses the design, construction, and motion control of an adjustable Scotch yoke mechanism replicating the kinematics of dolphin-like robots. Preliminary tests in a robotics context confirm the feasibility of this devised mechanism for use as a propulsor for bio-inspired movements. Low (2009) considers and discusses the biomimetic design and the workspace study of undulating fin propulsion mechanisms. He also presents examples for the BCF fish and the robotic counterpart developed in different laboratories and manufacturers around the world.

The present study focuses on the estimation of the aerodynamic flow characteristics and the propulsion velocity of a machine equipped with a nature inspired propulsion system. This is done by implementing in the Ansys-Fluent software