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Wake structure and aerodynamic characteristics of an auto-propelled pitching airfoil

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ABSTRACT

In the present study, we investigate the wake configuration as well as the flow aerodynamic and propulsive characteristics of a system equipped with a nature-inspired propulsion system. The study focuses on the effect of a set of pitching frequency and amplitude values on the flow behavior for a symmetric foil performing pitching sinusoidal rolling oscillations. The viscous, non-stationary flow around the pitching foil is simulated using ANSYS FLUENT 13. The foil movement is reproduced using the dynamic mesh technique and an in-house developed UDF (User Define Function). Our results show the influence of the pitching frequency and the amplitude on the wake. We provide the mechanisms relating the system behavior to the applied forces. The frequency varies from 1 to 400 Hz and the considered amplitudes are 18%, 24%, 30%, 37%, 53%, 82% and 114% of the foil chord.

1. Introduction

Insects, birds, bats and swimming animals use their bodies and members as a means of displacement in the air or water. The basic rules which allow this extraordinary mobility have been the subject of many studies during the past few years. The experimental approach is hard to set up owing to the fact that equipping an animal with means of measurements often disturbs the animals' behavior.

The phenomenon of force production via flapping motion has been extensively studied in the literature originating from the pioneering studies of Knoller (1909) and Betz (1912). In their works they pointed out that flapping wing motion generates an effective angle-of-attack which results in lift production with a thrust component, a phenomena known as the Knoller–Betz effect. The main property of the flow associated with an oscillating movement is the appearance of a pair of asymmetric vortices, which are located in the vicinity of the leading edge on both the extrados and the intrados.

While a steadily 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 all contribute to the efficient and agile movements (Yu et al., 2008). In the category of fish swimming, the carangiform swimmer has the advantage 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

A	non-dimensional maximal amplitude of the pitching movement
A_D	dimensionless pitching amplitude
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
D	foil semicircular leading edge diameter
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_0	non-dimensional maximal amplitude of the pitching movement
k_g	Garrick reduced frequency ($\pi f/u$)
m	mass of the body
Re_x	Reynolds number (based on airfoil velocity) ($\rho uc/\mu$)
St_D	width-based Strouhal number
t	time
u	longitudinal projection of the center of mass velocity
$\overline{u_x}$	average longitudinal velocity
U	longitudinal velocity of body center of mass
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
θ	instantaneous foil incidence angle according to the x axis
θ_{max}	maximal incidence angle of the pitching movement
μ	viscosity
ρ	density
σ	reduced frequency ($2\pi f/U$)

Fish and Lauder (2006) were interested in fish and aquatic mammal flows biological control mechanisms. The authors identified directions to investigate in order to understand the non-stationary nature of the movement.

Krylov and Porteous (2010) described results for the experimental investigation of a small-scale mono-hull model boat propelled by a localized flexural wave propagating along the plate of finite width forming the boat's keel. The boat forward velocity, the thrust, and the propulsive efficiency have been measured for different frequencies and amplitude values of the flexural wave. The obtained value for the propulsive efficiency in the optimum regime was 51%. This indicates that the efficiency of this type of aquatic propulsion is comparable to the efficiency of dolphins and sharks (around 75%) as well as a traditional propeller (around 70%). With a propeller though, the wave-like aquatic propulsion has the advantage of not generating underwater noise as well as being safe for people and marine animals.

At the beginning of the 21th century a few remarkable works sized the biological and hydrodynamic literature of the aspects of the aquatic locomotion (Bandyopadhyay, 2004; Fish, 2004; Lauder, 2005; Lauder and Drucker, 2004; Triantafyllou et al., 2000)

Postlethwaite et al. (2009) studied a model for the optimal movement of an electric fish searching for a prey. One of the most interesting results is that even if the model has six degrees of freedom enabled, thus, allowing for movements that the real fish cannot execute, the optimized trajectories still correspond to movements that the real fish can perform.

Schnipper et al. (2009) perform an experimental exploration of a symmetric foil performing pitching oscillations in a vertical flowing soap film. A variety of wakes with up to 16 vortices per oscillation period are visualized. They map out the wake types in a phase diagram spanned by the width-based Strouhal number and the dimensionless amplitude. Finally the model is used to describe the transition from the Von-Karman wake to the inverted Von-Karman wake.

Using a particle image velocimetry (PIV), Prangemeier et al. (2010) investigate the trailing-edge vortex manipulation of an airfoil undergoing harmonic plunging superimposed with a pitching motion near the bottom of the stroke. They achieve a reduction in trailing-edge vortex circulation without diminishing the strength of the leading-edge vortex, thus maintaining the lift augmentation achieved through dynamic stall.

Amiralaei et al. (2010) address the issues related to low Reynolds number aerodynamics of a harmonically pitching NACA0012 airfoil. The resulting numerical instantaneous lift coefficients are compared with analytical data from Theodorsen's method. They show that amplitude oscillation, reduced frequency and Reynolds number value are of great importance for improving the aerodynamic performance of the system. In fact, in order to achieve the optimum lift coefficient, a careful selection of these parameters is needed.

Kern and Koumoutsakos (2006) consider the hydrodynamics of anguilliform swimming motions using three-dimensional simulations of the fluid flow past a self-propelled body. The motion of the body is not specified *a priori*, but is instead obtained through an evolutionary algorithm used to optimize the swimming efficiency and the burst swimming speed. They conclude that the burst swimming velocity is 42% higher and the propulsive efficiency is 15% lower than the respective values during efficient swimming.