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Effects of Reynolds number on energy extraction performance of a two dimensional undulatory flexible body

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ABSTRACT

In this paper, a NACA0012 airfoil is used as a two-dimensional simplified model of a fish body undertaking undulating motion. Using numerical simulation and dynamic mesh method combined with the spring-based smoothing and the local remeshing, the effects of Reynolds number on energy extraction efficiency of an undulating flexible body are studied at different wave velocities and wavelengths. Based on unsteady incompressible Navier-Stokes (N-S) Equations, the flow field around an undulating two-dimensional fish-like body was simulated with the aid of CFD software Fluent 15.0. The present numerical results indicate that:

1. Given the maximum amplitude, the tendency of the variation energy extraction efficiency with Reynolds number at different dimensionless wave velocity and wavelength are generally similar: as the Reynolds number increases, the energy extraction efficiency increases at first and then decreases. Relatively high efficiency always occurs at moderate Reynolds numbers;

2. For each Reynolds number examined, when the wavelength is constant, the energy extraction efficiency first increases and then decreases with increasing dimensionless wave velocity. There is an optimum wave velocity at which the energy extraction efficiency achieve their maximum values;

3. For a given Reynolds number, there is a threshold value of dimensionless wave velocity, at which the energy extraction efficiency becomes zero and this is a turning point from energy extraction to energy consumption.

1. Introduction

In nature, aquatic animals have experienced billion years of evolution, obtaining gradually and completing fully their excellent swimming ability. Among them, fish not only possess high swimming efficiency, but also strong maneuverability. Therefore, a large number of studies have been made on fish swimming, which has significant influence on the development of the new concept of underwater bionic machine (such as robot fish). The study of fish swimming can be traced back to the “Gray's Paradox” proposed by British scientist Gray J. in 1936 (Gray, 1936). He found that the energy required to drag the rigid dolphin model is seven times the energy provided by the living dolphin at the same speed, indicating that living dolphins reduce the drag effectively in some way which contributes to the high swimming efficiency.

Theoretical researches on fish swimming have a rich history. Lighthill (1960) introduced the slender-body theory applied to deformable body, which pointed out several crucial conditions of higher propulsion efficiency achieved by slender fish body. Later, (Wu (1960, 1971) put forward the two-dimensional undulatory locomotion model, where the fish body was considered a flexible thin plate, and systematically developed two-dimensional waving plate theory, laying the foundation for three-dimensional waving plate theory. In 1969, Lighthill (1969) explained hydrodynamics principles of aquatic animal propulsion from zoological and hydromechanical aspects, and focused on the two swimming modes of Carangiform and Anguilliform. Also, Lighthill (1970, 1971) proposed the slender-body theory applied to analyze Carangiform and Anguilliform in 1970 and extended it in 1971, developing a large-amplitude enlongated-body theory used to describe regular or irregular fish locomotion. On the basis of these theories, Tong et al. (1991) (Cheng et al., 1991) build a three-dimensional waving plate theory to simulate fish swimming.

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Nomenclature

Re	Reynolds number
U	the incoming flow speed, m/s
p	the pressure acting on the top surface, Pa
L	the chord length, m
P_{sr}	the lateral power, W
P_{sr}^{p}	the lateral power caused by pressure gradient force, W
T	the undulation period, s
A_{max}	the maximum amplitude of the undulation wave, m
c_0	coefficient of amplitude function
c_m	the speed of a wave, m/s
c	dimensionless wave speed
η_E	the energy utilization efficiency
f_p^y	pressure drag, N
φ_d	the motion phase delay, °
$\overline{P}_s^p$	the time-averaged dimensionless lateral powers brought by pressure gradient force
d	the maximum lateral excursion of the airfoil motion over a cycle, m
u, v	the velocity components in the x and y directions
x, y_w	Cartesian coordinates
dt	Time step size
v_y	the y component of velocity, m/s
P_{sr}^{f}	the lateral power brought by friction force, W
ds	the infinitesimal element of surface
$A(x)$	the space-varying amplitude, m
P_s	a dimensionless lateral power
t	Time, s
E	the kinetic energy, J
$\dot{m}$	the mass flow rate of air (or water), kg/s
f_f^y	skin friction, N
C_{dd}	the drag coefficient
$\overline{P}_s^f$	the time-averaged dimensionless lateral powers brought by friction force
y	the displacement in the y direction

Greek Letters

ν	the kinematic viscosity, N s/m^2
λ	wavelength, m
μ	the dynamic viscosity of a fluid, m^2/s
ρ	a function of water density, kg/m^3

Subscripts

f	skin friction
p	pressure gradient force

Superscripts

y	the y direction

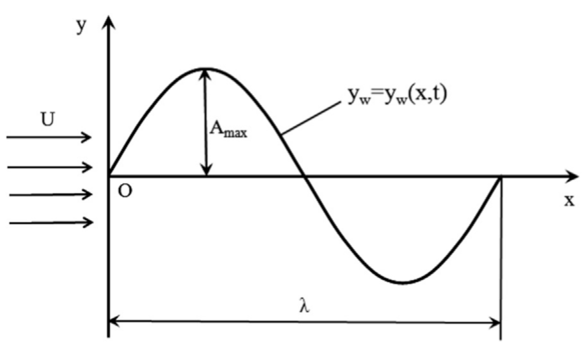

Fig. 1. A diagram of the undulatory lomotion.

Table 1
Results of comparison under laminar model and turbulence model.

Re	Viscous Model	P_s	η_E
70	laminar	0.00600	3.75%
70	transition *SST*	0.00596	3.73%
716.8	laminar	0.01731	10.82%
716.8	transition *SST*	0.01838	11.49%

Table 2
Y+ value in the near-wall region at each Re examined.

Re	Y+	Re	Y+
70	0–0.08	71,680	0–3.5
716.8	0–0.13	700,000	0–40
7000	0–0.6	7168,000	0–160

Experimentally, employing digital particle image velocimetry (DPIV), Wolfgang et al. (1999) measured the two-dimensional flow field structure as mackerel was swimming. It was found that during the swimming, vortices were generated on both sides of the fish body and moved towards tail gradually and shed at last. These vortexes can be utilized by caudal fins, which reduced the energy consumption. Triantafyllou and Triantafyllou (1991, 1995) carried out an experimental study on the oscillating airfoil in a water tunnel. It was found that optimal propulsive efficiency is just achieved within a limited range of Strouhal numbers (0.25–0.35) where a staggered array of reverse Karman vortices is formed in the wake. These experimental results have provided evidence that the manner in which the vortices are arranged behind the a fish's tail has considerable influence on the swimming efficiency. Barrett et al. (1999) conducted experiment on robot fish, discussing the effects of undulatory wavelength, amplitude and Strouhal number on the drag reduction.

In terms of numerical simulation, Dong (2006) studied the two-dimensional NACA0012 airfoil who underwent flexible deformation by solving the Navier-Stokes equation with the space-time finite element method, elucidating the influence of the wave velocity on the fish-like body's thrust and flow field. Borazjani and Sotiropoulos (2008) investigated the hydrodynamics of carangiform locomotion at varied Reynolds number, underscoring the importance of scale (Re) effects on the hydrodynamic performance. Chang et al. (2012) employed advanced numerical simulation technique to explore the effects of Reynolds number on swimming ability of Crescent-tail swimming mode, and compared results calculated by laminar model and two kinds of turbulent models, suggesting that Crescent-tail mode is suitable for swimming at high Reynolds number, while turbulent flow can weaken the flow separation in the leeward region of the fish, which helps to improve the cruising ability of Crescent-tail mode.

The most of previous work on undulatory flexible body are normally centered on propulsion not involved in energy extraction. On the contrary, Huang (Huang et al., 2017) initially put forward a new method for harvesting energy from fluid flow based on undulatory motion and identified the range of values of motion parameters at which the undulatory foil can be used as an energy harvester, which proved the feasibility of the proposed concept of an undulating foil