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Experimental and Numerical Study of Penguin Mode Flapping Foil Propulsion System for Ships

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Abstract

The use of biomimetic tandem flapping foils for ships and underwater vehicles is considered as a unique and interesting concept in the area of marine propulsion. The flapping wings can be used as a thrust producing, stabilizer and control devices which has both propulsion and maneuvering applications for marine vehicles. In the present study, the hydrodynamic performance of a pair of flexible flapping foils resembling penguin flippers is studied. A ship model of 3 m in length is fitted with a pair of counter flapping foils at its bottom mid-ship region. Model tests are carried out in a towing tank to estimate the propulsive performance of flapping foils in bollard and self propulsion modes. The same tests are performed in a numerical environment using a Computational Fluid Dynamics (CFD) software. The numerical and experimental results show reasonably good agreement in both bollard pull and self propulsion trials. The numerical studies are carried out on flexible flapping hydrofoil in unsteady conditions using moving unstructured grids. The efficiency and force coefficients of the flexible flapping foils are determined and presented as a function of Strouhal number.

Keywords: biomimetic propulsion, flapping foil, penguin locomotion, Strouhal number, tandem arrangement, thrust coefficient

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Nomenclature

α	Instantaneous angle of attack
α_0	Maximum angle of attack
$\dot{y}$	Instantaneous sway velocity
η	Efficiency
$\dot{P}$	Average power coefficient
(C_X)	Average thrust coefficient
$\bar{F}_X$	Average thrust
$\bar{P}$	Average power
D	Drag force
R	Resultant force
μ	Dynamic viscosity of fluid
ω	Circular flapping frequency
Φ	Phase difference between sway and yaw
ψ	Instantaneous yaw angle
ψ_0	Yaw amplitude
ρ	Fluid density
(x, y)	Effective flexible motion coordinates of centerline
ϕ	Conservative scalar quantity
A	Characteristic width of flapping hydrofoil
y_0	Sway amplitude
c	Chord length of the hydrofoil
C_X, C_Y	Force coefficients corresponding to F_X, F_Y
C_M	Moment coefficient
f	Flapping frequency
F_X, F_Y	Forces in x and y directions
L	Lift force
M	Moment due to lift and drag forces
P	Power
p	Pressure
Re	Reynolds number
s	Span of the hydrofoil
St	Strouhal number
t	Time

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t'	Non-dimensional time
T	Flapping period
U	Frees stream velocity
V	Control volume
y	Instantaneous sway position

1 Introduction

Subsea technology is among most exciting areas of modern engineering that currently experiences revolutionary changes. To flourish subsea applications such as ocean exploration, seafloor mining or submarine communications require intensive use of Autonomous Underwater Vehicles (AUVs) and Autonomous Surface Vehicles (ASVs) having longer endurance and eco-friendly with less disturbances. Marine mammals use less energy for their locomotion and create less noise compared to manmade propulsion systems. This study aims to explore a new design philosophy for autonomous crafts, inspired by propulsion mechanisms of aquatic organisms. A particular focus will be on aquatic birds such as turtles and penguins which are capable of swimming and maneuvering. They are considered to be the best performers among aquatic animal locomotion[1]. The present work will combine experimental and numerical studies of penguin type propulsion and motion mechanisms. This approach will allow identification of hydrodynamic behavior of penguin pectoral fins and its mechanisms in swimming, which benifits in the design and development of hybrid underwater robots which are able to swim and maneuver. Expected design solutions may go well beyond terrestrial applications and appear to be instrumental for development of AUVs for deployments in extraterrestrial seas such as Titan's Karken Mare[2].

Aquatic birds posses flying ability by using flapping wings to generate sufficient lift to stay afloat in water and produces thrust for propelling in the forward direction. Studies on aquatic animals have shown that flapping foils can be an efficient means of propulsion for marine vehicle[3–19]. Lua *et al.*[20] studied the aerodynamics of 2D flapping foils in tandem configuration in forward propulsion at $Re = 5000$ using experimental and numerical techniques. Both tandem foils are subject to symmetrical simple harmonic heave and pitch motions with a Strouhal number of 0.32. The observations show that the foil-wake interaction is favorable to thrust generation, which requires the tandem wing has to cross the shear layer shed from the front wing and results in increasing effective angle of attack of the foil. Liu *et al.*[21] performed numerical and hydrodynamic experiments to analyze the propulsive performance of an ocean wave energy extraction device called a Wave Glide Propulsor (WGP) in regular waves. The propulsor consists of six flapping rigid foils arranged in tandem with asynchronous flapping motion. From the comparison of computational and experimental results, the WGP produces larger thrust force at smaller wave length or at larger wave height. Yuan *et al.*[22] conducted water tunnel tests, for a pitching-plunging 2D airfoil and a flapping 3D wing. Force and Particle Image Velocimetry (PIV) measurements were carried out to acquire sets of data that are considered acceptable for the validation of corresponding Computational Fluid Dynamics (CFD) simulations. It shows good agreement between the experimental and numerical results. Chae *et al.*[23] studied the Fluid-Structure Interaction (FSI) response and stability of a flexible foil in dense, turbulent, and incompressible flow using unsteady RANS fluid solver coupled with a 2-DOF solid solver through an efficient and stable numerical algorithm. Politis and Politis[24] discuss about the effect of flapping wings on thrust production and motion control. Schouveiler *et al.*[25] conducted experimental studies on flapping hydrofoil propulsor, inspired from thunniform swimming mode. The study investigated the effects of variations of the Strouhal number and the maximum angle of attack on the thrust force and on the fin hydro-mechanical efficiency.

In the present work, numerical studies are carried out to ascertain the thrust producing mechanism of flapping foils and then experimental studies are performed on a ship model fitted with two flapping foils in tandem at its bottom. The current work attempts to investigate the thrust generation capability and efficiency of the flexible hydrofoil in open water condition and the results of which are compared with experimental ship model in self propulsion mode. The foil flexibility in CFD environment is introduced using an appropriate user defined function. The foils used in the ship model test are also flexible and the flexibility closely matches with the numerically simulated fin.

2 Hydrodynamics of flapping propulsion system

Penguins and other marine animals overcome the