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Numerical investigation of a wave glider in head seas

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ABSTRACT

A wave glider comprises a surface boat, which harvests energy from wave and solar power, a submerged glider containing six pairs of tandem hydrofoils and a tether connecting them in between. This paper presents a numerical simulation to predict the wave glider dynamic performance in head seas with the aid of computational fluid dynamic (CFD) method. The simulation involves two commercial CFD software packages, FINE/Marine and STAR-CCM+.

Firstly, unsteady Reynolds Averaged Navier-Stokes (URANS) simulation was built in FINE/Marine with volume of fluid (VOF) model to simulate the flow around the surface boat and the tandem hydrofoils as a system, followed by the high-fidelity simulation of the passive eccentric rotation of the underwater tandem hydrofoils in STAR-CCM + using overset mesh. By taking the advantages of both softwares, manual iteration was conducted to achieve a converged result. Consequently, by analyzing these results, the surge force acting on the surface boat and the passive eccentric rotation law of the hydrofoils have been achieved which are proved to be the main factors affecting the propulsion efficiency of the wave glider.

1. Introduction

Design and development of devices for oceanic research and atmospheric monitoring have drawn great attentions nowadays, especially for those meeting the requirement of lower-cost replacement and real-time communication worldwide. The first wave glider, developed by Liquid Robotics Corporation (Smith et al. (2011)), relies on the wave motion to propel the system to conduct surface as well as underwater missions. Therefore, it is crucial to understand the system's motion dynamics in the waves so that to achieve a better performance in the real seas.

The methodologies to predict the motion dynamics of the wave glider in the real seas can be either based on model-scale lab tests or numerical simulations. Model-scale lab tests are deemed to be the most effective way as well as the most expensive way due to the demand of highly specialized hydrodynamic testing facilities. With the benefit of conducting systematic investigations at a minimum cost, the later has often been the preferable option (Elhadad et al. (2014), Jia et al. (2014), Tian et al. (2015), Liu et al. (2016), Elhadad et al. (2014), Tian et al. (2014), Jia et al. (2014), Tian et al. (2015), Liu et al. (2016)). With the enhancement of the modern computational technology, numerical simulation using the unsteady Reynolds Averaged Navier-Stokes (URANS) is acknowledged to be an ideal solution to investigate the performance of the wave glider (Jia et al. (2014), Liu et al. (2016). Before this current study, the steady state CFD simulation based on RANS has been successfully applied to assess the velocity based thrust and drag coefficients of the wave glider. Jia et al. (2014) have made a comparison of the hydrodynamic results of NACA series' airfoil with plate wing under different flow velocities and various spacing by using CFD software ANSYS-Fluent. Elhadad et al. (2014) employed the Wigley model as the surface boat of Wave Glider and calculated the resistance characteristics at a range of Froude numbers, 0.1–0.4. Zheng et al. (2015) compared different factors influencing the drag force converted by the usage of NACA63-412 asymmetric airfoil and optimized them by making a comparison of the simulation results with the calculation results. However, the previous numerical simulation is often based on the steady simulation without considering the unsteady phenomenon nor the passive rotation of the wings; the multi-body dynamics of the wings was estimated via semi-empirical or empirical formulas. Ngo et al. (2013) applied the linear regression and Gauss regression model to discuss the environmental parameters that influence the movement of the wave glider and to predict the forward speed of the wave glider by inputting the wave parameters such as wave height, wave period, wind speed and current. Kraus (2012) established the six-degree-of-freedom nonlinear dynamic equation to determine the key hydrodynamic parameters according to the Newton's law of momentum theorem and momentum moment theorem with the consideration of the influence of wind, flow and added mass. Baoqiang

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Nomenclature

ξ	is the displacement of the wave glider in the x direction
γ	is the displacement of the wave glider in the y direction
ζ	is the displacement of the wave glider in the y direction
ψ	is the yaw angle of the wave glider
θ	is the pitch angle of the wave glider
ϕ	is the roll angle of the wave glider
ξ_b	is the displacement of the surface boat in the x direction
γ_b	is the displacement of the surface boat in the y direction
ζ_b	is the displacement of the surface boat in the y direction
ψ_b	is the yaw angle of the surface boat
θ_b	is the pitch angle of the surface boat
ϕ_b	is the roll angle of the surface boat
ξ_g	is the displacement of the glider in the x direction
γ_g	is the displacement of the glider in the y direction
ζ_g	is the displacement of the glider in the y direction
ψ_g	is the yaw angle of the glider
θ_g	is the pitch angle of the glider
ϕ_g	is the roll angle of the glider
H	is the wave height
T	is the wave period
S_f	is the waterplane area of the surface boat
P_{WGi}	is the wave energy absorption power of the wave glider
P_{WGm}	is the mechanical conversion power of the wave glider
$X_{WG}(t)$	is the time-varying forces of the surface boat in the x direction
$Z_{WG}(t)$	is the time-varying forces of the surface boat in the z direction
F_{WG}	is the time-averaged value of $X_{WG}(t)$
C_{WGPi}	is the wave energy absorption power coefficient
C_{WGPm}	is the mechanical conversion power coefficient of the wave glider
C_{WGT}	is the thrust coefficient of the wave glider
η_{WG}	is the propulsive efficiency of the wave glider
F_{TL}	is the force of the tether
K_T	is the stiffness of the tether
ΔL_S	is the variation of the tether length
$T_{initial}$	is the initial tension of the tether
I_{hy}	is the inertia moment of hydrofoil
$Q(t)$	is the resultant torque on the hydrofoil leading edge
T_S	is the linear spring force
k	is the linear spring stiffness
r_S	is the spring compression
P_{hym}	is the wave energy absorption power of the hydrofoil
$X_{hy}(t)$	is the time-varying forces of the hydrofoil in the x direction
$Z_{hy}(t)$	is the time-varying forces of the hydrofoil in the z direction
F_{hy}	is the time-averaged value of $X_{hy}(t)$
C_{hyPm}	is the mechanical conversion power coefficient of the hydrofoil
C_{hyT}	is the thrust coefficient of the hydrofoil
η_{hy}	is the propulsive efficiency of the hydrofoil

et al. (2014) concentrated on the movement efficiency of the wave glider. The model of movement efficiency was established from the perspective of energy conversion, and then this formula was further confirmed through direct comparison of the numerical results based on linear wave theory with experimental results. Furthermore, Tian et al. (2015) applied the D-H approach and the Lagrange mechanics to the simulation of the dynamic motion of the wave glider. From these simulations mentioned above, only the thrust and drag coefficients of the wave glider can be determined. In addition, there is lack of numerical simulation of the passive hydrodynamic rotation of the hydrofoils, which is essential to simulate the coupled motion of the surface boat and the glider.

The aim of the present study is to explore the feasibility of developing a high fidelity numerical simulation method to fully evaluate the motion characteristics of the wave glider in the waves. The simulations of only surface boat, the wave glider in head seas and the passive eccentric rotation of the hydrofoils are conducted using the URANS solver, all of which act to investigate the parameters that affect the motion of the wave glider.

2. Description of the wave glider

The wave glider model used in this paper was developed by China National Marine Technology Center, originally manufactured by Liquid Robotics Corporation. As shown in Fig. 1, there are three major components consisted in the wave glider: a surface boat housing sensors, a submerged glider containing six hinged flat hydrofoils which are arranged in tandem on both sides and a tether that connects the surface boat and the glider. The wave glider is symmetrical to its transversal midsection and the surface boat is also symmetrical to the longitudinal section in the center plane. A spring is introduced and mounted beneath each hydrofoil and the diagram is shown in Fig. 2. The distance between adjacent row of tandem hydrofoils is 90 mm. The chord of the hydrofoil is 160 mm and the rotational axis of the hydrofoil is placed 50 mm after the leading edge. The spring is wrapped in a sleeve and the neutral length is 120 mm. One end of the spring sleeve is installed at a distance of 40 mm from the rotation axis; the other end is installed 17 mm below the baseline of the hydrofoil to form an angle between the baseline of the hydrofoil and the spring, 7.9°. Therefore, when the hydrofoil rotates, the spring will slow down and limit the rotation of the hydrofoil to provide suitable angle of attack to produce the thrust. The oscillation angle of each hydrofoil is limited to $-45°$ to $60°$. The general parameters for a full-scale sized wave glider is shown in Table 1.

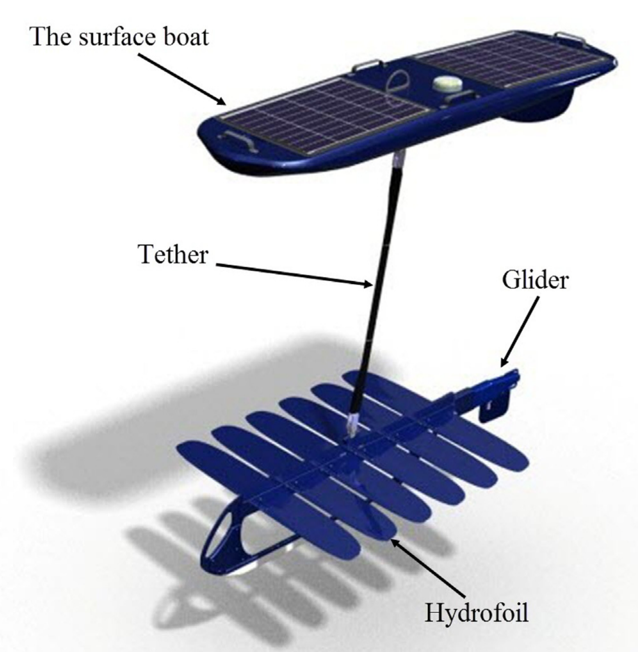

Fig. 1. The wave glider developed by China National Marine Technology Center.