Numerical Analysis of the Resistance Force of Floater of Wave Glider and Flapping Motion of Single Wave Glider NACA-0012 Foil

Erwandi¹ and Widodo²
¹ Technology Center of Maritime Industrial Engineering Technology, Agency for the Assessment and Application of Technology.
² Indonesian Hydrodynamic Laboratory, Agency for the Assessment and Application of Technology.

Abstract. In 2020, the Agency for the Assessment and Application of Technology – Indonesia (BPPT) is designing wave glider systems for Tsunami Early Warning System. The wave glider systems consist of two components, the floater at the water surface and the wave glider submerged 2 meters or more below the water surface. Wave glider contains several foils that can flap up and down due to the heave and pitch motion of the floater so that the system affords the force to move forward. This paper describes the numerical analysis of the resistance of floater and the selection of the pivot position of the foil where it flaps. The speed of the floater is set from 0.3 m/s up to 1 m/s. NACA-0012 is selected as the first choice of the foil. It flaps in pure pitch motion and coupled pitch and heave motion in the different pivot positions. The flapping frequency is set to 0.1 Hz since the peak period of the wave about 10 seconds. The surge forces due to the flapping motion are then analysed to determine the best position of the pivot. The numerical simulation shows that the pivot position at 2.5% - 5% of chord length from the leading edge of NACA-0012 generates the optimum surge force.

1. Introduction
Indonesia, as an archipelagic country, is part of the well known as “Ring of Fire”. The Ring of Fire is the area around the Pacific Ocean where seismic activities are massive. Earthquakes, volcanic eruptions, and tsunamis often hit this area [1][2].

In 2020, the Indonesian Government had been finished mitigating the potential impact of the tsunami. The government will manufacture 13 buoys of Indonesia tsunami early warning systems (INA TEWS) by the end of 2020 and install them in 2021 at several points in southern and eastern Indonesia water.

The conventional buoy type of tsunami early warning system is quite expensive. The system consists of a buoy, an ocean bottom unit (OBU), and a mooring system that connected the buoy and OBU. Buoy, which floats at the surface of the water, contains electronic devices, batteries, antenna, etc. The OBU has the role to detect the sudden pressure increment of the water column due to the under ocean earthquake. In addition, conventional buoy types are also prone to vandalism. Several buoys installed in 2009 had their moorings cut, missing antennas, etc.

In order to reduce the cost and simplified the system, the Agency for the Assessment and Application of Technology (BPPT) proposed to design the wave glider system that can have a function as a tsunami early warning system. According to Liquid Robotics company [3], wave glider is an autonomous unmanned water surface vehicle, that has several capabilities to bear some mission services i.e.: oceanographic and meteorology climate observation, tsunami detection and seismic monitoring,
fish and marine mammal monitoring, offshore energy, harbor security, and surveillance for illegal fishing.

It is claimed 24×7 Long-Duration Operations, station keeping or mobile data collection, has the capability for real-time communications and cuts the cost-effective operations. The type of long endurance and low maintenance is a key design goal for the wave glider [4].

![Wave glider system by China National Marine Technology Center.](image)

The wave glider systems consist of two components, the floater at the water surface and the wave glider submerged 2 meters or more below the water surface. The two-body system is coupled with flexible tether or umbilical. Figure 1 shows the wave glider system [5].

Wave glider contains several hydrofoils that can flap up and down due to the heave and pitch motion of the floater so that the system affords the force to move forward.

This paper describes the initial research stage of the design of Indonesian’s wave glider. It starts from the numerical analysis of the resistance of floater and the selection of the pivot position of the foil where it flaps.

The speed of the floater is set from 0.3 m/s up to 1 m/s. NACA-0012 is selected as the first choice of the hydrofoil. It flaps in pure pitch motion and coupled pitch and heave motion in the different pivot positions. The flapping frequency is set to 0.1 Hz since the peak period of the wave about 10 seconds. The surge forces due to the flapping motion are then analysed to determine the best position of the pivot.

2. Wave glider operational system

As shown in Figure 2 left [3], when the floater at water surface rides over the wavy water and moves up due to heave motion in the wave crest, the submerged glider will be pulled up thru the tether, it will cause the hydrofoil rotating and flapping downward and induce a thrust to drive the two-body system
moving forward. Similarly, when the floater moves down (Figure 2 right), the hydrofoil flapping upward, thus generate a thrust too. The hydrofoil will in a horizontal position, which means there is no thrust when the velocity of the floater is greater than the velocity of the wave glider.

3. Design of the floater

The designed BPPT’s floater of the wave glider is shown in Figure 3. The length of waterline (LWL) of floater wave glider is 2.966 m, draft amidship (T) is 0.138 m, beam amidship (B) is 0.675 m, and total displacement 171.3 kg. Figure 3 shows the lines plan of the design of the BPPT’s floater.

4. Numerical simulations

Since this research is in the early stage, the numerical simulation of the wave glider is divided into 2 steps. Firstly is the numerical simulation to predict the resistance force of the floater of the wave glider in calm water. Secondly is the prediction of the thrust force of the flapping foil of the NACA-0012 at different location of the rotation axis/pivot of the foil. The results is then employed to determine the pivot position of the foil where it flaps.

4.1. Setting-up of the numerical simulation of the resistance force of the floater
The numerical simulation for predicting the resistance force of the floater based on the CFD software Fluent in calm water. The objective of the simulation is to provide data that can be used to design the thrust force of the flapping foil. It is planned by the end of 2020, the physical model will be tested in the towing tank facility of the Indonesian Hydrodynamic Laboratory (IHL) BPPT, therefore the computational domain of the numerical simulation is then adapted to the size of the towing tank. We calls the method is numerical towing tank, with virtual towing tank represents LHI’s towing tank. The towing tank belongs to the IHL has the following dimensions: L = 235 meters, B = 11 meters, and water depth H = 5.5 meters.

As shown in Figure 4, the inlet boundary is set 25 m upstream from the point AP of the floater. The pressure outlet is positioned 50 meters. The bottom and side boundaries follow the dimension of the towing tank, 5.5 meters, and 5.5 meters (half of the towing tank width) respectively. The top boundary is set to 3 meter from point AP of the floater.

The flow around the floater is assumed incompressible and turbulent. Eulerian multiphase flow is applied at the Z plane as the water surface, 0.138 meters from baseline at the bottom of the floater. The implicit unsteady Reynolds Average Navier-Stokes (URANS) numerical scheme and the $K-\omega$ SST turbulence model are employed to the flow. The structured finite volume method is then used to discretize the computational domain. Figure 5 shows the result of the discretization mesh on the water surface around the floater. The dense mesh in the water surface about the FP of the floater is intended to catch the bow wave and wake when the floater moves forward.

![Figure 4. Computational domain of virtual towing tank.](image-url)
4.2. Numerical simulation set-up of the flapping foil of NACA-0012

Flapping foils in nature are very common [7], the tail motion of ocean mammal-like whale or dolphin, or the sinusoidal motion of squid fin are the examples of flapping foil. The flapping foil of the tails and fins of the sea animals are intended to produce thrust or lift force, so they can move forward or maneuver easily. In the air, the birds flap their wings in order to generate lift to fly or to hover while they seek food. Those phenomena attract the curiosity of many scholars to understand the mechanism which can be applied in engineering.

Babu et.al. have applied the flapping foil for the propulsion system of the ship and underwater vehicles [8]. Xu, J., Sun, H., studied experimentally the oscillating foil to harvest energy from marine current [9].

In this research, we conduct the simulation of the passive flapping foil which is affected by the heaving motion of the floater while riding over the wave. The single foil NACA-0012 [5][10] is utilized to flap at a certain position of pivot or rotation axis in the pure pitch motion, pure heave motion, and couple heave and pitch motion. The pivot positions are then varied their distance from the leading edge of NACA-0012 foil. Figure 6 shows the profile of NACA-0012 foil.

A three-dimensional (3D) computational domain is prepared to simulate the motion of NACA-0012 foil as shown in Figure 7. The chimera meshing method is applied for the movement of the foil mesh through computational domain background mesh [11].

Since the problem of the pitch and heave motion of the foil can be simplified in a two-dimensional (2D) computational domain, thus the computational domain of Figure 7 is then converted to a 2D computational domain.

The generated mesh in the 2D computational domain is shown in Figure 8 (a) and (b). Figure 8(a) is a structured background mesh. It surrounds the structured dense mesh around the mesh of the foil, called overlap mesh. Inside the overlap mesh there is denser mesh surround the foil as shown in Figure 8(b), which is the chimera overset mesh. It can move over the background mesh over overlap mesh. The
movement of the foil and chimera mesh follows the following equation (1) for pure pitch motion and equation (2) for pure heave motion.

\[ \theta(t) = \theta_0 \cdot \sin(2\pi f t) \]  
where: \( \theta(t) \) is pitch motion (deg).  
\( \theta_0 \) is maximum amplitude of angle of pitch motion (deg).  
\( f \) is pitch oscillation frequency (Hz).  
\( t \) is time variable (seconds).

\[ h(t) = h_0 \cdot \sin(2\pi f t + \Phi) \]  
where: \( h(t) \) is heave motion (m).  
\( h_0 \) is maximum amplitude of heave motion (m).  
\( f \) is heave oscillation frequency (Hz).  
\( t \) is time variable (seconds).  
\( \Phi \) is the phase difference between heave and pitch motion.

The frequency oscillation usually is set through kinematic parameter Strouhal number [12]. Figure 9 shows a schematic diagram demonstrating various dimensions and kinematic parameters of the foil motion. The kinematic parameter Strouhal number is expressed in the equation (3).

\[ St = \frac{2h_0 f}{U} \]  
where: \( h_0 \) is maximum amplitude of heave motion (m).  
\( f \) is heave oscillation frequency (Hz).  
\( U \) is free stream velocity (m/s).  
\( \Phi \) is the phase difference between heave and pitch motion.
Figure 7. Computational domain of the flapping NACA 0012 foil.

Figure 8. Generated structure mesh (a) background mesh surrounds overlap mesh, (b) overlap mesh surrounds chimera overset mesh around foil NACA-0012.
5. Results and Discussion

5.1. Results of numerical resistance test

The incremental time of the CFD solver for numerical simulation resistance is set 0.001 seconds (1000 Hz) and generate a snapshot report every 0.01 second (100 Hz). The inner iteration is 20 iterations. It follows the ITTC recommendation for numerical prediction of resistance tests [5].

The visualization of the numerical simulation result of the resistance test in the towing tank at snapshot time 20 seconds is shown in Figure 10. In that figure, the velocity fed to the inlet boundary is 3 knots. It shows the contour of the profile of the wave-making resistance. The prediction of the resistance force of the floater starting from 1.0 knots up to 3.0 knots is shown in Figure 11. It will be compared with the physical model tow resistance test that will conduct at the end of 2020.

The increment of the resistance force is quite rapid starting from a speed of 1.6 knots. It needs a bigger thrust in order for the floater can move more than 1.6 knots. It is mentioned in the specification sheet of the wave glider produced by Liquid Robotics company [3] that the speed of wave glider is typically 1.3 knots.

Figure 10. The wave profile of the floater when moving forward at 3.0 knots.
5.2. Results of numerical flapping NACA-0012 foils

The numerical simulation of the flapping foil of the NACA-0012 is set at different positions of the pivot (rotation axis) of the foil. The pivot coordinate position is determined from the distance of it to the leading edge point of the foil. The distance between leading edge to the pivot point in horizontal axis of the foil is expressed in the non-dimensional length (in %) as shown in equation (4).

\[ L(\%) = \frac{X_P - X_{LE}}{C} \times 100 \]  \hspace{1cm} (4)

Where:

- \( L \): is the distance between pivot point and leading edge point (\%).
- \( X_P \): is the coordinate position of the pivot (m).
- \( X_{LE} \): is the coordinate position of the leading edge (m).
- \( C \): is the chord length of the foil (m).

The pivot position is set at -10\%, -5\%, 0, 2.5\%, 5\%, 7.5\%, 10\%, 20\%, and 30\% from the leading edge for pure pitch. According to Dave et.al. [12], the ideal operating range in terms of thrust and efficiency of the flapping foil has been found to be between \( St = 0.2 \) to 0.4, with pitch amplitudes between 40 and 60, however since the peak periods \( T_p \) of the significant wave height in Indonesian ocean is typically around 9 – 11 seconds, then we take 10 seconds as the peak periods of the wave, so the frequency \( f \) is set \( 1/T_p = 0.1 \) Hz. The velocity in the inlet boundary, pressure outlet boundary, top, and bottom boundaries are all set to 0 since there is no variable that is fed to the boundaries.

The amplitude angle of pitch motion which is fed to numerical simulation is set to 60\°. For pure heave, the amplitude heave motion is 0.5 m. Figure 12 shows the velocity magnitude of the fluid around the foil which flapping in pure pitch motion, where the pivot position is 5\% of the chord length from the leading edge. The samples of the thrust force produced by the flapping foil is shown in Figure 13 for the position of the pivot from the leading edge 5\%, 0\%, -5\% respectively. If we see Figure 12, the foil NACA-0012 faces the left or minus direction of the X-axis. It means that the thrust force will give a negative value to propel the foil in the left direction. If we observe the time history of the thrust force in Figure 13 for example, the value of the force is dominantly negative or if we take the average
value we will obtain a negative value, it means the flapping foil will thrust the foil forward to the minus direction of X-axis.

Figure 12. The velocity magnitude distribution of pure pitch motion where pivot position 5%C from leading edge.

Figure 13. Time history of thrust force of flapping NACA-0012 foil pure pitch motion where pivot position 5%C from leading edge.

Figure 14. Time history of thrust force of flapping NACA-0012 foil pure pitch motion where pivot position 0%C from leading edge.
Figure 15. Time history of thrust force of flapping NACA-0012 foil pure pitch motion where pivot position -5%C from leading edge.

If the time histories of the thrust forces at every pivot position are averaged we will know the best pivot position which gives the highest thrust force caused by the pure pitching motion. Figure 16 shows the average thrust force at every pivot position -10%C, -5%C, 0, 2.5%C, 5%C, 7.5%C, 10%C, 20%C, and 30% C from leading edge of the foil. It indicates that the pivot position in the range 2.5%C – 5%C produces the highest thrust force for flapping foil in the pure pitching motion.

Figure 16. The average thrust forces produced by flapping foil in pure pitch motion at different pivot position.

Figure 17. The velocity magnitude in pure heave motion.
The velocity magnitude distribution around NACA-0012 foil which oscillating in pure heave motion is shown in Figure 17. The pivot position is put in the leading edge point of the foil. In heave motion, there is no effect on the difference of the pivot position.

The thrust force generated by oscillating foil in pure heave motion is given in Figure 18. It shows that the thrust force in pure heave motion is a dominantly negative value. It means that the oscillating foil in heave motion produces an optimum thrust force and bring the foil moving forward.

Figure 18. Time history of thrust force of flapping NACA-0012 foil pure heave motion

6. Conclusions
The numerical method for the unsteady RANS simulation for the prediction of the resistance of the floater of the wave glider and the motion of the single NACA-0012 foil is proposed. The method can be harnessed to predict the resistance force of the floater and thrust force generated by a single flapping foil in pure pitch and heave motion. The pivot position of the flapping NACA-0012 foil in pure pitch motion has a big role to produce the thrust forces. However, since the research is in the early-stage more studies are needed for the optimum design for a floater in wavy water and simulation of a group of foils to simulate the thrust force required by the wave glider system.

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