Numerical Prediction of Foils Configuration in A Design of Buoy Glider System for Supporting Tsunami Early Warning

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Abstract. Geographically, Indonesia is a disaster-prone country, with the potential to cause damage to public infrastructure not only cause enormous loss of life. Based on the tsunami risk map released by BNPB in 2018, it needs more attention so that mitigation can be implemented properly. It is necessary to revitalize nationally developed by BPPT the buoy-based early warning system for tsunami disasters. Early generation tsunami buoy designs were successfully developed and operated in several waters in Indonesia. In order to improve the performance of the tsunami buoy, a new vehicle system known as the Wave Buoy Glider (WBG) is proposed. It is hoped that this WBG design can cover a wider monitoring area as well as more wave elevation measurement data related to tsunami events. In this research some of the buoy glider design parameters such as sizes and configurations of foil are studied in order to obtain the optimal pulling force of the wave glider to the surface floater. A numerical calculation using the CFD technique is used to determine the hydrodynamic force. So that from this study, it can be seen that an increasing number used foils, the drag and lift forces also tend to increase. The larger the span foil, the greater the value of the drag and lift forces, especially at the larger AoA angle. The positive values of drag forces at any lift forces confirm that wave glider always move forward with every vertical movement of the floater.

1. Introduction

These Geographically, Indonesia is a disaster-prone country, with the potential to cause damage to public infrastructure and basic connectivity not only cause enormous loss of life. Based on the tsunami risk map released by BNPB in 2018, it needs more attention so that mitigation can be implemented properly. An Early Warning System is required for minimizing of the tsunami risk.

In accordance with the mitigation policy as stated by Indonesia Government, it is urgently to revitalize the buoy-based early warning system developed by BPPT. Early generation tsunami buoy designs were successfully developed and operated in several waters in Indonesia. However, the designed buoy has a weakness in the power supply capacity and the data recording area is not wide enough.

In order to improve the performance of the tsunami buoy system, a new vehicle system known as the Wave Buoy Glider (WBG) is proposed. There is a unique characteristic of this wave glider. It utilize a harvest environmental energy such as wave energy as the propulsion of the vehicle and solar energy as electronic, communication and sensor power supply [1].
This marine vehicle consists of two main parts; a floating part which is located on the surface of the ocean (the float) and the submerged part (the glider) which is gliding approximately eight meters below the surface of the ocean. These parts are connected via (umbilical) a tether cable which is mainly responsible to transfer the forward motion of the submerged glider to the surface floater as shown in Figure 1. Since the surface floater elevates with the waves in the ocean, it pulls the submerged glider up. Lift force generated by the surface floater will be converted into forward thrust because of the aerofoil shaped fins located on the submerged glider.

According to the capability of the designed buoy glider, it is hoped that this buoy glider design can cover a wider monitoring area as well as more wave elevation measurement data related to tsunami events. The WBG can also be designed for another marine applications in order to gather useful data such as ocean’s salinity, temperature, climate, fishery, environmental assessment and oil and gas, etc. [2][3]. The designed buoy glider capability improvement can be achieved by involving parameters of hydrodynamic performance in the WBG design such as the drag and lift coefficients [4].

Up to now, significant efforts have been taken on the wave-induced motion analysis of the wave glider. Manley and Willcox [5] as previously explained, the forward motion of the surface glider is caused by the pulling force of the wave glider which is influenced by the heave motion of the surface floater. In order the surface floater can cause a pulling force on the floater, it is necessary to design the foil configuration on the wave glider correctly. There are several foil configurations with specific aspect ratios that are proposed for the wave glider design.

In this paper, a numerical method will be introduced to describe dynamic behaviour of this glider correlate to the propulsion system of the surface floater. Furthermore, a final CFD model will be introduced and the results will be discussed accordingly.

### 2. Background

A number of studies of the dynamic behaviour of marine vehicles has been done by numerous scientists. For a marine vehicle similar to the WBG vehicle, there are only a few papers describing the dynamic modelling of such systems.

An ASC (Autonomous Surface Craft) ARTEMIS was developed firstly by MIT Sea Grant College Program [6]. One of the main disadvantages of the design is its small size, which limits its applications and durability. In June 2000, the mechanical systems of the ASC were heavily modified in such that some potential improvements in the basic platform design were identified as desirable [7].

Kraus and Bingham [8] proposed an estimation algorithm and an extended Kalman filter, using two body dynamics to describe the potential of the Wave Glider for precise localization. The focus of the mentioned work was on the relative motions of the float and glider. Nicholas D. Kraus [9]
published their work considering six-degree-of-freedom in the dynamics equations of motion of the Wave Glider. The work was consistent with the common method of dynamic modeling of marine vehicles which can be found in numerous marine literatures. The focus of the work was to analyze the kinetics of the Wave Glider with respect to three different coordinate systems located on each part independently, then transfer all parameters to the main coordinate frame located on the tethered (umbilical) between the float and the glider and describe the motion with respect to that origin. The main issue with that work was the inconsistent results from simulation results compared to the real time data. Lack of enough hydrodynamic parameters especially for the submerged part and also complicated propulsion system of this vehicle could be mentioned as one of the valid reasons for such inconsistency.

In this paper, two parts of the WBG vehicle are considered separately. The submerged glider which plays the role of the propulsion system of the vehicle is simplified and it is replaced with its effective forces only. The surface floater is considered as an object sailing through the ocean which uses the power supplied by the glider’s propulsive force.

3. Related Theory

3.1 Regular wave

Where \( \zeta(x,t) \) is the wave elevation at time \( t \) and position \( x \), \( \omega \) is the frequency of the wave, \( \varepsilon \) is the phase difference and \( k \) is the wave number which is defined by \( 2\pi / \lambda \), in which \( \lambda \) is the wavelength. Figure 2 illustrates a regular wave with described formula and its parameters.

![Figure 2. Wave Parameters of Regular Waves.](image)

In figure 2, \( H \) is defined as height of a regular wave. In practice, to work with a better accuracy, significant wave height is usually reported as \( H_{1/3} \) which is the average of the heights of the largest one third of the waves.

Regular wave theory describes ocean waves as sinusoidal waves. Regular wave mathematic is presented in Equation 1 [10].

\[
\zeta(x,t) = \zeta_0 \sin(\omega t - kx + \varepsilon)
\]  

For fluid dynamic analysis as well as dynamic modeling of the WBG vehicle, it is necessary to consider the condition of the elevation of the vehicle in the ocean. For that matter, characteristics of sea state 3 is considered.

3.2. Numerical Modelling.

As previously explained, the Submerged Glider is planned to consist of a rigid structure equipped with a number of foil-shaped wings. The submerged glider is mainly responsible for providing thrust for the surface floater and keeping it on a predefined course. Basically, When a foil-shaped structure moves in a fluid, 2 (two) forces will arise which are referred to as drag and lift forces, as illustrated by Figure 3 below.
Figure 3. Drag and Lift Force of Glider Foil.

The drag and lift forces acting on the foil can be determined using equations (3) and (4) as follows.

\[ F_D = \frac{1}{2} C_D \rho u^2 A \]  
\[ F_L = \frac{1}{2} C_L \rho u^2 A \]

Where:
\( F_D \): Drag force
\( F_L \): Lift force
\( C_D \): Drag coefficient
\( C_L \): Lift coefficient
\( \rho \): Fluid density
\( u \): Fluid velocity
\( A \): Surface area of foil

*The Conservation of Momentum*

Imagine a Newton second law, with the famous definition:

\[ F = m \cdot a \]

The definition of force itself basicaly is the rate of change of momentum

\[ F = \frac{dp}{dt} = m \frac{dv}{dt} \]

The sum of momentum (mass * velocity) of the collided body will always be constant or conserved. This law also states the total forces exerted on the body is the sum of the forces from external as well as from the internal body itself (inertial force, gravity, pressure, viscosity etc.).

In the fluid dynamics equation, the forces are divided by volume and then can be rearranged as the following equation (in the x-direction):

\[ \frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \]

The above equation is known as the famous Navier-Stokes equation. But, the Navier-Stokes equation sometimes refers to the continuity and energy equation as well.

The Navier-Stokes equations for the incompressible flow around the foil are discretized and solved by a finite volume method over a circular domain large of 50 chords having the NACA airfoil at the center. A structured mesh is built, coming from refined cells near the airfoil wall, where the gradients are expected to be important, to coarse cells at the external boundaries. Uniform velocity inlet and pressure outlet boundary conditions are assumed on the fluid boundaries, while a smooth wall no-slip condition is applied over the solid boundary, just as shown in Figure 4.
A Reynolds Averaged Navier-Stokes (RANS) approach is chosen for the modeling of the turbulence. The one-equation Spalart-Allmaras model (designed specifically for airfoil simulations) and the two-equation k-ω SST model (providing better results for separating flows) are compared in the validations cases. Two near-wall treatment strategies are tested: the wall function approach, where a model is assumed instead of solving the equations down deep into the boundary layers, and the solve wall approach, which requires a very high mesh refinement for the first cells near the wall.

The designed submerged Glider as it is shown in Figure 5 represents the WBG’s propulsion system which is motivated with propulsion force, via the foils. These foils are designed to move the vehicle by converting the lift force of the glider into thrust.

Considering only the wings of the submerged glider and applying fluid dynamic analysis on them, the thrust forces have been obtained. This work will be done with the help of a Computational Fluid Dynamic (CFD) software package such as ANSYS. In this work, these forces have been considered as the propulsive forces of the vehicle. The boundary conditions in numerical modeling of CFD wave buoy glider are as shown in Figure 6 below.
It is necessary to make the model as simplified as it is possible for the purpose of fluid dynamic analysis. These simplifications resulted in delivering the outputs of the software in shorter time. In addition, on some cases the results are more reliable. In this work, since the model is symmetric and all the foils have equal dimensions, the analysis can be done for one foil only and then repeated for other foils.

In addition, it is necessary to make appropriate assumptions. These assumptions are listed as follows:

- The submerged glider is negative buoyant proportional regarding to its volume. This means that the force caused by weight of the submerged glider has higher value than its buoyancy.
- The foils are the only components which supply the glider with a thrust force.
- The submerged glider always has at higher acceleration than the surface floater. In other words, the tethered umbilical is always in tension.
- The ocean waves assumed to follow the exact ideal pattern (regular wave) which is presented by numerous marine literatures.
- Constant values for the fluid analysis are considered for chosen sea states characteristics based on data obtained from Bales [11].
- Heading angles are assumed to be the same for the float and the glider.

4. Results and Discussion

Based on a numerical calculation has been done, it has been obtained lift and drag forces and then be converted to lift and drag coefficients as function change of foil Angle of Attack as shown in Table 1, 2 and 3 and presented in Figure 7 and 8 below.

| AoA (deg) | Lift Force (N) | Lift Coeff | Drag Force (N) | Drag Coeff |
|-----------|---------------|------------|----------------|------------|
| 30        | 562.6330      | 0.0206     | 353.1206       | 0.0129     |
| 20        | 483.5112      | 0.0177     | 219.1964       | 0.0080     |
| 10        | 240.0983      | 0.0088     | 95.8139        | 0.0035     |
| 0         | -0.3972       | 0.0000     | 57.3500        | 0.0021     |
| -10       | -228.2380     | -0.0083    | 92.9270        | 0.0034     |
| -20       | -513.7380     | -0.0188    | 329.3490       | 0.0120     |
| -30       | -535.5480     | -0.0197    | 468.1607       | 0.0172     |

| AoA (deg) | Lift Force (N) | Lift Coeff | Drag Force (N) | Drag Coeff |
|-----------|---------------|------------|----------------|------------|
| 30        | 815.1746      | 0.0259     | 527.2376       | 0.0167     |
| 20        | 645.0772      | 0.0205     | 307.9832       | 0.0098     |
| 10        | 387.3090      | 0.0123     | 156.9679       | 0.0050     |
| 0         | 0.1317        | 0.0000     | 86.6205        | 0.0027     |
| -10       | -371.0019     | -0.0118    | 153.4016       | 0.0049     |
| -20       | -784.6629     | -0.0249    | 513.9262       | 0.0163     |
| -30       | -865.8700     | -0.0275    | 771.2266       | 0.0245     |
Table 3. Result of 6 Wings Configuration.

| AoA (deg) | Lift Force (N) | Lift Coeff | Drag Force (N) | Drag Coeff |
|-----------|----------------|------------|----------------|------------|
| 30        | 862.4542       | 0.0274     | 570.3803       | 0.0181     |
| 20        | 671.1469       | 0.0213     | 332.5493       | 0.0105     |
| 10        | 351.9175       | 0.0112     | 157.2340       | 0.0050     |
| 0         | -0.0653        | 0.0000     | 81.4905        | 0.0026     |
| -10       | -350.8834      | -0.0111    | 158.8921       | 0.0050     |
| -20       | -861.3293      | -0.0273    | 572.7470       | 0.0182     |
| -30       | -928.5336      | -0.0295    | 831.8585       | 0.0264     |

Figure 7. Drag Force Comparison of 2, 4 and 6 Foils Configuration.

Figure 8. Lift Force Comparison of 2, 4 and 6 Foils Configuration.
Based on these figures above, it can be seen that the greater the Angle of Attack (AoA) of the foil, the greater drag and lift forces. Likewise, in the case of changes in the configuration of 2, 4 and 6 foils, the more the number of foils used, the drag and lift forces also tend to increase. The numerical calculation results of the lift and drag forces on the wave glider design which are influenced by changes in the span of foils are shown in Tables 4 - 7, and these results are presented in graphical form as shown in Figures 9 and 10 below.

Table 4. Result of 6 Wings Configuration (Span = 550mm).

| AoA (deg) | Lift Force (N) | Lift Coeff | Drag Force (N) | Drag Coeff |
|-----------|----------------|------------|----------------|------------|
| 30        | 485.1623       | 0.0154     | 286.2960       | 0.0091     |
| 20        | 484.1353       | 0.0154     | 190.9680       | 0.0061     |
| 10        | 336.2130       | 0.0107     | 91.3220        | 0.0029     |
| 0         | 7.8590         | 0.0002     | 42.9990        | 0.0014     |
| -10       | -325.9520      | -0.0103    | 89.3592        | 0.0028     |
| -20       | -487.9460      | -0.0154    | 192.0476       | 0.0061     |
| -30       | -501.7479      | -0.0159    | 293.7624       | 0.0093     |

Table 5. Result of 6 Wings Configuration (Span = 750mm).

| AoA (deg) | Lift Force (N) | Lift Coeff | Drag Force (N) | Drag Coeff |
|-----------|----------------|------------|----------------|------------|
| 30        | 677.9137       | 0.0215     | 401.0426       | 0.0127     |
| 20        | 677.3550       | 0.0215     | 267.2990       | 0.0085     |
| 10        | 484.8560       | 0.0153     | 127.3302       | 0.0040     |
| 0         | 6.3130         | 0.0002     | 56.9460        | 0.0018     |
| -10       | -472.2380      | -0.0150    | 120.5500       | 0.0038     |
| -20       | -705.1210      | -0.0224    | 270.9725       | 0.0086     |
| -30       | -719.7525      | -0.0228    | 414.3294       | 0.0131     |

Table 6. Result of 6 Wings Configuration (Span = 850mm).

| AoA (deg) | Lift Force (N) | Lift Coeff | Drag Force (N) | Drag Coeff |
|-----------|----------------|------------|----------------|------------|
| 30        | 778.8572       | 0.0247     | 458.9685       | 0.0146     |
| 20        | 789.7500       | 0.0250     | 309.5400       | 0.0098     |
| 10        | 570.5960       | 0.0181     | 144.8290       | 0.0046     |
| 0         | 2.5294         | 0.0001     | 63.6520        | 0.0020     |
| -10       | -570.0085      | -0.0180    | 141.1603       | 0.0045     |
| -20       | -814.5370      | -0.0258    | 309.8979       | 0.0098     |
| -30       | -823.1083      | -0.0261    | 476.0105       | 0.0151     |
Table 7. Result of 6 Wings Configuration (Span = 1000mm).

| AoA (deg) | Lift Force (N) | Lift Coeff | Drag Force (N) | Drag Coeff |
|-----------|----------------|------------|----------------|------------|
| 30        | 967.6928       | 0.0307     | 574.5480       | 0.0182     |
| 20        | 973.0994       | 0.0308     | 380.7926       | 0.0121     |
| 10        | 736.3180       | 0.0234     | 182.5451       | 0.0058     |
| 0         | 34.2860        | 0.0011     | 74.3293        | 0.0024     |
| -10       | -707.1829      | -0.0224    | 168.7563       | 0.0054     |
| -20       | -1007.2590     | -0.0320    | 383.7394       | 0.0122     |
| -30       | -1024.9670     | -0.0325    | 588.4294       | 0.0187     |

Figure 9. Drag Force Comparison of Different Span Foils Configuration.

Figure 10. Lift Force Comparison of Different Span Foils Configuration.
Based on these figures above, it can be seen that the greater the Angle of Attack (AoA) of the foil, the greater drag force. However, increasing the lift force effectively occurs at a change in Angle of Attack of foil from 0 to 20 degrees. At a larger angle it does not affect the lift force so much. The larger the span foil, the greater the value of the drag and lift forces, especially at the larger AoA angle.

5. Conclusion
In the design of the Wave Buoy Glider vehicle to support the provision of early warning tools against tsunami hazards, a numerical simulation of the effect of the foil configuration on the drag and lift forces has been carried out. Based on the analysis of the results of numerical calculations that have been carried out, the following conclusions can be drawn:

- The greater the Angle of Attack (AoA) of the foil, the greater of drag and lift forces. Likewise, in the case of changes in the configuration of 2, 4 and 6 foils, the more the number of foils used, the drag and lift forces also tend to increase.
- The larger the span foil, the greater the value of the drag and lift forces, especially at the larger AoA angle.
- The positive values of drag forces at any lift forces confirm that wave glider always move forward with every vertical movement of the floater.
- From this research, it was clear that a foil configuration play an important role in the design of Wave Glider Buoy, in order to determine an optimum dimension of the designed foils for WBG.
- It is necessary to do another research by modeling the excitation wave force to get a more realistic pulling force of wave glider to surface floater.

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