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RUDDER PROFILE OF POWER-FREE UNDERWATER VEHICLE FOR KUROSHIO POWER GENERATION

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Kuroshio is one of the ocean currents in the north Pacific, passing through the east of Taiwan. Kuroshio current has a steady flow in which the direction of 75-80% heads the north and the northeast. It is still difficult to harvest Kuroshio energy due to the conditions of deep seabed more than 400m and surface wave of current flow affected by season winds and typhoons. In order to obtain higher efficiency of Kuroshio energy, a power-free underwater vehicle, which works under the sea to carry generation turbines, was developed. This underwater vehicle can move upward and downward by means of changing rudders without applying power supply. In this study, to find the optimal rudder profile for the power-free underwater vehicle several symmetric profiles of the rudder in accordance with National Advisory Committee for Aeronautics (NACA) airfoil designation are selected to investigate the lifting and drag force in the Kuroshio current. Results indicate that the optimum rudder profile is NACA0008-L5 by considering the lift force and mechanical strength of the rudder. The rudder profile NACA0008-L5 at a 30° attack angle in 1.0 m/s uniform flow offers a 19.1% increment of lifting force, more efficient than the other rudder profiles.

Keywords: Ocean current, Energy harvest, Computational fluid dynamics, Steady flow, Deep seabed, Surface wave, Typhoon.

1 INTRODUCTION

Due to the excessive use of fossil fuels causing global pollution and warming, exploitation of clean and renewable energy becomes urgent worldwide. The area of the ocean occupies more than 70.8% of the total surface area of the earth (Jeng, 2011). Ocean energy has better potential and effective in developing power generation than wind power due to the higher density of seawater than air. Power generation from ocean energy is beneficial to reduce CO_2 emitted in the atmosphere and the global warming problem. Kuroshio is the maximum current in the North Pacific Ocean, with a band of 120km–170km in width and 400km in length, passing through the east of Taiwan. When Kuroshio flows through the eastern coast of Taiwan, the flow speed is stable with 1.0–1.5 m/s according to on-site measurement (Andres *et al*. 2008, Johns *et al*. 2001). There are many estimations of Kuroshio power near Taiwan, such as the power approaches to 5.5 GW by ocean flow (Tang 2010), according to monsoons and seasonal variation influence the total power decreases to 4 GW in winter and increases to 10 GW in summer (Hsin *et al*. 2008, Chen 2010). Estimated reserves of Kuroshio power near Taiwan are at least 30GW (Hsu *et al*. 1999, Chen 2010, Tang 2010).

However, it was difficult to develop Kuroshio power generation because of the essential factors about the capacity of water turbines, water depth, and extreme climate (Kuo *et al*. 2013, Hsu *et al*. 1999). For the capacity of water turbines, some water turbines suitable for Kuroshio power generation in speed less than 2.0 m/s have been exploited (Pan *et al*. 2013, Kuo *et al*. 2008). Except for water depth, which the Kuroshio current passes through eastern Taiwan, complex wave fields due to typhoons and Kuroshio currents interaction might also endanger power generation equipment. To overcome the effect of water depth and extreme climate, a power-free underwater vehicle carrying turbines was developed to work in Kuroshio current (Lee *et al*. 2017). The rising and sinking of the power-free underwater vehicle are controlled by rudders. The power-free underwater vehicle is needed for Kuroshio current power generation. The lift force of the power-free underwater vehicle depends on the Kuroshio flow speed and attack angle of the rudders. To provide enough lift force of rudders on the power-free underwater vehicle is still a big challenge for Kuroshio power generation.

In this study, the rudder profile of a power-free underwater vehicle worked at the speed of 1.0 m/s is discussed. Based on rudder profiles with symmetric shape conformed with the National Advisory Committee for Aeronautics (NACA), the lift of rudders is calculated at 30 degrees (Lee *et al*. 2013) of the attack angle, and the optimal rudder profile is proposed.

2 RUDDLE PROFILE AND CALCULATIONS

2.1 Rudder Profile of NACA

For rudder profiles worked at a lower speed, NACA has provided a guideline of rudder profiles to design the rudder shape in the aviation industry. When the performing airfoil is converted to the thickness, the thickness distribution is almost the same as the airfoil profile. Those rudder profiles have a regular distribution of patterns in thickness as follows.

$$\bar{y}_c = \frac{\bar{c}}{0.2}(0.29690\sqrt{\bar{x}} - 0.12600\bar{x} - 0.35160\bar{x}^2 + 0.28430\bar{x}^3 - 0.10150\bar{x}^4) \tag{1}$$

where $\bar{y}_c$ = the thickness of each of the *x* coordinates, $\bar{x}$ = the position of the maximum thickness, and $\bar{c}$= the maximum thickness (*t*) in percentage of chord (%). Eq. (1) is the best distribution function of rudder thickness. The NACA considered the relation of Eq. (1), relative camber, and the position of maximum camber to assign the airfoil coefficient of rudders with the expression of NACA XYZZ, where X= the maximum camber in the percentage of the chord (airfoil length), Y= the position of the maximum camber in tenths of a chord, and ZZ= the maximum thickness (t) of the airfoil in the percentage of a chord, and schematically in Figure 1.

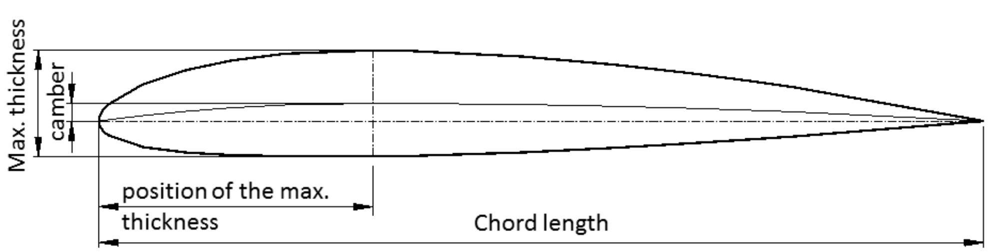

Figure 1. The NACA Profile geometry.

2.2 The Selection of Rudder Profile

Based on the NACA airfoil designation, NACA provides a series of NACA00 rudders in the range of 0006–0024 suitable for the lower speed of the rudder. Nine profile numbers with 0006, 0008, 0009, 0010, 0012, 0015, 0018, 0021, and 0024, respectively, were suggested according to a 1% increment if the maximum thickness of rudders $\bar{c}$ assigned at $\bar{x}_c$ = 30%. This type of rudder shape is symmetric. In this study, the NACA symmetrical rudder profiles in 0006–0024 (nine shapes) were considered and calculated from Eq. (1) to evaluate the lift force of the rudder on the power-free underwater vehicle. In addition, some rudders with the shape not complying with NACA guidelines were also calculated at 0 relative camber and $\bar{x}_c$ = 0.328. The span width and chord line length of the rudder are 4,000 mm and 3,200 mm, respectively, in calculations. For instance, the profile number 0010 means that the position of maximum thickness is at 10% chord length, or the position of $\bar{c}$ at 320 mm in the calculation, and the other part of rudder size can be calculated from Eq. (1).

2.3 CFD Calculations

The power-free underwater vehicle with two rudders is designed to carry the turbines for Kuroshio power generation, shown in Figure 2. The width and length of the vehicle (buoy) are 4,500 mm and 25,000 mm, respectively. To reduce the effect of turbulent flow on the rear rudder induced by the front rudder, Pan *et al*. (2012) pointed out that the distance between two rudders is at least 5 times of chord line. In Figure 2, five times of chord line (16,000 mm) between two rudders were assigned and the attack angle of 30 degrees was fixed in calculations.

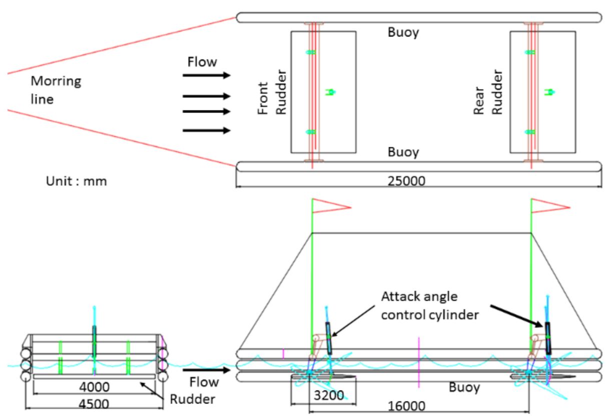

Figure 2. The power-free underwater vehicle.

The computational fluid dynamics (CFD) simulation, based on the standard k-ε model (k = turbulent kinetic energy, ε = dissipation rate), was used to calculate lift force (LF) and drag force (DF) over the rudder at 1 m/s net flow velocity. Assuming that the direction of Kuroshio current flows to and perpendicular to the front rudder to obtain higher power generation efficiency of water turbines, and the shape of the rudder in the Z direction remains unchanged.

Two-dimensional (2-D) unstructured mesh grids have been used to divide the computational domain ($35.2\times60m^2$) into small control elements with a total of 2.246×10^6 nodes and 2.238×10^6 elements, shown in Figure 3. The inlet speed at the left side of the boundary (Figure 3) is 1.0 m/s, and the upper and the lower boundary are considered as the wall (fixed end). When the outlet speed at the right side of the boundary (Figure 3) is equal to the inlet one speed, the lift and drag forces of the rudder are calculated as follows.

$$\mathrm{LF} = \frac{1}{2} \cdot \mathrm{C}_L \cdot \rho \cdot A \cdot V^2 \quad (2)$$

$$\mathrm{LD} = \frac{1}{2} \cdot \mathrm{C}_D \cdot \rho \cdot A \cdot V^2 \quad (3)$$

where C_L and C_D are the lift and drag coefficient, respectively. The parameters A, ρ and V represent the projected area of the rudder (m^2), density of seawater with 1025 kg/m^3 and average flow velocity, in turn.

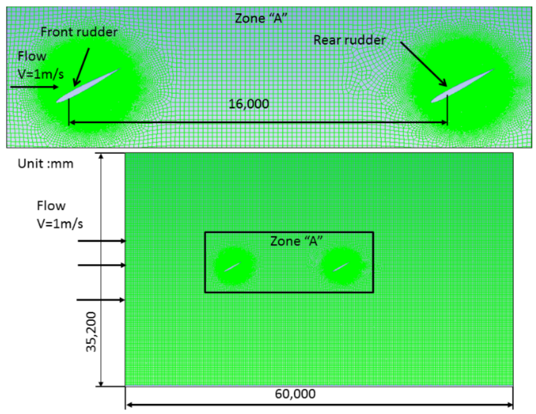

Figure 3. Two-dimensional quadrilateral dominant method control elements at 30° attack angles.

3 RESULTS AND DISCUSSION

From Eq. (2) and Eq. (3), the lift and drag forces are proportional to the C_L and C_D, respectively. Higher C_L and C_D values corresponding to higher lift and drag force are found. Figure 4 shows the relation of C_L and rudder profile at 30° attack angles of the rudder, where the negative value of C_L represents the downward direction of the lift force. In Figure 4, the absolute value of C_L decreases as the thickness of the rudder profile increases (higher airfoil coefficient). In other words, the rudder of an underwater vehicle with the lower airfoil coefficient has a higher lift force under Kuroshio current.

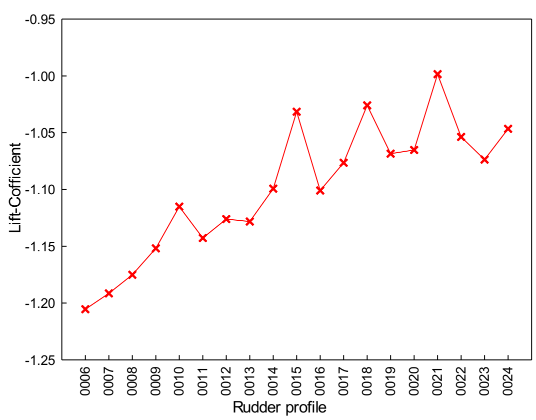

Figure 4. Lift coefficient at 30° attack angles of the rudder.

In addition, there is a bending point on the curve lying in the range of rudder 0007–0010 in Figure 4. The lift and drag coefficient of extra rudder profiles at 0007.5 and 0008.5 is also calculated and the results are listed in Table 1. By comparing with the C_L values of the front rudder, three better rudders, 0006, 0007, and 0008.5, are found, with higher C_L values shown in Table 1. Among them, the rudder 0008.5 and 0007 have the same C_L values or the same lift force. The thickness (h) of rudder 0008.5 is 1.21 times of rudder 0007, such that section modulus of rudder 0008.5 is 1.47 times (h^2) greater than rudder 0007, almost equivalent to mechanical strength having 1.5 times. In the meantime, the lift force of rudder 0006 is only 1% greater than rudder 0008.5, but the mechanical strength of rudder 0008.5 is twice of rudder 0006. Thereby, the best rudder profile with 0008.5 is suggested to use in Kuroshio current by considering probable damage of power generation equipment causing by driftwood and typhoon surge. The rudder profile 0008.5 suitable for Kuroshio power generation is named NACA0008-L5 due to no definition in NACA designation. The dimensions of rudder profile no. NACA0008-L5 is shown in Figure 5. For the power-free underwater vehicle (Figure 2) with two NACA0008-L5 rudders at the same level, the lift force is 1.925 times that with a single rudder (listed in Table 1). This is due to the effect of turbulent flow caused by the front rudder, leading to less lift force provided by the rear rudder, with only 61.62% of the front rudder. Table 1 also displays that the drag force of two NACA0008-L5 rudders is only 1.179 times of a single rudder, and the drag force on the rear rudder is 59.45% compared with the front rudder.

Table 1. Lift and drag coefficient of rudder.

Profile No.	Two Rudder		Front Rudder		Rear Rudder		Remarks
	C_L	C_D	C_L	C_D	C_L	C_D	
0006	-1.954	1.196	-1.205	0.745	-0.749	0.451	NACA guidelines
0007	-1.930	1.171	-1.191	0.733	-0.739	0.438	
0007.5	-1.904	1.142	-1.164	0.697	-0.740	0.445	
0008	-1.902	1.181	-1.175	0.739	-0.727	0.442	NACA guidelines
0008.5	-1.925	1.179	-1.191	0.740	-0.734	0.440	
0009	-1.879	1.148	-1.152	0.715	-0.727	0.433	NACA guidelines

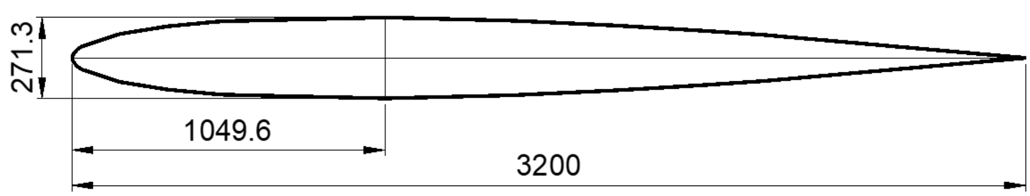

Figure 5. Schematic of rudder profile no. NACA0008-L5 and dimensions (mm).

4 CONCLUSIONS

The rudder profiles of the power-free underwater vehicle for Kuroshio power generation was investigated by using CFD simulation. The following conclusions are drawn.

(1) The thickness of the rudder profile is an important factor influencing the lift force and drag force.
(2) The rudder profile of NACA0008-L5 at a 30° attack angle in 1.0m/s uniform flow offers a 19.1% increment of lifting force.
(3) The rudder profile of NACA0008-L5, compared with profile 0006 and 0007, provides 2 times and 1.5 times of mechanical strength, respectively.
(4) Two NACA0008-L5 rudders worked at the same level provide 1.925 times lift force, not 2 times, due to the effect of turbulent flow.
(5) By considering the optimum influence on lift force and mechanical strength, the rudder profile NACA0008-L5 has been found suitable for power-free underwater vehicles worked in Kuroshio current.

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