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Rudder Controlling of Underwater Vehicle Using in Kuroshio

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Abstract. In this paper, we investigate an underwater vehicle with two rudders suitable for working in Kuroshio near the eastern Taiwan, where the flow field of ocean current is less than 1.0m/sec. Lift and drag forces of the underwater vehicle submerged in the sea were calculated at different attack of angles and rudders by using finite element method. An on-site experiment with a prototype vehicle was also conducted located on Hsinta Fishing Harbor. Results show that lift force for the rudder of prototype vehicle near the sea surface is only 60% of theoretical calculations. To reduce the turbulence effect, the position of rudders in the front and the rear for the underwater vehicle should not be at the same level. Drag forces increase tremendously with increasing attack of angles compared with the effect of rudder's quantity. The power-free underwater vehicle has been built and controlled steadily at 0.6~0.7m/sec flow velocity, suitable for carrying generators in Kuroshio.

Introduction

For lack of natural resources in Taiwan, there is 98% energy consumption imported from foreign countries. Most of them belong to fossil fuel such as coal and petroleum so that many CO_2 emit to the atmosphere if use. It is a bad energy policy to have less energy substitutes and to use the energy of fossil fuel. The need of clean energy becomes urgent especially for Taiwan. Taiwan is an island, and Kuroshio, one of ocean currents in the Pacific, passes through the east of Taiwan. This ocean energy provides a kind of clean energy and is able to utilize, similar to solar energy and wind power. Moreover, due to higher density of sea water than the wind, ocean energy is more potential and effective for power generating.

Four ocean energies including ocean current power, thermal power, tidal power and wave power can theoretically employ to generate electric power. Among them, ocean current power with stable flow speed and direction is worthy to explore in practical applications. Kuroshio is the maximum current in North Pacific Ocean with a band of 120 km~170km in width. When Kuroshio passes between the eastern coast of Taiwan and Green Island, the flow velocity is pretty stable with 1.0~1.5 m/sec and the flow capacity is about 20.7~22.1Sv [1], where Green Island is a small volcanic island in Pacific ocean, about 33 km off the eastern coast of Taiwan. Estimated reserves of Kuroshio power near the coast of Green Island are at least 30GW [2-4].

Techniques of ocean power exploiting are still developing. Recently, some seawater turbine generators have been operated to generate power, but the flow speed of sea water has to greater than 2m/sec [5-6]. Up to now, no turbine generators can capture Kuroshio energy to generate electricity commercially due to low flow velocity. For Kuroshio power, we need to build high performance turbine generators suitable for flow velocity less than 1.5m/sec. Meanwhile, a floating vehicle is essential to carry dynamo for generating electricity in Kuroshio area. This power-free vehicle needs to sink while turbine generators are working, and to float when generators are dysfunctional. Thereby, an anchor cable set to bear drag forces induced from underwater vehicles is necessary.

Here, we concentrate on the floating and sinking of the underwater vehicle containing traditional rudders in low flow velocity condition. Different from airplanes and ships [7], the underwater vehicle within Kuroshio does not install any propeller or jet engine to produce the high velocity over the rudder that increases uplifting, descending or turning power. How to control the floating and sinking underwater vehicle in Kuroshio without acceleration is a big challenge. In the following, we calculate lift and drag forces for different attacks of angles by using computational fluid dynamics (CFD) at 1.0 m/sec flow, and compare the numerical results with the experiments by a prototype vehicle containing two rudders. Pressure field in the vicinity of the rudder has been presented for various angles.

Computational Model

Three types of analyses in the fluid mechanics are well known: experimental fluid dynamics (EFD), analytical fluid dynamics (AFD) and computational fluid dynamics. Recent developments in the computational techniques with higher memories enable researchers and engineers using CFD widely [8], especially in a marine rudder without propeller and ship was taken into account [9]. Marine engineers also have been used CFD to simulate ship flow to realize the flow field of a ship under the same conditions as with tank experiments [10].

In this CFD simulation, effects of attack angle of underwater vehicle rudders without propeller are investigated. Fig. 1 shows the dimension of rudder, where the span width of the rudder is 4 m and chord line length is 2.13 m.

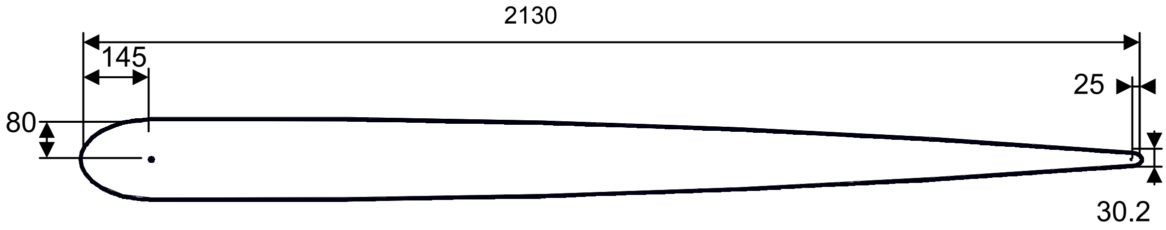


Fig. 1 Sketch of rudder layout and dimension

Two-dimensional (2-D) unstructured mesh grids have been used to divide the computational domain into small control elements. Mesh structure has been designed as denser at the leading and trailing edges of the rudder by using sizing function. Fig. 2 shows 2-D unstructured elements for two rudders with a distance of 7.2 m. Computational domain is 3.2x2.6 m^2 and mesh structure has 25326 nodes. Velocity inlet of 1.0 m/sec is applied. The effects of the attack angle on the lift (LF) and drag (DF) forces are calculated as follows.

$$\mathrm{LF} = \frac{1}{2} \cdot C_L \cdot \rho \cdot A \cdot V^2 \tag{1}$$

$$\mathrm{DF} = \frac{1}{2} \cdot C_\mathrm{D} \cdot \rho \cdot A \cdot V^2 \tag{2}$$

where C_L and C_D are 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 velocity, in turn.

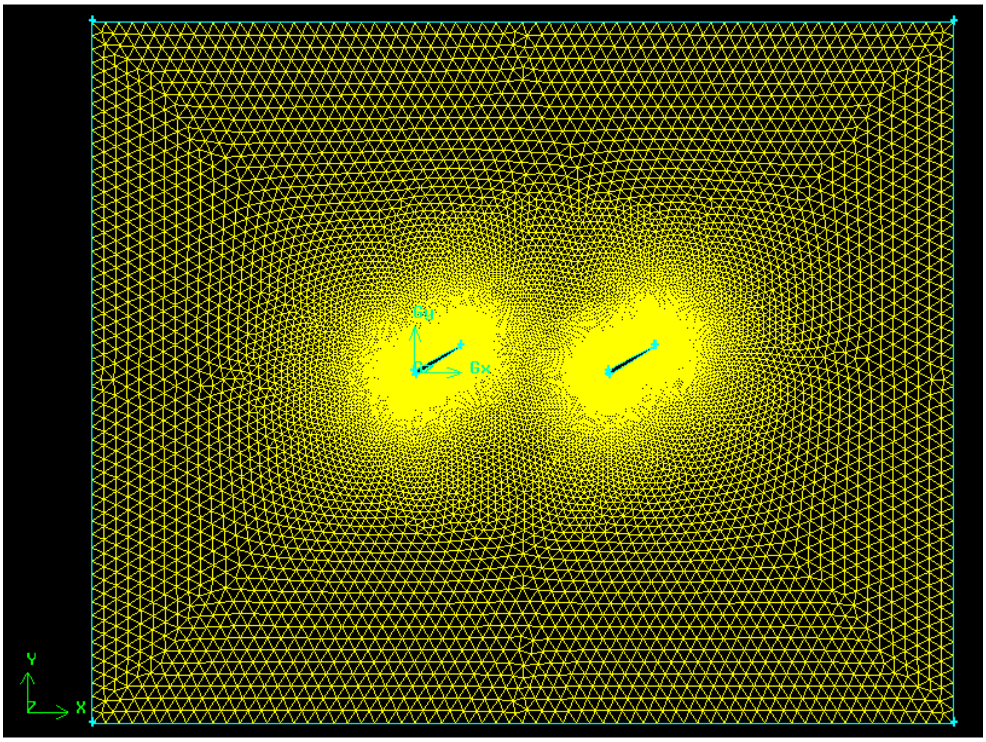


Fig. 2 Two-dimensional unstructured elements

Field Site Experiments

The tested vehicle shown in Fig. 3, which made by the Wan-Chi Steel Industry Co., Ltd. (Taiwan), is 12 meter in length and 4.5 meter in width. There are three pipe rafts on both left and right sides to be the buoyancy source of the vehicle. Two tested rudders are separately set up on the front side and back side of the vehicle. The distance between two rudders is 7.2 meter. The span width of the rudder is 4.0 meter and chord line length is 2.13 meter. The manufactured weight of this vehicle is 38.9 kN. Two hydraulic cylinders are installed in this vehicle to adjust the attack angle of rudders. Furthermore, there are two balanced rudders in the central position of this vehicle to keep the posture being under balance.

The location of experiment is at Hsinta Fishing Harbor in Kaohsiung (Taiwan), where the depth of sea bed is 5~6.5 m and tide fluctuation is less 0.5m, shown in Fig.4. The test area is in the southeast side of inner harbor marked in Fig.4, and the tested vehicle totally submerged in the sea. The tested vehicle does not install any propellers or engine, and the only designed power comes from ocean current of Kuroshio. Here, the controlled velocity of current in the inner Hsinta Harbor is 0.6~0.7 m/sec for the tested vehicle. To firm up underwater vehicles, we use the cable connected to capstan on the bank. A wireless transmission apparatus was also used to command and adjust the attack angles of rudder so as to control the tested vehicle up and down in the sea.

From the calculation result, the buoyancy force is up to 54.0 kN when the tested vehicle totally submerged in the water. Thereby, a surcharge of 5.3 kN is added to let the reserved buoyancy force up to 9.8 kN during the first tested stage. Besides, four automatically inflatable bladders and counterweight falling-off devices are installed in the PVC pipe rafts for automatically floating on the sea surface in case of the vehicle losing its function.

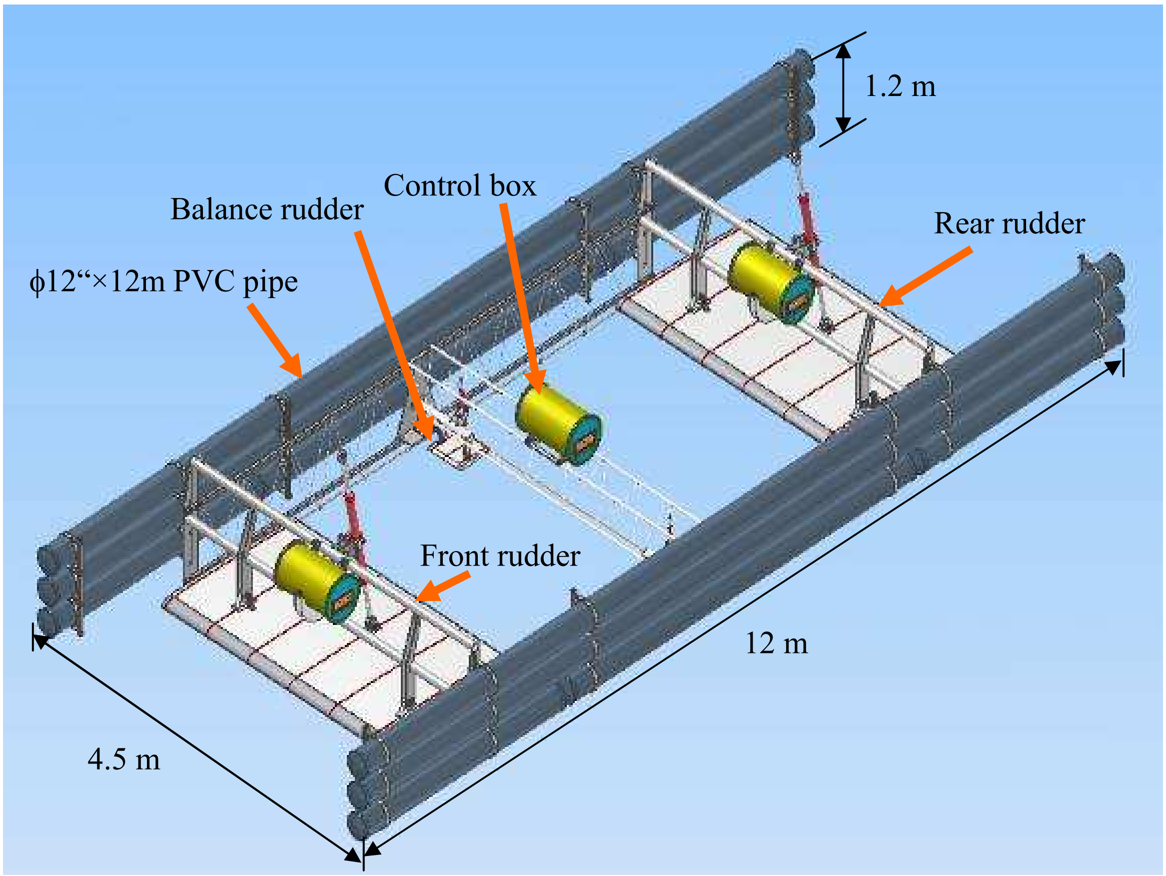


Fig. 3 Prototype of tested vehicle

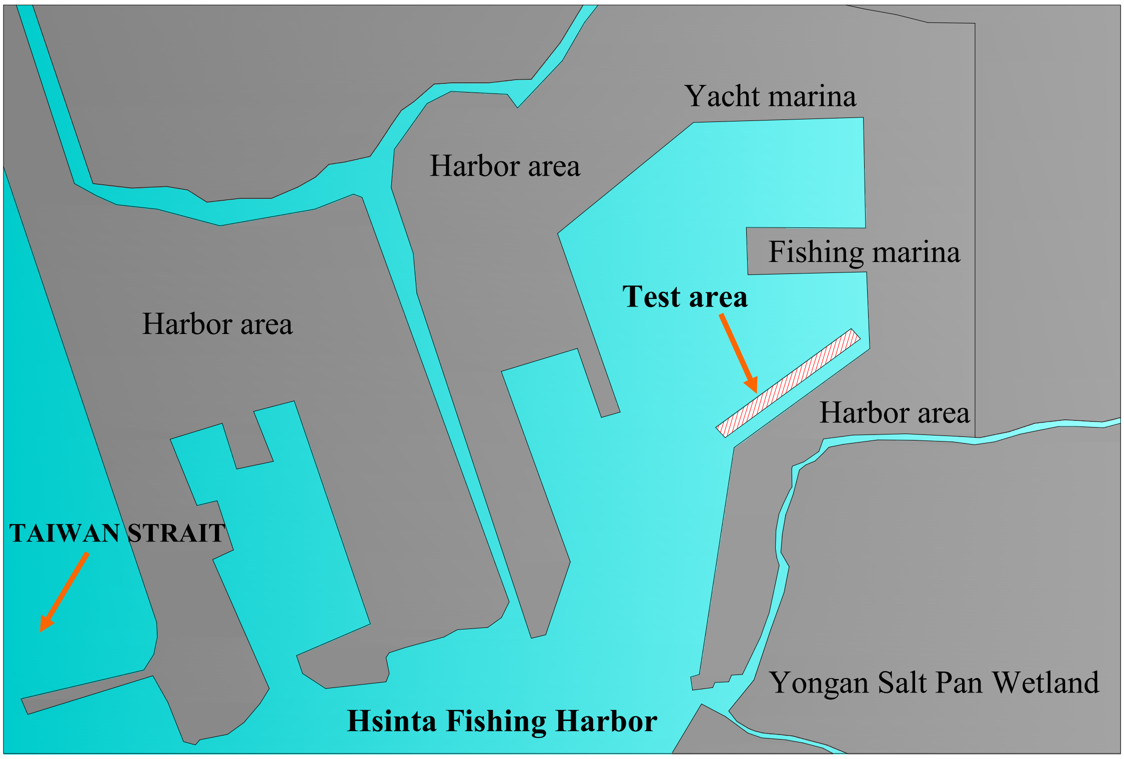


Fig. 4 Test studied area at Hsinta Fishing Harbor

Results and Discussion

Model Computation. Simulated results were calculated by CFD computations for the non steady state when the vehicle submerged, shown in Table 1, where flow velocity of 1.0 m/sec was applied to the rudder. Lift and drag forces on single or two rudders for attack angles of 10°, 20° and 30° were determined, and plotted in Fig. 5.

Table 1. Simulated results by CFD

quantity of rudder	attack of angle (degree)	coefficient of lift	lift force (kN)	coefficient of drag	drag force (kN)
1	10	0.8	-3.51	0.06	0.28
1	20	0.92	-4.01	0.23	0.99
1	30	1.33	-5.82	0.65	2.86
2	10	-	-6.95	-	0.53
2	20	-	-6.37	-	1.74
2	30	-	-7.49	-	3.80

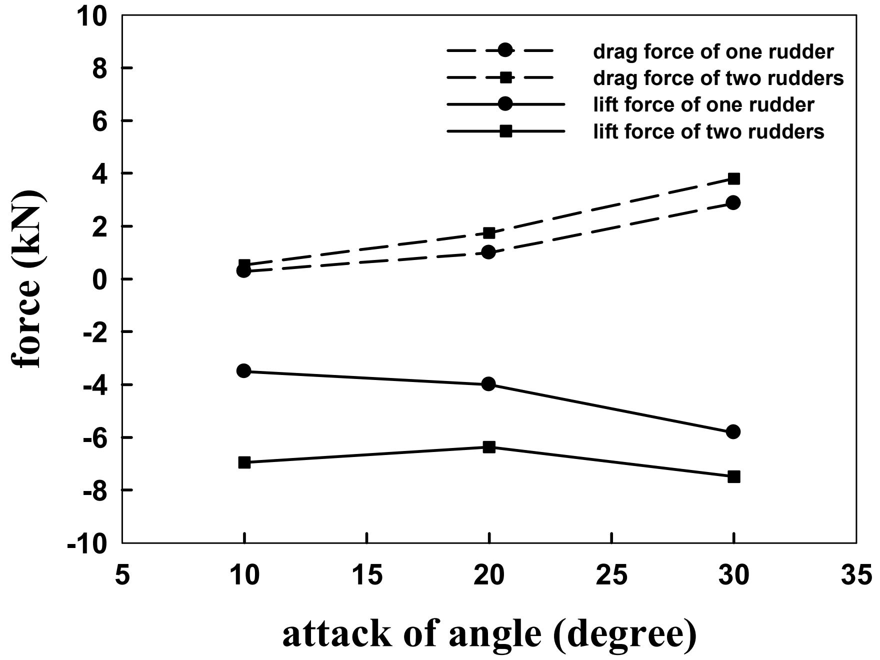


Fig. 5 Lift and drag forces of rudders

As the attack angles of the rudder increase, lift force of single rudder for 10°, 20° and 30° is -3.51 kN, -4.01 kN and -5.82 kN respectively, where the negative value means a downward pressure. Obviously, lift forces in term of attack of angles have no linear relation found. Similarly, the underwater vehicle with two rudders also has the same tendency shown in Fig. 5.

For the attack angles of 30°, for example, there is a lift force of -5.82 kN on the single rudder, and -7.49 kN on two rudders, shown in Table 1. Lift force on two rudders is only 29% more compared with single rudder. Lift force cannot double when the rudder is double, due to the action of turbulent flow. This turbulent flow is tail water caused by the front rudder will affect lift forces of the rear rudder. From Fig. 5, the turbulence effect becomes important as attack angles of the rudder gradually increase.

The underwater vehicle with rudders is able to hold by the cable during the operation in Kuroshio, prevented from floating aimless. The allowable strength of the cable should be greater than drag forces of the rudder calculated from Eq. (2). The drag forces, shown in Table 1, demonstrate the attack angle is a dominant factor compared with the quantity of rudder. For example, the drag force of two rudders at the attack angle of 10° is 0.53 kN, and at 30° is 3.80 kN. The drag force increases tremendously, more than seven times. When many underwater vehicles are composed of a series connection of the cable, we should pay attention to total drag forces change with increasing the attack of angle.

Meanwhile, from Table 1 and Fig. 6, coefficient of lift C_L is always greater than coefficient of drag C_D on single rudder. From Eq. (1) and (2), the magnitude of lift forces also has the same trend compared with drag forces at the attack of angles from 10° to 30°. Both coefficients increase with increasing the attack of angle.

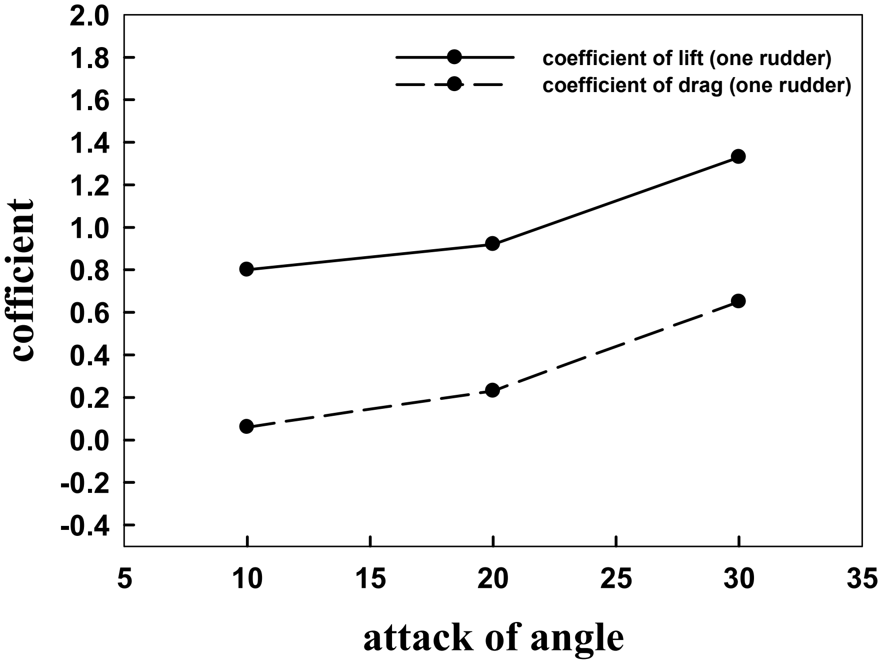
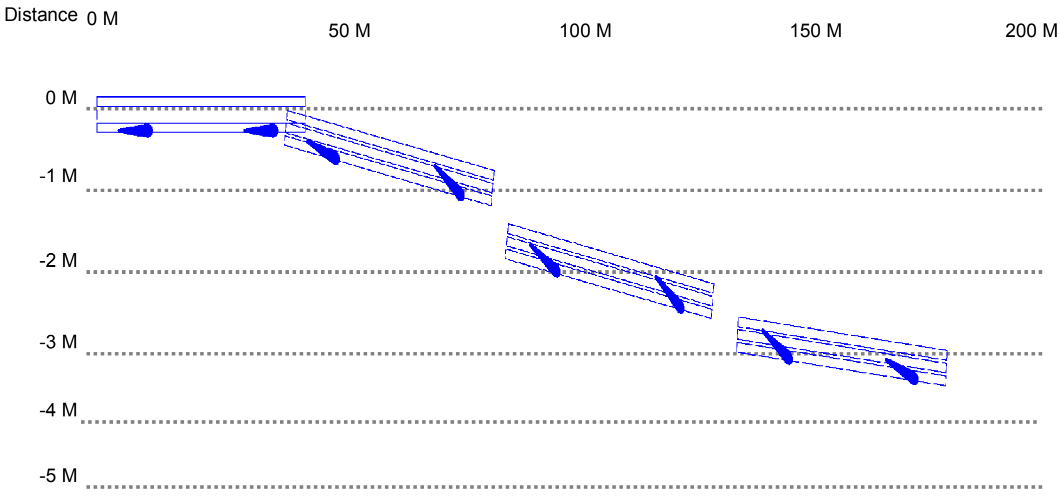


Fig. 6 Coefficients of lift and drag on single rudder

Experimental Results. The prototype vehicle containing two rudders shown in Fig.3 was tested at the average flow velocity of 0.65 m/sec at Hsinta Harbor. Before the test, we need to examine downward pressure to ensure the tested vehicle submergible. From Table 1, the simulated lift force at the attack angle of 30° is -7.49 kN during flow velocity of 1.0 m/sec. As the velocity becomes 0.65 m/sec, lift force calculated from Eq. (1) is 3.16 kN. Therefore, let the reserved buoyancy force for the tested vehicle be 1.96 kN in advance.

Results show that the prototype vehicle did not completely submerge until the pitch angles of two rudders reach 10°. This result is the same as CFD simulations. Compared with Table 1, downward pressure of the vehicle near the sea surface is about 60% of theoretical calculations. This is because the turbulent flow caused by tail flow of the front rudder and the rudders doing virtual work near the sea surface consume the rest 40% downward pressure. To avoid the effect of turbulent flow, the level of rear rudder had better differ from that of the front rudder.

Fig. 7 shows the optimum combinations of pitch angles, attack angles and the depth when the prototype vehicle moves under the sea with 0.65 m/sec current. The prototype vehicle is in a controllable condition steadily if pitch angles and attack angles are in the range shown in Fig. 7. For example, attack of angle in the front and rear rudder is 22°~30° and 7°~15°, respectively, to maintain the vehicle steadily at the water depth of 0 ~ -1m.



Depth (M)	0	0 ~ -1	-1 ~ -2	-2 ~ -3
Pitch angle (deg)	0	+8 ~ +10	+9 ~ +11	+5 ~ +7
Attack of angle in front rudder (deg)	0	+22 ~ +30	+22 ~ +30	+15 ~ +24
Attack of angle in rear rudder (deg)	0	+7 ~ +15	+15 ~ +23	+22 ~ +30

Fig. 7 Optimum angles at 0.65 m/sec current

Conclusions

The tested underwater vehicle with two rudders working in Kuroshio for carrying generators was investigated by CFD simulation and the experiments. We conclude this study as follows.

(1) To overcome buoyancy force of the prototype vehicle at the sea surface, we need to apply the pitch angle first, and then, two rudders reach its corresponding maximum attack angle. This procedure guarantees the vehicle to steadily move under water.

(2) Only 60% effective downward pressure for the rudder exists as the vehicle works near the sea surface.

(3) To reduce the effect of turbulent flow, the level of rear rudder and front rudder had better differ from each other.

(4) Attack angle is a dominant factor for drag forces compared with the quantity of rudder.

(5) An underwater vehicle suitable for low flow velocity has been developed.

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