Study of the Underwater Observation System in Fast Water Current

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***Abstract*-The port area is a specific region where the water depth is not so deep, the change of the flow is complex, and the transparency of the seawater is low. In the construction and the management of port facilities, it is very important to observe the situation under the water.**

In this paper, the "Autonomous Towed Vehicle" used in three navigation modes (towed, autonomous and "kite") is proposed as an underwater observation system in the fast current area according to the level of turbulence.

First of all, necessary functions were examined for the given missions as an underwater observation system. At the next step, the stability of this system was verified by the simulation concerning the basic motion based on the supposed physical values.

As a result, it was clarified that increase of the added weight and the area of the forewings were necessary to ensure the stability of this system which had the special feature as the towed vehicle. It was also shown that not only heave and pitch control by the parallel-motion of the forewings but also roll control by the differential-motion of the forewings were necessary. Furthermore, the hydrodynamic coefficients were obtained by the 1/2 model towing tank test.

The observation system developed in this research can be applied to an environment monitoring system in similar conditions, and can be used for various investigations in port area.

I. INTRODUCTION

In various investigations of the port area and the construction management of the port facilities, it is quite important to observe underwater state, to supervise underwater operations, and to inspect the completion of the underwater construction by viewing. These work are carried out mainly by divers and partly by ROVs at present. However, it is very difficult to work in the fast water current because the stability of divers and ROVs is low.

On the project of the improvement of the Tokyo Bay Waterway, it is needed to observe and take pictures of underwater images to confirm the effect of the artificial fish reeves constructed by the blocks of the ruined Third Fort of Tokyo Bay (constructed in Meiji era and destroyed by the Great Kanto Earthquake of 1923) and to maintain the function of the waterway. However, the current is fast and the water depth is too deep for divers to work in this area. Therefore, it is needed to research and develop a new underwater observation system in order to carry out viewing work safely and efficiently.

Consequently, we are developing a new underwater observation system using an "Autonomous Towed Vehicle". The results of this research can be applied as the technique of the environmental monitoring work such as the investigation of seawater property in the similar conditions of strong external forces.

This paper describes the basic constitution of the "Autonomous Towed Vehicle" system, and presents the results of the basic motion simulation and towing tank test.

II. OBSERVATION SYSTEM

A. Details of the mission

It is important to clarify the operating condition in beginning of the research and development to construct a reasonable system for the mission. The mission given to this system is as follows.

1) Observation area
   Sea area around the destroyed Third Fort of Tokyo Bay
2) Observation object
   Taking a picture of image of the fish for effect confirmation of the artificial fish reeves
   Taking a picture of image of sea bottom situation for maintenance of the function of the Waterway
3) Configurations of fish reeves
   The reef (5 to 8m tall and about 100m×100m wide) is constructed by the destroyed blocks which are 1 to 6m cubes. And several reeves are scattered in observation area.
4) Maximum observation depth 60m
5) Maximum water current 3knots

B. Basic system

An autonomous type and a remotely controlled type can be applied as the control technique of the vehicle. It is basically required for the vehicle to cruise on the decided route keeping constant altitude or depth because the main mission of the vehicle is taking a picture of image in the sea bottom. It is also thought to be a suitable mission for the autonomous control type because this system should observe a comparatively wide area. Therefore, the AUV (Autonomous Underwater Vehicle) was selected as a basic vehicle of this system.

For taking a picture of image in the fast water current, it is necessary to move stably against the strong external force. Most AUVs developed so far are for the mission in the deep sea and the lakes in which the flow is almost constant and not so fast. If the vehicle is equipped with the high power thruster, it is theoretically possible to cruise stably in maximum current only by its own thrust. However, it is not reasonable because it will be a quite large-scale system with bulky energy source.

On the other hand, the observation with clear real-time images is preferable to confirm the effect of the fish reeves. Accordingly, taking a picture of image by the vehicle and transmission of the image data to the shipboard should be done at the same time. By the above-mentioned, it is an adequate solution to equip the vehicle with the cable witch has the function to maintain the position in fast water current and to

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transmit the image data. Consequently, the combination of tow ship and the towed autonomous vehicle was adopted as a basic system.

C. Expansion of availability

Actually, it seems that there are considerably many cases to use the system below the maximum current speed. The autonomous navigation with no cable in these cases will enable the increase of the movement area and the more efficient observation. Therefore, the system which can be used as an AUV without the cable below a certain current speed was planned.

It is necessary to keep ground speed below a certain value for taking a clear picture of the image. Therefore, when the current speed increases, the counter-water speed of the towed vehicle might exceed the range in which the vehicle can be controlled suitably. In this case, it is thought that to make the towed vehicle advance in slow speed by winding up with a winch on the shipboard is effective (The towing velocity is nearly 0. It is called "kite mode" in this paper hereafter).

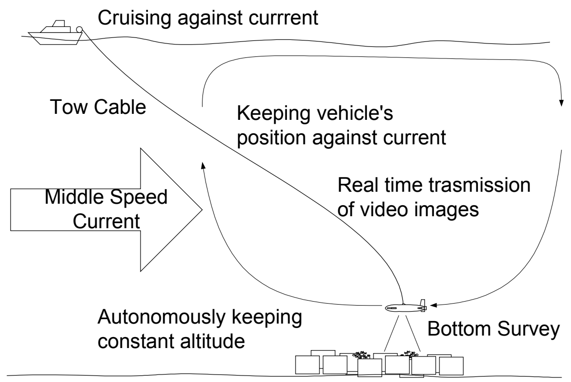

Fig. 1. Towed mode

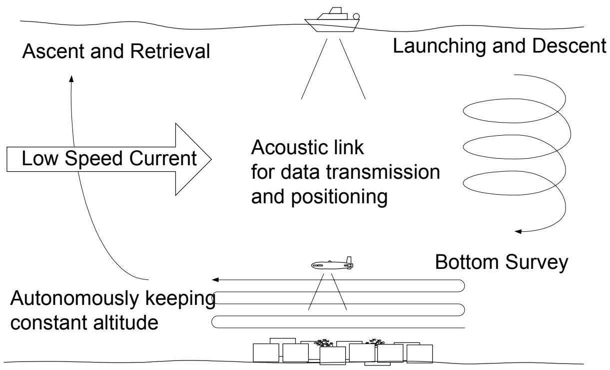

Fig. 2. Autonomous mode

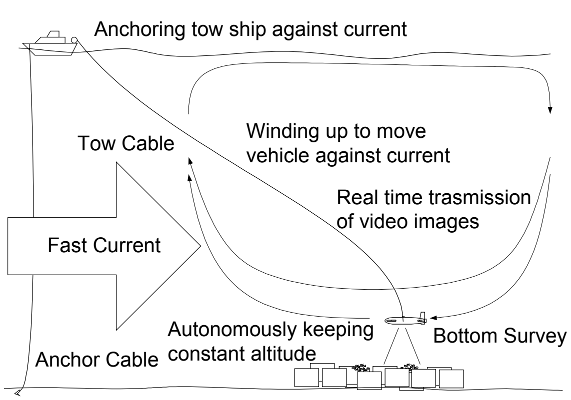

Fig. 3. Kite mode

As a result of above examinations, the system operated by three modes (towed mode, autonomous mode and kite mode) according to the current conditions as shown in Fig. 1-Fig. 3. was proposed as a new underwater observation system.

D. Functions of the system (planned)

1) Dimensions, weight and equipment of towed vehicle

Dimensions of the vehicle are determined within the size which men can easily handle. Weight in the air is limited under the value which can be descended and retrieved with the winch aft of the tow ship. Namely, the vehicle is 300kg or less in weight in the air and about 3m in total length. The towed vehicle has neutrally buoyancy and its weight in the water is adjusted by ballast. The vehicle is equipped with forewings and the tail wings, and the thruster as sailing device.

2) Observation equipments

To take a picture of the image in sea bottom, the underwater TV camera and a lighting device are mounted as observation equipments. To complement the optical image data, a narrow multi-beam sonar which can obtain the acoustic image data is planned to be installed in the future as optional equipment. This sonar is used only in towed mode and kite mode because of the size of the processor and the problem of the transmission of ultrasonic data. The transducer is planned to be installed outside of the main body, and the stability of the towed vehicle was examined in this case too. The view data are recorded by the hard disk built-in the vehicle in autonomous mode. It is recorded both by the VCR on the shipboard and by the hard disk built-in the towed vehicle in towed mode and kite mode.

3) Position measurement

The position of the vehicle is calculated from information of RTK-GPS and SSBL mounted on the tow ship, and the result is transmitted to the vehicle through the acoustic link.

4) Autonomy capability

In autonomous mode, the vehicle autonomously cruises along the given route while keeping a constant altitude or depth and a constant ground speed, taking automatically a picture of image of the fish reeves. The motion in the horizontal plane is controlled by the thrust of the vehicle. The motion in direction of depth is controlled by the forewings and the thrust of the vehicle. In towed mode, the towed vehicle drawn out from the tow ship which sails toward the current, moves autonomously just like in autonomous mode. In this case, the motion in the direction of depth is controlled by the towing velocity the forewings and the thrust. In kite mode, the towed vehicle wound up by the winch on the tow ship anchored toward the current, moves at constant altitude or depth. In this mode, the motion in the direction of depth is controlled by the forewings, the thrust, and the winding up speed of the winch. The ability of the autonomous collision avoidance for fish reeves or other forward obstacles is needed for the vehicle.

5) Range of navigation mode

To accomplish the reliable mission, autonomous mode will be applied when the current is 2knots or less, towed mode for 2-3knots, and kite mode for over 3knots. To enable these choices, the towed vehicle should be controlled at the counter-water speed within the range of 1-4knots.

6) Base machine of the vehicle

A conventional AUV was used as a base machine of our research from the view point of technical and economical rationality. It was planned to remodel a conventional AUV to the towed vehicle based on the result of simulation and towing tank test in our research. After the examination of necessary specifications and a basic configuration, "AQUA EXPLORER 2" (hereafter, AE-2) was selected as the base machine [1, 2].

III. BASIC MOTION SIMULATION

The numerical simulation of the motion of the towed vehicle was executed to confirm its stability and to obtain data necessary for design of the prototype.

A. Analysis technique

The simulation model for our research should be able to represent the influence of the tow cable. Therefore, improved analysis technique and the numerical calculation method which had been developed by the Research Institute for Applied Mechanics, Kyusyu University were used [3, 4]. The object motion is modeled in six degree freedom, and heaving motion can be acted on the upper end of the tow cable in this model. It is able to tow the object along the loci which are combinations of the straight lines and the circular arcs and the current distribution in the direction of depth can be modeled. The Runge Kutta Gill Method was used as a numerical procedure of the vehicle motion. The motion of the tow cable was modeled by Lumped Mass Method, Runge Kutta Gill Method and Predictor Corrector Method were used as a numerical calculation method.

The design data of AE-2 were used partially as the basic data [1, 2]. Because turbulence concerning roll and surge of AUVs is extremely little in general, neither forced roll test nor forced surge test were done in towing tank test of AE-2. However, the external forces by the tow cable are large in case of the towed vehicle. Therefore, the needed data were theoretically presumed in the simulation [1-5].

B. Examinations of static stability

The towed vehicle should be submerged compulsorily because the underwater weight of the vehicle is 0. Therefore, the method to obtain the submerged depth by the downward lift generated by adjusting the angle and area of the forewings was examined. As a result, it was clarified that adjustment of the angle of the forewings to 8deg and the increase of the area of the wing by extending the forewings by 76mm to both sides (right and left) compared with AE-2 were necessary. Fig. 4 shows the static balance of the tow cable (length 100m, towing velocity 1.5m/s). It was confirmed that the towed vehicle was able to submerge up to almost 60m in depth from this figure.

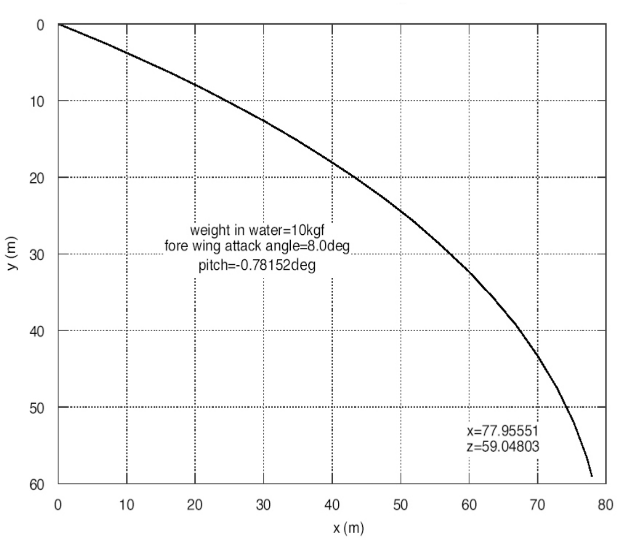

Fig. 4. Static configuration of tow cable

C. Examinations of dynamic stability

The navigation pattern of towed mode is usually composed of straight advancement to the current and the turn for the next straight advancement. Therefore, stability in each navigation pattern was examined.

1) Straight line tow

The value of heave, pitch angle and the cable tension varied greatly when heaving motion of sine wave (period is 6s and amplitude is 1m) was acted to the upper end of the tow cable. From this result, it is clarified that active control of heave and pitch of the towed vehicle is necessary to ensure the stability of this system. Therefore, the method to control heave and pitch by the parallel-motion of forewings (controlling the elevator angle of a right and left forewings in the same direction) was adopted. The following formula was used as a compensator referring to [4].

$$\delta = k_1(z_0 - z) + k_2\dot{z} + k_3\theta + k_4\dot{\theta} \quad (1)$$

Where:

δ : Elevator angle of the forewing

(The same direction as the pitch angle θ is +.).

$k_1 \cdots k_4$: Control gains.

z_0 : Dsired depth.

z : Present depth of the vehicle.

$\dot{z}$: Vertical velocity of the vehicle.

θ : Pitch angle of the vehicle.

$\dot{\theta}$: Pitch angular velocity of the vehicle.

2) Turn tow

Next, stability while turning was examined. The loci of the towed vehicle and the tow ship while turning by 50m in radius are shown in Fig. 5 and the behavior of the towed vehicle is shown in Fig. 6. In Fig. 5, -x- shows the locus of tow ship and -.- shows the locus of the towed vehicle. Each graph shows the sine wave acted on the tow cable, heave, pitch angle, roll angle of the towed vehicle, elevator angle of the forewings (parallel-motion) and the cable tension respectively from the top of Fig. 6. It can be seen that the towed vehicle becomes unstable by 150-200s from Fig. 6. It may be the reason that the value of roll which acts on the towed vehicle while turning exceeds the range of righting lever.

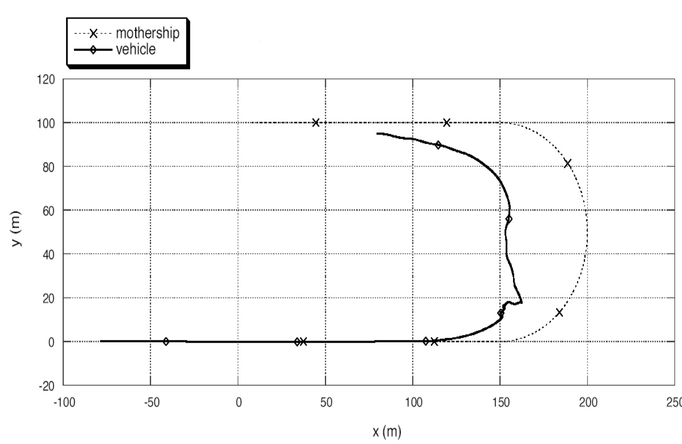

Fig. 5. Loci of towed vehicle and tow ship (Radius of turn=50m)

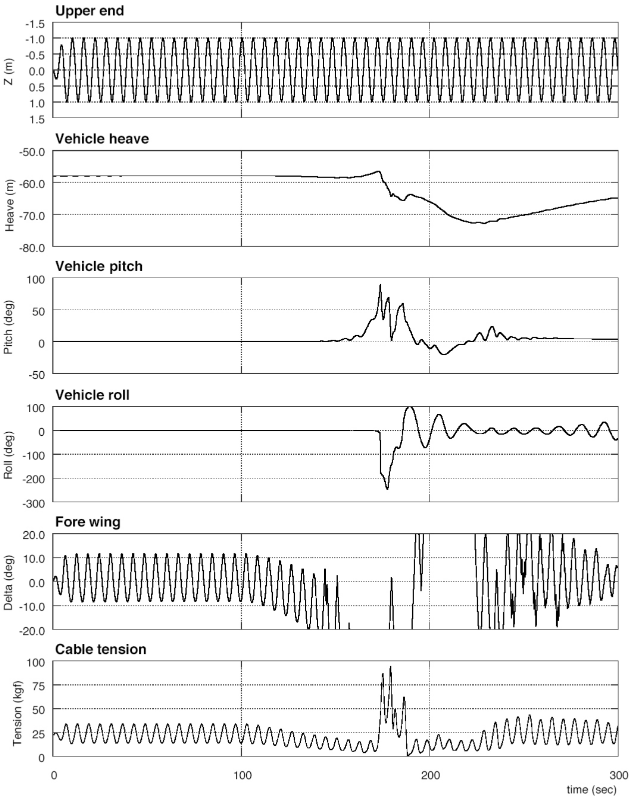

Fig. 6. Motion of towed vehicle (Radius of turn=50m)

It was examined to control roll by the differential-motion of the forewings (controlling the elevator angle of right and left forewings in the opposite directions) to stabilize the towed vehicle while turning. The next formula was made as a compensator referring to [4].

$$\beta = AS\dot{\phi} \quad (2)$$

where:

β : Differential angle of the each elevators (It's a right wing angle to the left. And the same direction to δ is $+$.).

AS : Control gain.

$\dot{\phi}$: Roll angular velocity.

The simulations of radii of turns of 70 to 100m showed that roll control was effective. As a typical example, the loci of tow ship and the towed vehicle while turning by 70m in radius with the narrow multi-beam sonar are shown in Fig. 7. The locus is stable and the towed vehicle follows the tow ship. The behavior of the towed vehicle is shown in Fig. 8 too. Each graph shows the sine wave acted on the upper end of the tow cable, heave, pitch angle, roll angle of the towed vehicle, elevator angle of the forewings (parallel-motion), elevator angle of the forewings (differential-motion) and the cable tension respectively from the top of Fig. 8. The control gain was supposed to be k_1=-10, k_2=20, k_3=-10, k_4=-20 and AS=10. As a result, although roll angle reached 20deg in the maximum, it was proved that the towed vehicle was stable.

When the behavior of the towed vehicle becomes unstable while turning, its advanced speed decreases and it descends by the loosening of the tow cable. At this time, the control of the towed vehicle with the forewings seems to become impossible. Accordingly, it is necessary to keep always the advanced speed of the towed vehicle by the method such as winding up the tow cable while turning.

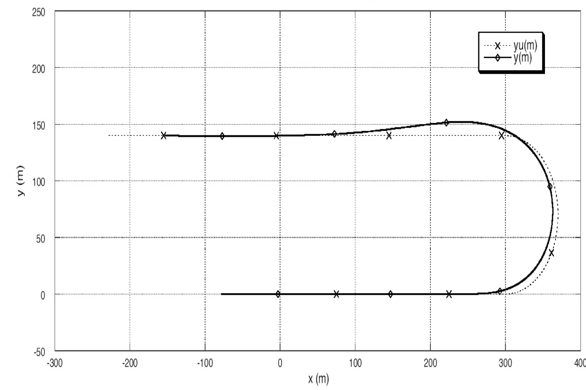

Fig. 7. Loci of towed vehicle and tow ship (Radius of turn=70m)

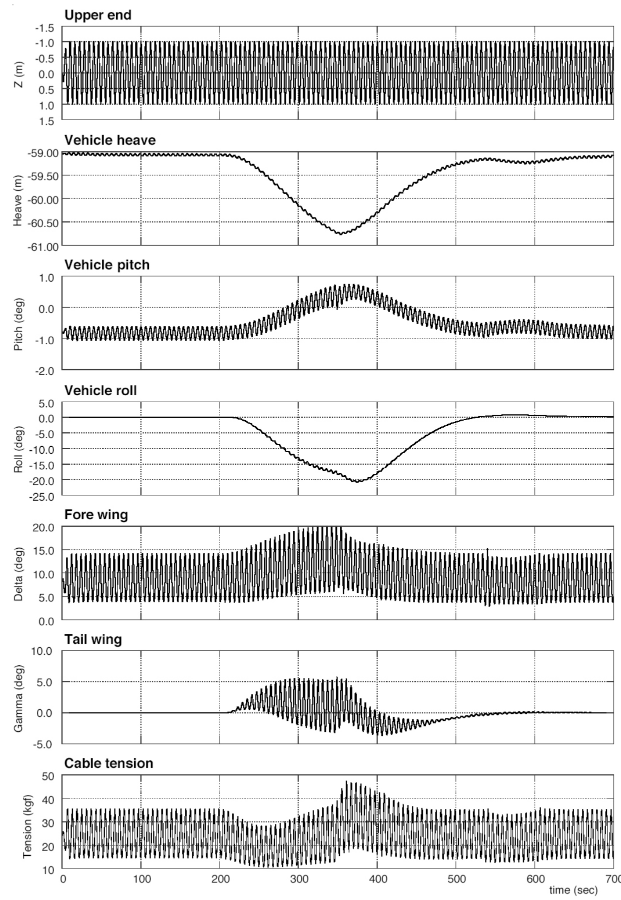

Fig. 8. Motion of towed vehicle (Radius of turn=70m)

IV. TOWING TANK TEST

To obtain necessary hydrodynamic coefficients for the development of the autonomous control software, the test model was manufactured and the resistance test, the oblique motion test, the elevator angle test, and the forced oscillation test were carried out.

A. Configuration of test model

The test model was manufactured based on the simulation outputs. It is made of artificial wood and 1/2 of the prototype. It is composed of the main body, wings and additional parts. The wings are connected to the main body. The moving part of the forewings has the mechanism by which the right and left elevator angle can be changed independently with gears. And the waterproof three component loadcell for the hydrodynamic force measurement is installed in the test model. The model of narrow multi-beam sonar is removable. The test model is shown in Fig. 9.

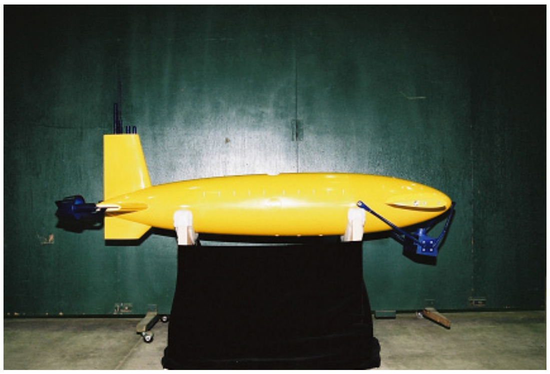

Fig. 9. Test model (equipped with the sonar model)

B. Details of test

The following four kinds of tests were performed. All tests were executed under two conditions, with and without the sonar. The coordinate system used for the test is shown in Fig. 10.

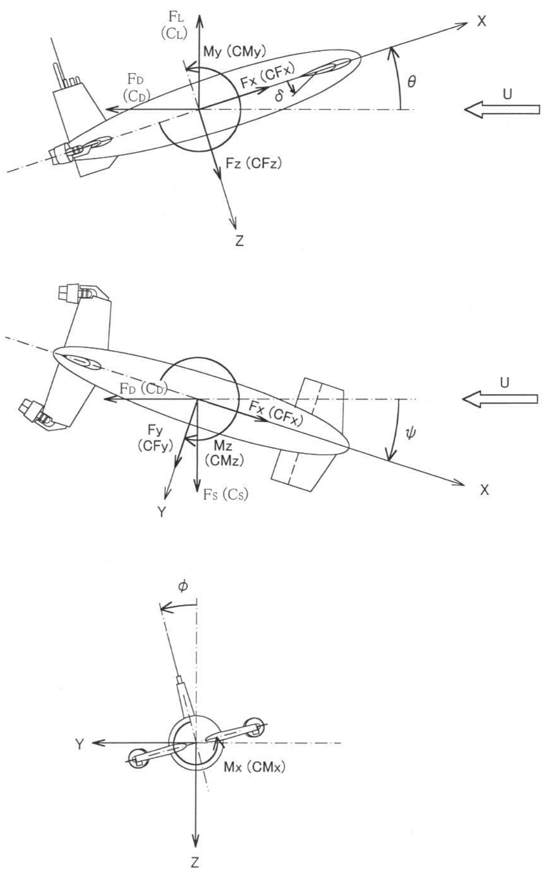

Fig. 10. The coordinate system

1) Resistance test

When the towing velocity *U* is varying (*U*=0.5-3.0m/s) under the condition that pitch angle of the vehicle θ and the elevator angle of the forewings δ are constant (θ=0deg, δ=0deg), the resistance of the vehicle is measured.

2) Oblique motion test (in direction of pith and yaw)

When pitch angle and yaw angle ψ are varying (θ=-30 to +30deg, ψ=0-30deg) under the condition that the towing velocity and the elevator angle are constant (*U*=1.0m/s, δ=0deg), the hydrodynamic force of the vehicle is measured.

3) Elevator angle test

When the elevator angle is varying under the condition that the towing velocity and pitch angle are constant (*U*=1.5m/s, θ=0deg), the hydrodynamic force of the vehicle is measured. The test range of the elevator angle is -30 to +30deg for the parallel-motion test and -10 to -30deg for the differential-motion test.

4) Forced oscillation test

The force oscillation test of heave, pitch, sway and roll are carried out to determine the hydrodynamic force derivative.

C. Analysis technique

1) Resistance test etc.

The output of resistance test was made dimensionless by the formula as follows. And the other results were made dimensionless by the similar technique.

$$C_D = F_X \Big/ \left(1/2 \cdot \rho \cdot U^2 \cdot L \cdot d\right) \tag{3}$$

where:

C_D : Drag coefficient.

F_X : Total drag foce.

ρ : Density of water.

U : Towing velocity.

L : Hull length(1.500m).

d : Hull height(0.2625m).

Because wave making resistance is not included in total resistance, it is possible to replace it by the viscous drag. Then, the coefficient of viscous drag is expressed by the coefficient of skin friction and form factor by the following formula.

$$C_V = (1+K)\cdot C_F \tag{4}$$

where:

C_V : Coefficient of viscos drag.

C_F : Coefficient of skin friction.

K : Form factor.

The coefficient of skin friction is obtained from the next formula by which the approximation of International Towing Tank Conference (ITTC) is matched to the method to make data dimensionless in this paper.

$$C_F = 0.075 \Big/ \left\{\log_{10}(Re) - 2\right\}^2 \cdot \left(S/L \cdot d\right) \tag{5}$$

where:

Re : Reynolds number($Re = U \cdot L/\nu$).

S : Flooded surface area

(without sonar;1.4548m^2, with sonar;1.5436m^2).

ν : Coefficient of kinematic viscosity of water.

2) Forced oscillation test

Various hydrodynamic force derivatives were determined from the average of sine and cosine component in two periods obtained by Fourier Analysis.

D. Test results

1) Resistance test

The form factor calculated from the value of the drag coefficient when the towing velocity is 1-3m/s is shown in Table 1. The form factor when in the case with the sonar reaches a quite big value (about 3.3 times) compared with the case without the sonar. It is realized that the pressure resistance was the most part of total drag in the case with the sonar.

TABLE 1
RESULT OF RESISTANCE TEST

Sonar	Form factor	Coefficient of viscous drag
Without	1.85	$C_V=(1+1.85) \times C_F$
With	6.11	$C_V=(1+6.11) \times C_F$

2) Oblique motion test

The drag coefficient was approximated by the quadratic equation and the lift coefficient C_L, the lateral force coefficient C_S and the moment coefficient C_{Mx}, C_{Mz} were approximated linear by the least square method based on the test results. The results are shown in Table 2 and 3.

TABLE 2
RESULT OF OBLIQUE MOTION TEST IN DIRECTION OF PITCH

	Without sonar	With sonar
C_D	$1.433\theta^2-0.0103\theta+0.0387$	$1.482\theta^2-0.1256\theta+0.0987$
C_L	1.386θ	1.465θ
C_{My}	0.165θ	$0.204\theta-0.0156$

TABLE 3
RESULT OF OBLIQUE MOTION TEST IN DIRECTION OF YAW

	Without sonar	With sonar
C_D	$0.504\psi^2+0.0219\psi+0.0376$	$0.599\psi^2-0.0025\psi+0.1048$
C_S	0.465ψ	0.520ψ
C_{Mz}	-0.0098ψ	-0.0222ψ

3) Elevator angle test

The drag coefficient and the moment coefficient C_{Mx} were approximated by the quadratic equation based on the test results. On the other hand, the lift coefficient and the moment coefficient C_{My} were approximated by the cubic equation because the vehicle stalled when the elevator angle increased. Results are shown in Table 4 and 5.

TABLE 4
RESULT OF ELEVATOR ANGLE TEST (PARALLEL-MOTION)

	Without sonar	With sonar
C_D	$0.108\delta^2- 0.0045\delta+0.041$	$0.110\delta^2- 0.0096\delta+0.106$
C_L	$-0.436\delta^3-0.0209\delta^2+0.373\delta+0.00005$	$-0.407\delta^3-0.0099\delta^2+0.358\delta+0.0043$
C_{My}	$-0.218\delta^3+0.0005\delta^2+0.201\delta-0.0092$	$-0.285\delta^3+0.026\delta^2+0.211\delta-0.0228$

TABLE 5
RESULT OF ELEVATOR ANGLE TEST (DIFFERENCIAL-MOTION)

	Without sonar	With sonar
C_D	$0.0826\delta^2+0.0122\delta+0.0405$	$0.0729\delta^2+0.0223\delta+0.105$
C_{Mx}	$0.0115\delta^2-0.017\delta$	$0.0104\delta^2-0.0134\delta$

4) Forced oscillation test

The influence of the sonar was hardly seen in the main element of the hydrodynamic force derivatives in vertical, horizontal, and roll direction. However, the absolute value of the damping force of roll while moving is considerably large compared with that during stoppage.

V. CONCLUSION

We proposed the “Autonomous Towed Vehicle” system as a method of safe and efficient underwater observation in the fast water current. The fundamental structure of this system was determined and the stability of the system was confirmed by the numerical simulation. Necessary conditions to achieve the stable navigation are as follows.

1) The added weight of about 10kg is necessary compared with the base machine.

2) It is necessary to extend the length of the forewings about 10cm longer than the base machine to increase the area of the wings.
3) The initial value of the elevator angle of the forewings should be 8deg.
4) It is necessary to control heave and pitch by the parallel-motion of the forewings and to control roll by the differential-motion of the forewings.

In addition, the hydrodynamic characteristics of the vehicle were realized by the towing tank test. The kinematic performance of the vehicle will be confirmed by the final simulation based on these data in the next step. We plan to develop the prototype in 2003, and to experiment in the real sea in 2004.

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