Proceedings of the 2001 IEEE
International Conference on Robotics & Automation
Seoul, Korea · May 21-26, 2001

Maneuverability of A Flat-Streamlined Underwater Vehicle

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Abstract - Maneuverability describes a vehicle's ability to change course or turn. Maneuverability of conventional underwater vehicles, such as torpedoes, can be determined by altering the position and length of control fins. To perform large-area surveying tasks, autonomous underwater vehicles (AUVs) generally require different maneuverability characteristics in their vertical and horizontal planes of motion. Furthermore, AUVs are significantly slower than torpedoes, and control fins are relatively ineffective at slow speeds. While relying solely on control fins to determine the maneuverability, this study investigates the maneuverability characteristics of a flat-streamlined underwater vehicle. A Planar Motion Mechanism (PMM) testing system is adopted to conduct a series of captive model tests in order to measure the stability derivatives of the vehicle, AUV-HM1. Stability and maneuvering indices are then derived from the measured data of stability derivatives. Finally, maneuvering criteria of a flat, baseline vehicle are evaluated using a prediction method.
Keywords: AUVs, Maneuverability, Stability

I. Introduction

Several "flat-fish" type autonomous underwater vehicles (AUVs) have been developed recently. The mission designation of PTEROA, the vehicle developed by the group at the University of Tokyo (Ura, 1989) is two fold: high gliding performance, and the ability to maintain a steady altitude while cruising over the sea bed. The vehicle AQUA EXPLORER developed at the KDD has been designed to track submarine telecommunication cables. (Asakawa et al., 1993). Furthermore, MARIUS was developed for environmental surveying and the acquisition of oceanographic data in coastal waters (Pascoal et al., 1997). Meanwhile, an AUV named VORAM is being developed at KRISO for observing and investigating the sea bed (Lee et al. , 1998). This work investigates the maneuverability of a flat, streamlined AUV, AUV-Hai-Min (Guo et al., 1995). The designated mission of the AUV-HM1 includes area searches and surveys in shallow water. A typical search/survey scenario requires good responsiveness to control in the horizontal plane of motion, and good ability to maintain altitude in the vertical plane. This study aims to further reveal the maneuverability and stability of vehicles with flat cross-sections, using experimental and theoretical methods.

Maneuverability measures the effectiveness of control inputs that are directly related to hull form and fin size. Maneuverability must be analyzed during the preliminary design stage. This work performed straight-line captive-model experiments in the vertical and horizontal planes of motion to find the stability and control characteristics of the autonomous underwater vehicle, AUV-HM1. The experiments were performed for the following configurations, excluding propellers: (1) the hull plus control surfaces in the vertical plane of motion, (2) the hull plus control surfaces in the horizontal plane. The experiments were performed in a model basin on a towing carriage (130m x 8m x 4m) using a Vertical Planar Motion Mechanism (VPMM). Captive model tests included angle of attack and elevator angle tests in the oblique-towing mode; and pure heave, pure pitch, and combined pitch/heave tests in the forced motion mode. The hydrodynamic force and moment measurements were non-dimensionalized using the total length of the vehicle body. Stability derivatives are referred to axes which originate at a point 1.0 meter aft of the nose on the hull centerline. The maneuvering behavior of the vehicle in its vertical and horizontal configurations is then determined using stability indices derived from the experimental data.

II. Testing Model

The testing model has the same dimensions as the AUV-HM1, as listed in Table 1. Meanwhile, Figure 1 illustrates the horizontal and longitudinal center planes, with all cross sections being elliptical. Following Landweber et al. (1950), the longitudinal center plane is a sixth-degree polynomial form. Figure 2 presents configurations of the elevators and fixed vertical fins. The fin profiles selected are NACA0012, and the model is supported by a pair a vertical struts. The force gauge located beneath the struts was used to measure the longitudinal, normal, lateral forces, and rolling moment with respect to the body axes, and the pitching moment around the reference point was determined from the

Table 1 Principal particulars of the testing model

Length (body/overall)	2.0/2.0 m
Breadth (body/including elevators)	1.0/1.6 m
Height	0.6/0.6 m
Project area of body	1.791 m^2
Wetted surface area of body	4.38 m^2
Displaced volume of body	0.677 m^3
Centroid of body	0.909m from nose
Project area of horizontal fins	0.091 m^2
Project area of vertical fins	0.148 m^2

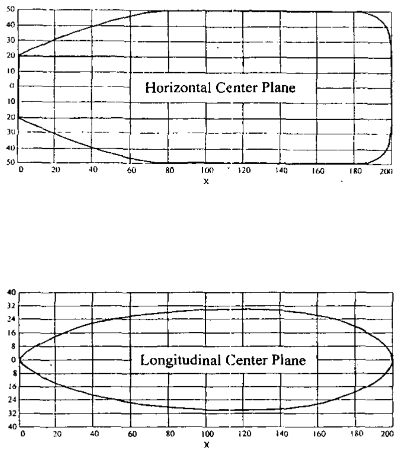

Fig. 1 Profile of the body

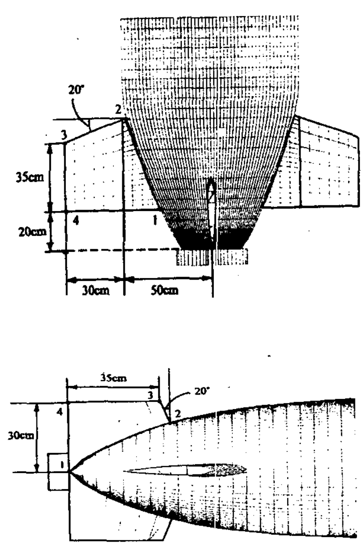

Fig. 2 Profile of fins and elevators

difference in the measured reaction forces at each strut multiplied by half of the distance between the struts. The distance between the struts is 1.0 m, the center of rotation is 0.778 m from the nose, and the model is submerged at a depth of 2.0 m.

III. EQUATIONS OF MOTION

1. Coordinate System

1.1 Configuration A

A set of body-fixed coordinate axes is used to describe the motion of the AUV-HM1. Figure 3 displays the positive direction of the axes and angles, while α denotes the angle of attack in the vertical plane. Furthermore, δ_e represents the angular deflection of the vertical fins. The z-axis is defined as being positive in the downwards direction, and the longitudinal and transverse horizontal axes of the AUV are represented by the x- and y-axes, respectively. For hydrodynamical analysis, the origin of the coordinate axes is located at the center of rotation of the test mechanism. For maneuvering analysis, stability derivatives are calculated with respect to the axes which originate from a point 1.0 m aft of the nose on the hull centerline using coordinate transformation.

1.2 Configuration B

To measure the horizontal plane of motion, the model is heeled starboard side down by 90 degrees. The coordinate axes defined in this configuration are illustrated in Fig. 4.

2. Linearized Maneuvering Equations of Motion

By reference to the body axes, the linearized equations of motion can be expressed as

$$
\begin{aligned}
&(m+m'_z)\dot{w}' - Z'_w w' - (m'x'_G + m'_z x'_z)\dot{q}' \\
&\qquad - \{Z'_q + (m' + m'_x)\}q' = Z'_\delta \delta \\
&(I'_{yy} + J'_{yy})\dot{q}' - \{M'_q - (m'x'_G + m'_z x'_z)\}q' \\
&\qquad - (m'x'_G + m'_z x'_z)\dot{w}' - M'_w w' = M'_\delta \delta
\end{aligned} \tag{1}
$$

where the control mechanisms are $Z_\delta = Z'_{\delta e}$, $M_\delta = M'_{\delta e}$, and $\delta = \delta_e$ for configuration A; and $Z_\delta = 0$, $M'_\delta = \frac{\ell'}{2}$, and $\delta = \Delta T$ for configuration B. The non-dimensional coefficients are defined as

$m' = m/0.5\rho L^3, m'_x = m_x/0.5\rho L^3, m'_z = m_z/0.5\rho L^3,$

$x'_G = x_G/L, x'_z = x_z/L, I'_{yy} = Iyy/0.5\rho L^5,$

$J'_{yy} = J_{yy}/0.5\rho L^5, Z'_w = Z_w/0.5\rho L^2 U,$

$M'_w = M_w/0.5\rho L^3 U, \dot{Z}'_q = Z_q/0.5\rho L^3 U,$

$M'_q = M_q/0.5\rho L^4 U, Z'_{\delta e} = Z_{\delta e}/0.5\rho L^2 U^2,$

$M'_{\delta e} = M_{\delta e}/0.5\rho L^3 U^2, \Delta T' = \Delta T/0.5\rho L^2 U^2, \ell' = \ell/L$

,and $\rho = 101.82 kg_f \sec^2 / m^4$ for 20℃ fresh water.

where m denotes the mass of the model with its enclosed water; x_G represents the x coordinate of the center of gravity; m_x is the added mass in x-axis; m_z is the added mass in the z-axis; x_z denotes the x coordinate of the center of gravity in the z-axis; I_{yy} represents the pitching moment of inertia including enclosed water; J_{yy} is the added moment of inertia in the pitch; Z_w, Z_q and M_w, M_q are derivatives of the normal force and moment components with respect to the linear velocity in z-direction w and angular velocity in y-direction q respectively; $Z_{\delta e}$ and $M_{\delta e}$ are the force and moment rate caused by control surface displacement δ_e; ΔT is the thrust force difference; ℓ is the distance between thrusters; and U is the forward speed.

IV. MODEL EXPERIMENTS

1. Test Apparatus and Test Conditions

The apparatus for measuring hydrodynamic force and moment is capable of performing ± 150mm in heaving amplitude, ± 15deg in pitching, 0.2 ~ 1.5Hz in oscillation frequency. The capacity of the force gauge is ± 300kgf. Test conditions are as follows:

a. forward speed : 1.414, 2.000, 2.828 (m/sec)

b. oscillation frequency:0.3,0.4,0.5 (Hz)

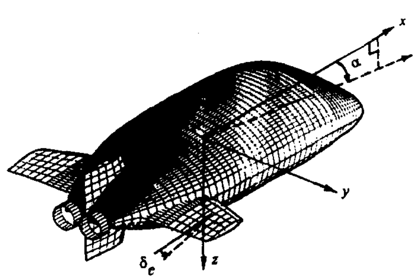

Fig. 3 Configuration A

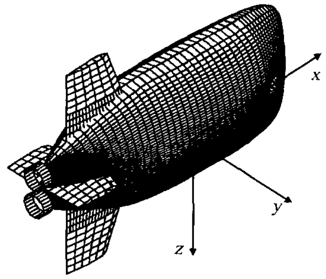

Fig. 4 Configuration B

pure heaving amplitude : 20, 40, 60(mm)

pure pitching amplitude : 2.0, 4.0, 6.0 (deg.)

combine pitching amplitude : 2.0, 4.0, 6.0 (deg.)

c. angle of attack for oblique towing tests : -6.0 ~ +14.0 (deg.)

2. Data Presentation

Non-dimensional data are presented in tabular form herein. Table 2 summarizes the results of oblique towing tests and PMM tests using the model in configuration A. The accuracy of experiments is discussed by Chiu et al. (1996, 1997). These derivatives are referred to axes which originate at the center of rotation of the test apparatus. Table 3 lists data obtained using the model in configuration B, while Table 4 presents the stability derivatives referred to the origin for maneuvering analysis.

Table 2 Results of oblique towing tests and PMM tests in configuration A

(a) Results of oblique towing tests

U(m/sec)	Z'_w	M'_w
1.414	-0.664	0.00521
2.000	-0.673	-0.00338
2.828	-0.655	-0.00197

(b)Added inertia obtained by PMM tests

m'_x	m'_z	x'_z	J'_{yy}
0.023	0.077	-0.107	0.0044

(c)Damping terms obtained by PMM tests

Z'_w	M'_w	Z'_q	M'_q
-0.0874	0.0194	-0.0424	-0.0260

(d) Results of elevator force tests

	$Z'_{\delta e}$			$M'_{\delta e}$		
α(deg) / $U(m/s)$	0	3	6	0	3	6
1.414	-0.169	-0.167	-0.184	-0.0524	-0.0497	-0.0552
2.000	-0.176	-0.159	-0.178	-0.0531	-0.0478	-0.0575
2.828	-0.182	-0.165	-0.188	-0.0529	-0.0515	-0.0584

Table 3 Results of oblique towing tests and PMM tests in configuration B

(a) Results of oblique towing tests

U(m/sec)	Z'_w	M'_w
1.414	-0.0998	0.0162
2.000	-0.0981	0.0242
2.828	-0.0902	0.0288
Average	-0.096	0.023

(b)Added inertia obtained by PMM tests

m'_x	m'_z	x'_z	J'_{yy}
0.023	0.077	-0.107	0.0044

(c)Damping terms obtained by PMM tests

Z'_w	M'_w	Z'_q	M'_q
-0.0874	0.0194	-0.0424	-0.0260

Table 4 Non-dimensionalized stability derivatives Obtained by coordinate transformation

.	Configuration A	Configuration B
m'_x	0.023	0.023
m'_z	0.239	0.077
x'_z	-0.022	0.004
J'_{yy}	0.0117	0.00352
Z'_w	-0.673(O.T.)	-0.0960(O.T.)
M'_w	0.0712(O.T.)	0.0337(O.T.)
Z'_q	-0.156	-0.0317
M'_q	-0.078	-0.0250
Z_{δ_e}	-0.176	----
M_{δ_e}	-0.0336	----
*Origin is located at 1.000m from nose **O.T. represents results from oblique towing tests		

Table 5 Non-dimensionlized stability and turning indices calculated from stability derivatives

Stability Indices	Configuration A	Configuration B
T_1	0.693	0.413
T_2	0.289	-2.987
T_3	-0.415	-2.552
T	1.397	-0.021
l_q	2.083	0.159
l_w	0.106	0.351
G	0.949	-1.21
K	-0.754	-3.27
*Origin is located at 1.000m from nose $m = 0.168$; $x_G = 0$; $I_{yy} = 0.0113$		

V. MANEUVERING CRITERIA

Equation (1) can be written as a decoupled second order equation, as follows:

$$T_1' T_2' \ddot{q}' + (T_1' + T_2')\dot{q}' + q' = K'\delta' + K' T_3' \dot{\delta}' \quad (2)$$

where

$$T_1' T_2' = \frac{(m' + m_z')(I'_{yy} + J'_{yy}) - (m'x_G' + m_z'x_z')^2}{[M_q' - (m'x_G' + m_z'x_z')]Z'_w - M'_w[Z_q' + (m' + m_x')]}$$

$$T_1' + T_2' = \frac{-(m' + m_z')[M_q' - (m'x_G' + m_z'x_z')] - (I'_{yy} + J'_{yy})Z'_w - (m'x_G' + m_z'x_z')[Z_q' + (m' + m_x')] - M'_w(m'x_G' + m_z'x_z')}{[M_q' - (m'x_G' + m_z'x_z')]Z'_w - M'_w[Z_q' + (m' + m_x')]}$$

$$K' = \frac{M_w' Z_{\delta e}' - M_{\delta e}' Z_w'}{[M_q' - (m'x_G' + m_z'x_z')]Z_w' - M_w'[Z_q' + (m' + m_x')]}$$

$$T_3' = \frac{(m'x_G' + m_z'x_z')Z'_{\delta e} - M'_{\delta e}(m' + m_z')}{M'_w Z'_{\delta e} - M'_{\delta e} Z'_w}$$

T_1', T_2' are roots of the characteristic equation of Eq. (2), and are generally referred to as stability indices. Meanwhile, K' is the index of turning ability. For maneuvering at low frequencies, Eq.(2) can be approximated by a first order equation, with time constant $T' \equiv T_1' + T_2' - T_3'$,

$$T'\dot{q}' + q' = K'\delta' \quad (3)$$

Responsiveness to control inputs is an appropriate definition of maneuverability. Consequently, the maneuverability index is taken to be the extent of heading angle turned from an initial straight course, per unit control input applied, after the vehicle has traveled one body length. For situations in which the controls are fixed, the maneuverability index P (Nomoto and Norrbin, 1965) is defined as follows

$$P = \frac{\theta}{\delta} = K\left[1 - T + T e^{-1/T}\right] \approx \frac{1}{2}\frac{K}{T} \quad (4)$$

where θ denotes the pitching response of the vehicle after moving one body length. The P value in configuration A is -0.27, implying approximately 2.7 degrees of heading change within one body length, when the elevator angle is over 10 degrees. For configuration B, the P value is 0.7, implying that given a thrust difference of 10kgf, the vehicle experiences a heading change of 0.25 degrees within a single body length.

The measure of dynamic stability can be defined as

$$G \equiv 1 - \frac{l'_w}{l'_q} \tag{5}$$

where

$$l'_q = \frac{-M'_q + (m'x'_G + m'_z x'_z)}{Z'_q + (m' + m'_x)}$$

$$l'_w = \frac{M'_w}{-Z'_w}$$

The system is unstable if G is negative, statically stable if G exceeds 1m and dynamically stable if G is between 0 and 1. Table 5 lists stability and turning indices of the AUV-HM1 in both configurations. Notably, configuration A is dynamically more stable.

VI. Prediction Of Stability And Maneuverability

Methods of predicting hydrodynamic force coefficients for slender bodies such as airplanes and torpedoes are well established, while similar methods for flat-streamlined underwater vehicles, such as the AUV-HM1, are neglected. Maeda et al. (1989) presented a method suitable for undersea vehicles and based on DATCOM (Hoak et al.,1978), a public-domain empirical method determining aircraft stability properties. Meanwhile, for estimating the stability derivatives of AUV-HM1, Chiu et al. (1996, 1997) have examined the validity of using empirical formula proposed for standard torpedoes by Botaccini. The efficacy of estimations that use a modified Botaccini method is confirmed by comparing the measured and estimated coefficients. Equivalent ellipsoids were applied herein to approximate the shape of the vehicle and its control fins. A theoretical method based on potential flow theory was used for estimating inertia terms, while the Botaccini method was used to predict the damping coefficients of the vehicle. The maneuverability and dynamic stability index is calculated herein using various body lengths, while maintaining the water displacement volume of the vehicle constant. Figure 5 displays the profile of the baseline vehicle used for the prediction, while Figs. 6 and 7 illustrate the variations of maneuverability and stability with increasing body length. Simulation results indicate that the flat body significantly influences maneuverability and dynamic stability. With an increasing body length, the cross-section becomes increasingly symmetrical, causing vehicle behavior to become increasingly similar in the lateral and horizontal modes.

VII. Conclusion

The AUV-HM1 is designed for area search and survey missions in shallow water. Search/survey scenarios generally require sufficient responsiveness to control in the horizontal plane of motion, with high stability for performing depth control in the vertical plane. The maneuverability of the AUV-HM1 is characterized using indexes G, P, representing stability, and responsiveness to control, respectively. Configuration A of the vehicle is found to be more stable. However, configuration B of the vehicle is found to have a superior turning performance. Maneuvering behavior in configuration A corresponds to the vertical plane of motion of the AUV-HM1, while that of configuration B corresponds to the horizontal plane. We conclude that this flat-streamlined design of the hull form is compatible with the operational requirements of the AUV-HM1. Performance of a flat, baseline vehicle was also predicted, and the G and P values of the baseline configuration are illustrated using different body lengths while maintaining the displacement volume of the vehicle constant. Flattening the body of the vehicle is found to reduce stability in the horizontal plane while increasing stability in the vertical plane. The flat body is more responsive in relation to axis-symmetric body in both the horizontal and vertical planes.

Acknowledgments

The authors would like to thank the National Science Council of R.O.C., for financially supporting this research under Contract number NSC84-2611-E-002-026 and NSC85-2611-E-002-012. Yi-Yuan Chang, Chieh-Chih Wang, Chien-Chen Huang, Chun-Chin Wei, Jen-Chao Chung , and Wei-Chen Tsai are appreciated for their assistance in the PMM experiments.

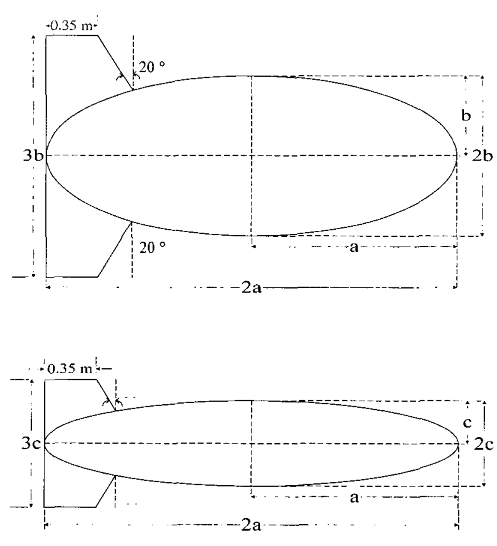

Fig. 5 Baseline arrangement of the body and fins used in the predictions herein. The upper plot corresponds to configuration A, and the lower plot corresponds to configuration B.

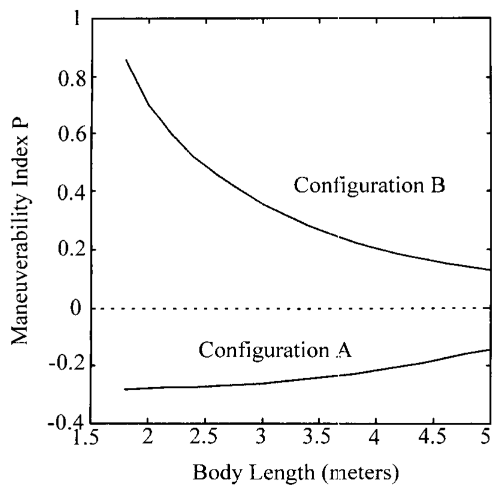

Fig. 6 Maneuverability with different body lengths

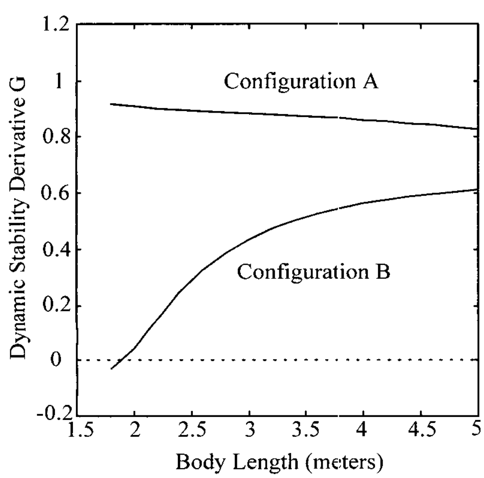

Fig. 7 Dynamic stability with different body lengths

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