Hydrodynamic Forces and Moment Acting on a Submersible Surface Ship in Vertical Motion

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***Abstract*-The submersible surface ship (SSS) is a ship that can avoid rough seas by going underwater. In order to submerge the SSS uses wings producing downward lift. The SSS, in submerged condition, keeps residual buoyancy for its safety. A prototype of SSS of which configuration is a hull, a pair of main wings and a pair of horizontal tail wings is designed and its model ship for tank tests is made. The circular motion test was carried out and hydrodynamic forces and moment in vertical motion were measured. The effect of submerged depth on the resistance and wings performances, and the effect of attack angle and pitch rate on the longitudinal and vertical forces and pitch moment acting on the SSS model are clarified. A method to estimate linear hydrodynamic derivatives is applied to the SSS model and compared with the results of tank test data analysis. The validity of the method and test data together with its effective utilization is discussed.**

I. Introduction

Rough seas often cause the cargo damages, seasickness of passengers and arrival time delay for conventional ships. In order to avoid these negative effects a new concept ship, a submersible surface ship (SSS), has been proposed by Hirayama et al. [1]. A SSS can avoid rough seas by submerging and cruising underwater. The proposed SSS consists of a hull, a pair of main wings and a pair of tail wings. In calm and moderate seas the SSS goes on surface. But in rough seas the SSS goes underwater using its main and tail wings. In submerged condition the SSS keeps residual buoyancy for the safety.

The feasibility of SSS was studied using a SSS model which was converted from a conventional container ship model at the Yokohama National University (YNU model). Hirayama et al. [1] carried out a trial tank test using a self-propelled SSS model and studied the wings area necessary to submerge and its vertical motion control. Hirayama et al. [2] studied the relation between the submerged depth, downward lift and resistance acting on the SSS having modified bow shape. Koyama et al. [3] calculated a submerging motion of the self-propelled SSS model in waves and discussed its vertical stability. Hirakawa et al. [4] studied the vertical motion control of the self-propelled SSS model in the submerging and emerging motion by a tank test and simulation calculations. Ueno [5] studied the equation of six-degree-of-freedom motion of a SSS and proposed a procedure to estimate linear hydrodynamic derivatives of a SSS.

In this paper a prototype of SSS is proposed. The prototype consists of a hull, a pair of main wings and a pair of tail wings and a bridge deck or a sail. The shapes of cross sections and profiles of its hull are expressed by mathematical formulae. A model of the prototype SSS is made for calcifying the hydrodynamic characteristics in vertical motion by tank tests. The tank tests were carried out at the Ocean Engineering Basin of the National Maritime Research Institute. Using the circular motion test facility [6] the vertical motion relative to the SSS model was realized. Tank test parameters are longitudinal velocity, vertical velocity or attack angle, pitch or vertical turning rate, submerged depth, main wing angle and tail wing angle. The effect of submerged depth on the resistance and wings performance, the effect of attack angel and pitch rate on the vertical force and pitch moment together with the resistance are clarified experimentally.

The tank test data were analyzed and the linear hydrodynamic derivatives with respect to the vertical motion are obtained. These hydrodynamic derivatives are also estimated using the method proposed by one of the authors [5] and compared with the experimental results. Discussions are provided about the hydrodynamic characteristics of the SSS in vertical motion and the validity of the estimation method.

II. SSS Model and Tank Tests

A. *SSS configuration*

The coordinate system is shown in Fig. 1. The origin is located at the cross point of the center plane, midship section and water plane when the SSS is on the surface. The coordinates x, y and z point forward, starboard and downward respectively. Translational and rotational velocity components are represented by u, v, w and p, q, r. Forces and moments are represented by X, Y, Z and K, M and N. Definitions and polarity of control surfaces are also shown in Fig. 1. The main wings work both as the elevator and as the aileron of which angles are δ_{ew} and δ_a respectively. The tail wings work as the elevator of which angle is δ_{et}. The rudder angle is δ_r.

The body plan of the prototype SSS is shown in Fig. 2. The underwater part of the prototype SSS is similar to that of the parent container ship of the YNU model [1]. Slight modifications are made to express cross sectional shapes and profiles by mathematical formulae. Most of the cross sections

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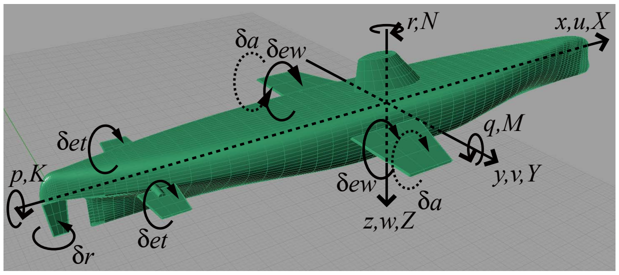

Figure 1. Coordinate system. The origin is at the cross point of the center plane, midship section and water plane when the SSS is on the surface.

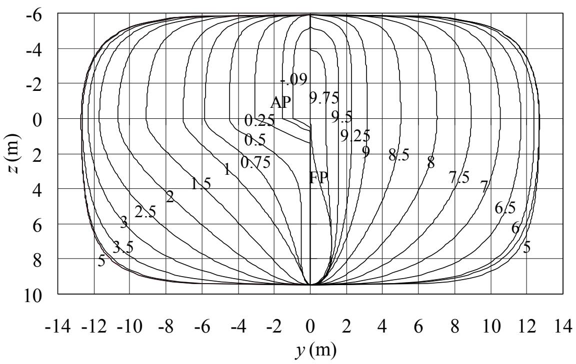

Figure 2. Body plan of hull of the prototype SSS. Square stations are numbered. *z*=0 represents the water plane when the SSS is on the surface.

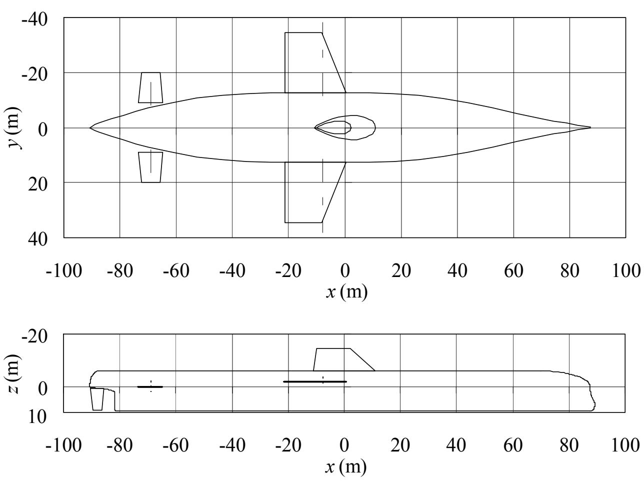

Figure 3. Horizontal (top) and vertical (bottom) plans of the prototype SSS. In the horizontal plan, hull line represents the waterline when the SSS is on the surface. The chain lines represent the rotation axes of wings in the horizontal plan.

TABLE I
DIMENSIONS OF THE PROTOTYPE SSS

Item	Unit	Ship	Model	Note
[Hull]				
L_{oa}	m	179.950	0.8226	Length overall
L_{pp}	m	175.000	0.8000	Length between perpendiculars
B	m	25.400	0.1161	Breadth
D	m	15.400	0.0704	Depth
>On the surface (9.5m Waterline)				
d_s	m	9.500	0.0434	Draft
d_{As}	m	5.900	0.0270	Air draft
Vol_s	m^3	23895.0	0.0022828	Displaced volume
x_{bs}	m	-2.626	-0.0120	x-coord. of center of buoyancy
z_{bs}	m	-4.180	-0.0191	z-coord. of center of buoyancy
BM	m	5.364	0.0245	Metacentric height
>Underwater (15.4m Waterline)				
d_u	m	15.400	0.0704	Draft
Vol_u	m^3	40899.0	0.0039072	Displaced volume
x_{bu}	m	-4.501	-0.0206	x-coord. of center of buoyancy
z_{bu}	m	-1.295	-0.0059	z-coord. of center of buoyancy
[Main wing (single)]				
S_w	m	21.875	0.1000	Span of main wing
C_{wr}	m	21.875	0.1000	Chord length of main wing (root
C_{wt}	m	13.125	0.0600	Chord length of main wing (tip)
A_w	m^2	382.81	0.008000	Area of main wing
x_{wle}	m	-21.284	-0.0973	x-coord. of trailing edge
y_{wr}	m	12.698	0.0581	y-coord. of root
x_{wa}	m	-7.875	-0.0360	x-coord. of axis
z_{wa}	m	-1.788	-0.0082	z-coord. of axis
[Tail wing (single)]				
S_t	m	10.938	0.0500	Span of tail wing
C_{tr}	m	8.750	0.0400	Chord length of tail wing (root)
C_{tt}	m	6.563	0.0300	Chord length of tail wing (tip)
A_t	m^2	83.74	0.001750	Area of tail wing
x_{tle}	m	-73.500	-0.3360	x-coord. of trailing edge
y_{tr}	m	8.859	0.0405	y-coord. of root
x_{ta}	m	-69.125	-0.3160	x-coord. of axis
z_{ta}	m	-0.006	0.0000	z-coord. of axis
[Bridge deck (midship position)]				
H_B	m	8.750	0.0400	Bridge height
L_{Bt}	m	12.031	0.0550	Bridge length (top)
L_{Bb}	m	21.875	0.1000	Bridge length (bottom)
B_b	m	8.750	0.0400	Bridge breadth (bottom)
x_{Bt}	m	2.188	0.0100	x-coord. of bridge front top
x_{Bb}	m	10.938	0.0500	x-coord. of bridge front bottom
Vol_B	m^3	915.3	0.0000874	Bridge volume

are represented by the Lewis forms [7] and some sections and parts of profile are expressed using elliptic arcs and the following formula.

$$\eta = \pm p_{\pm}\sqrt{1-\exp\left\{-s\frac{\pi}{4}\left(\frac{\xi}{p_{\pm}}\right)^2\right\}}. \qquad (1)$$

Equation (1) is an S-shape function in ξη-plane where *s* is an arbitrary value proportional to the slope at origin and p_+ and p_- are the asymptotic values of η corresponding to positive and negative infinity of ξ. The range of ξ is selected depending on portions of sectional shape or profile to be applied.

The cross sections and profile of above water part are also represented using Lewis forms, elliptic arcs and Eq. (1). The air draft on the surface and the depth of prototype SSS is equal to those of the parent container ship of the YNU model though the air draft of the YNU model does not corresponds to that of its parent container ship.

The horizontal and vertical plan of the prototype SSS is shown in Fig. 3. The primary objective of main wings is to produce downward lift. While that of tail wings is to control trim angle and pitch motion. The main wing is located at the height of waterline corresponding to 105% displaced volume of the SSS on the surface. The tail wing is below the main wing by 10% mean aerodynamic chord of the main wing. The bridge deck is assumed to be at around midship and to have stream lined horizontal sections. The rudder is same as the parent container ship.

B. *Prototype model and tank test setup*

A model of the prototype SSS was made for tank tests to clarify hydrodynamic characteristics. The model length is 0.8m. Dimensions of the model are shown in Table I. The main and tail wing angles are variable. The bridge deck of the model can also be located where its longitudinal center is at S.S. 9/8. The rudder was not realized for the model since the large part of the rudder position was occupied by the strut mentioned later.

The model was fixed to a sting type strut [8] as shown Fig. 4. The lower end of the strut and the model were connected through a watertight load cell. The other end of the strut was fixed to the carriage of the Ocean Engineering Basin. The carriage system is able to provide arbitrary horizontal motion consisting of longitudinal and lateral velocity components and turning rate [6]. The model was fixed to the strut in two ways. One is the horizontal mode setup and the other is the vertical mode setup as shown in Fig. 5. In the latter setup the vertical velocity w and pitch rate q relative to the model are realized by the horizontal carriage movement.

C. *Test condition and data analysis*

Table II shows tank test conditions. U is the towing velocity. The attack angle α was chosen as a test parameter representing the vertical velocity. The attack angle α is defined as $\sin^{-1}(w/U)$. In the shallowest submerged depth condition, H/L_{pp}=0.03375 (H/L=0.034 hereafter), the upper deck top of model hull is at the level of water surface.

Measured forces and moments in circular motion modes are corrected by subtracting centrifugal force component. Measured moments are converted to those around the origin of the coordinate system, Fig.1. Hydrodynamic forces and moments that do not include inertia forces are discussed in the following sections.

III. Hydrodynamic Characteristics

A. *Effect of towing velocity and submerged depth*

Figure 6 shows the nondimensional longitudinal force X, vertical force Z and pitch moment M in the conditions of various towing velocity and submerged depth. The main and tail wings angles are set to be zero. The vertical velocity w and pitch rate q are also zero. In figures hereafter L is used for L_{pp}.

In the deep submerged condition, H/L=0.75, the vertical force Z points downward and the pitch moment M works in the bow-up direction. The effect of submerged depth grows larger from around the H/L=0.2 condition. In the shallowest submerged depth condition, H/L=0.034, the resistance decreases, the vertical downward force Z increases and the pitch moment M works in the opposite bow-down direction. These hydrodynamic characteristics seem to be favorable when the prototype SSS is going to submerge. However, the tendency is not monotonous. In the H/L=0.1 condition the resistance increases, the vertical force Z can point upward depending on the towing velocity. These are considered to be attributable to the wave-making effects.

The data tendency at different towing velocity and submerged depth imply that the condition of H/L=0.75 is sufficiently deep for the prototype SSS.

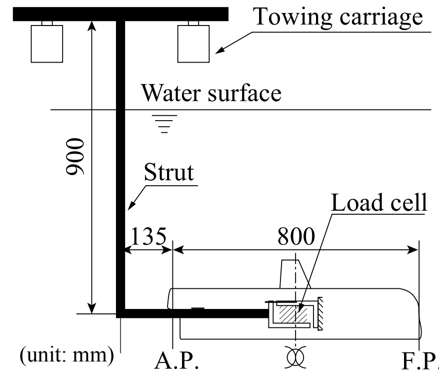

Figure 4. Illustrated setup of the prototype SSS model for the tank test

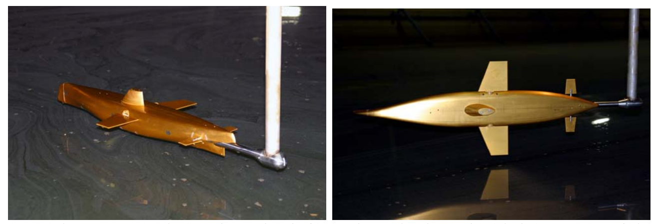
Figure 5. Horizontal mode (left) and vertical mode (right) setups of the prototype SSS model

TABLE II
TANK TEST CONDITIONS

Item	Unit	Hor. mode	Ver.mode	Note
U	m/s	0.400 to 1.000	0.700	Towing velocity
Fn		0.143 to 0.357	0.250	Froud number
α (=$\sin^{-1}(w/U)$)	deg.	-	-10 to +10	Attack angle
q' (=qL_{pp}/U)	-	-	-0.2 to +0.2	Non-dim. pitch rate
H	m	0.027 to 0.600	0.600	Submerged depth
H' (=H/L_{pp})	-	0.03375 to 0.750	0.750	Submerged depth ratio
δ_{ew}	deg.	-20 to +20	-5 to +5	Main wing elevator angle
δ_{et}	deg.	-15 to +15	-	Tail wing elevator angle

B. Main and tail wing performance

Figure 7 shows the effect of main wing angle δ_{ew} and submerged depth. The vertical velocity w and pitch rate q are zero. The tail wing angle δ_{et} is also zero.

The shallow submerged depth effect becomes significant at the shallowest H/L=0.034 condition. For the pitch moment M the shallow submerged depth effect is large in H/L=0.1 conditions with negative main wing angle. The resistance grows rapidly in conditions with large main wing angles. Linearity of the vertical force Z and the pitch moment M can be seen in deep submerged conditions with the main wing angle ranging from –15 to +15 degrees.

These data tell, for example, that 5 degrees of the main wing angle δ_{ew} produces the downward lift about 6.5 percent of the displacement of the SSS when on the surface, 3.8 percent when underwater. This gives an idea about the relation between the residual buoyancy and the corresponding necessary main wing angle.

Figure 8 shows the effect of tail wing angle δ_{et} and submerged depth. The vertical velocity w, pitch rate q and the main wing angle δ_{ew} are zero.

The shallow submerged effects are significant in the shallowest H/L=0.034 condition as seen in Fig. 7. The longitudinal force X and the vertical force Z is not so sensitive to the tail wing angle δ_{et} than to the main wing angle δ_{ew}. This is because the tail wing area is smaller than the main wing area. However, the effect of the tail wing angle δ_{et} on the pitch moment M is larger than that of the main wing. This is because the point of action of tail wing force is farther from the midship than that of the main wing. The vertical force Z and pitch moment M shows the linearity in the whole range of tail wing angle δ_{et} for measurement, from –20 to +20 degrees.

Figure 9 shows the interaction effects of the main wing angle δ_{ew} and tail wing angle δ_{et} on the longitudinal force X, vertical force Z and pitch moment M. Two kinds of data are compared with each other. The filled marks represent

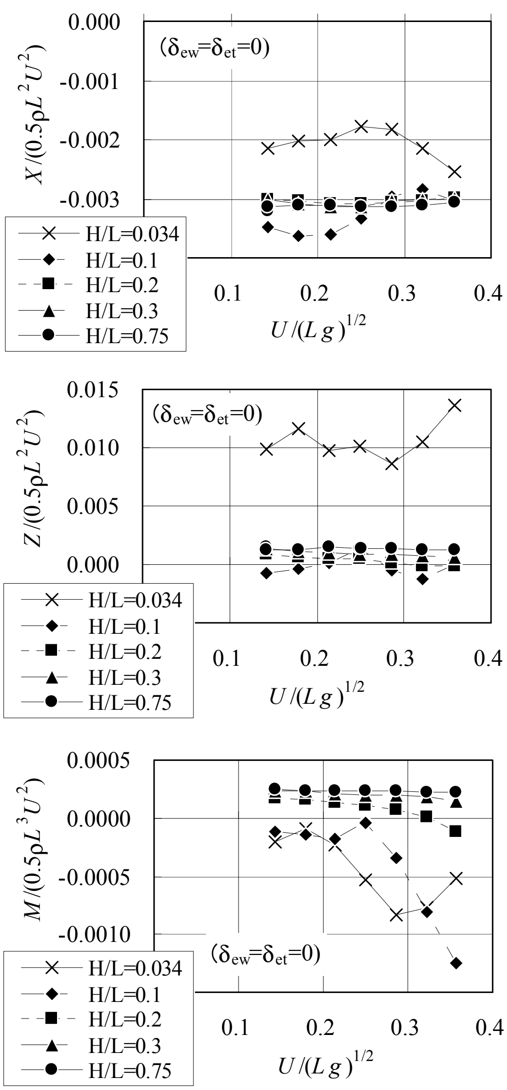

Figure 6. Effects of the towing velocity and submerged depth on longitudinal force X, vertical force Z and pitch moment M. (F_n=0.25.)

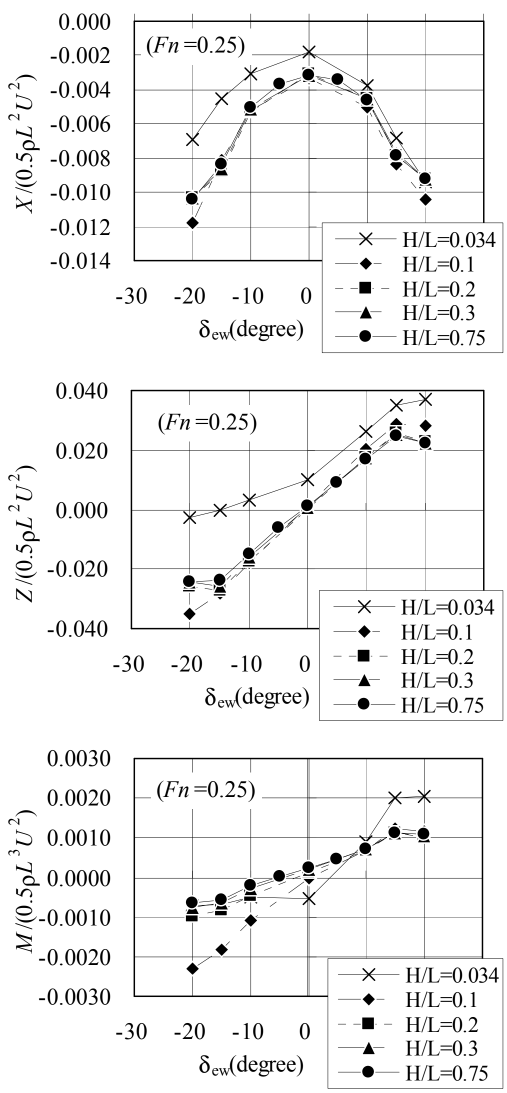

Figure 7. Effects of the main wing elevator angle and submerged depth on longitudinal force X, vertical force Z and pitch moment M. (F_n=0.25.)

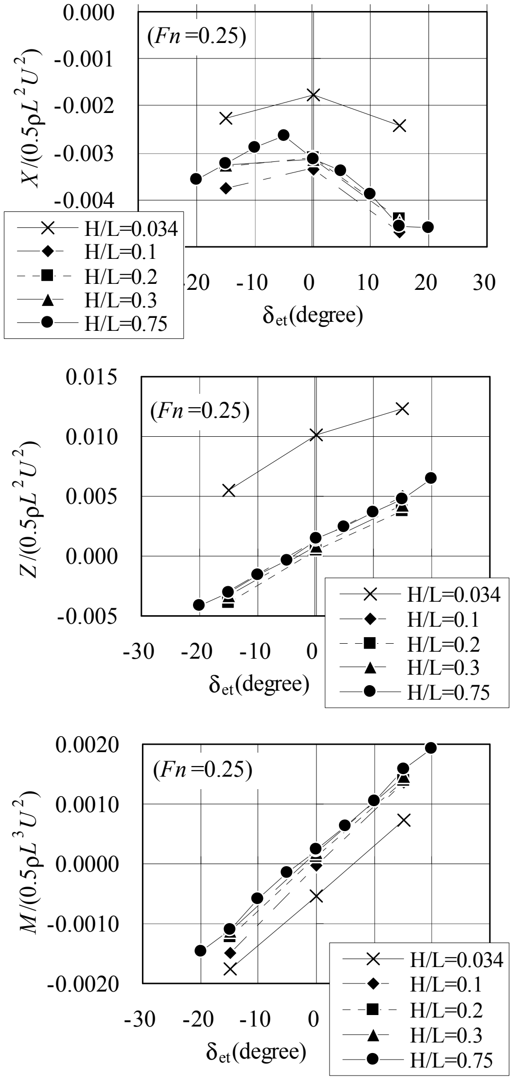

Figure 8. Effects of the tail wing elevator angle and submerged depth on longitudinal force X, vertical force Z and pitch moment M. (F_n=0.25.)

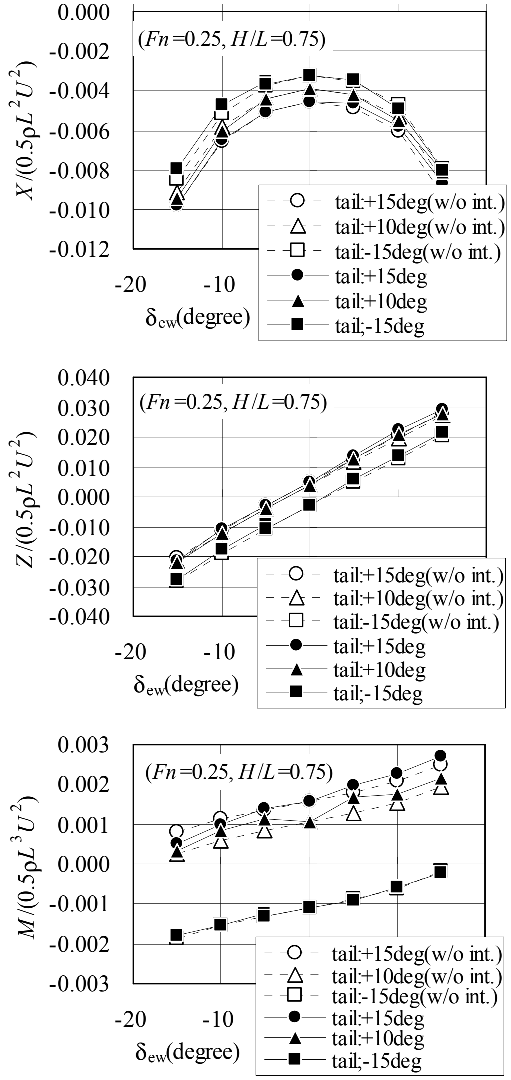

Figure 9. Interaction effects of the main wing angle δew and tail wing angle δet on the longitudinal force X, vertical force Z and pitch moment M. (F_n=0.25, H/L=0.75.)

measured data in conditions in which the combination of main and tail wing angles are varied. While the open marks, noted 'w/o int.', represent values that do not include the interaction effects between main and tail wings. These 'w/o int.' values are worked out using the following equation.

$$F(w/o\ int) = F(\delta_{ew} \neq 0, \delta_{et} = 0) + F(\delta_{ew} = 0, \delta_{et} \neq 0) - F(without\ wings) \quad (2)$$

In Eq. (2) F is for any of the longitudinal force X, vertical force Z or pitch moment M. The first and second terms in the right hand side of Eq. (2) corresponds to data shown in Fig. 7 and Fig. 8 respectively. The third term F(*without wings*) in Eq. (2) stands for measured data in the condition in which the model has neither main and tail wings and both the vertical velocity w and pitch rate q are zero. The data corresponding the third term are included in Fig. 10 about which is explained in the following subsection. Since the open marks are not far from the filled ones, the interaction effect between the main and tail wings is considered small. This means that the tail wings vertical location, below the main wings by 10% of the mean aerodynamic chord of main wing, is sufficient to avoid the large interaction effect of the main and tail wings performances.

The effect of submerged depth on the interaction between main and tail wings is confirmed to be small by related tank test data, though the data are not shown here.

C. *Effect of vertical motion*

Figure 10 shows the effects of the attack angle α and pitch rate q on the longitudinal force X, vertical force Z and pitch moment M in two conditions. One is that the main and tail wing angles are set to be zero. The other is that the main and tail wings were removed and only the hull and the bridge deck remain.

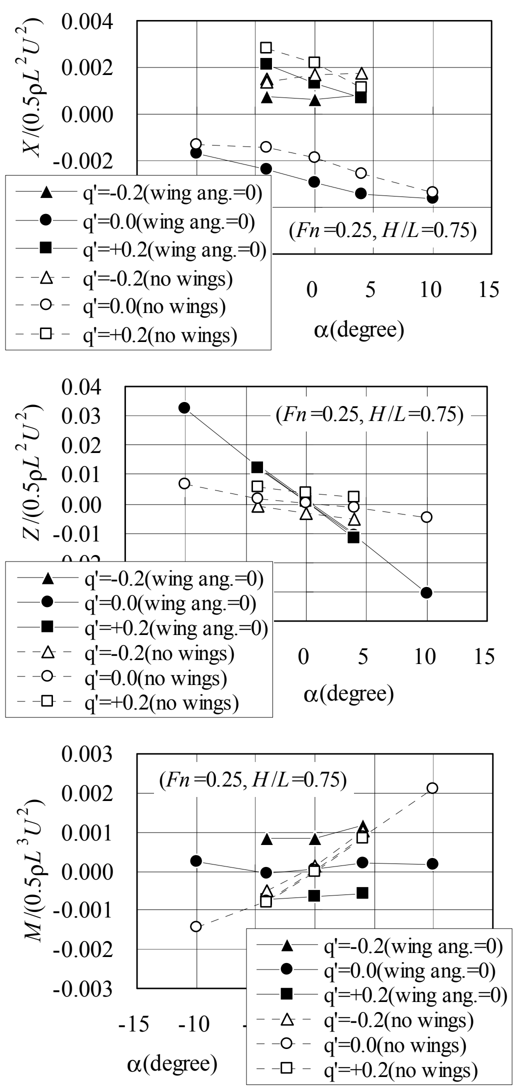

Figure 10. Effects of the attack angle and pitch rate on the longitudinal force X, vertical force Z and pitch moment M. (F_n=0.25, H/L=0.75.)

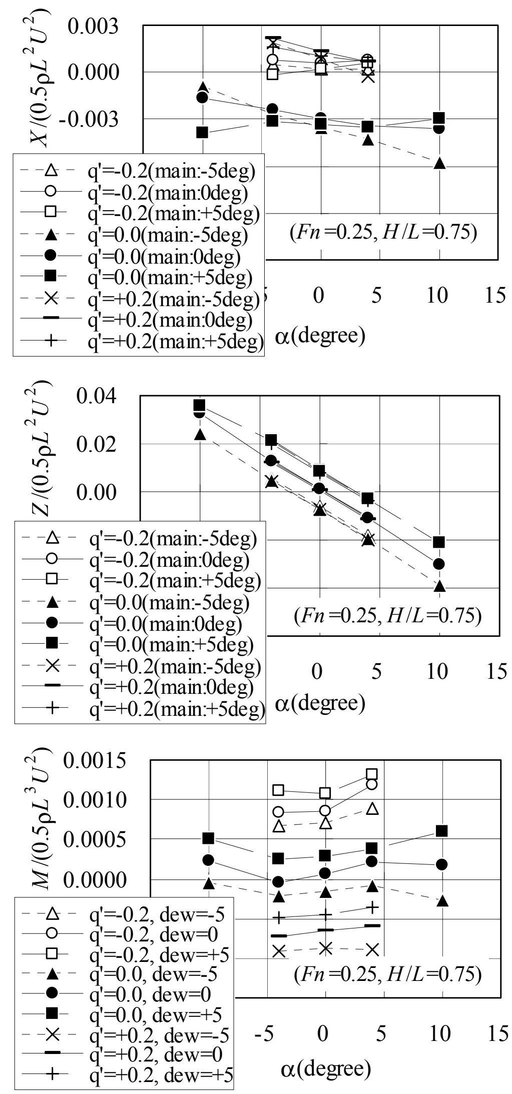

Figure 11. Effects of the attack angle and pitch rate on the main wing component of the longitudinal force X, vertical force Z and pitch moment M. (F_n=0.25, H/L=0.75.)

The difference of the longitudinal force X in these two conditions is mainly attributed to that of the drag component of wings. The pitch rate q has more influence than the attack angle α on the longitudinal force X.

When the wings exist the attack angle α has an influence on the vertical force Z but not much on the pitch moment M. On the other hand, the pitch rate q has an influence on the pitch moment M but not much on the vertical force Z.

When the wings do not exist the data show different hydrodynamic characteristics from that when the wings exist. The hull component in the vertical force and pitch moment is clarified not to be negligible but comparable to that of wings. These components are compared quantitatively in the next section.

Figure 11 shows the effects of attack angle α and pitch rate q on the main wing component of longitudinal force X, vertical force Z and pitch moment M when the main wing angle is ± 5 degrees.

The main wing components in the vertical force Z and pitch moment M seem to be almost constant in conditions with various combination of the attack angle α and pitch rate r. The main wing angle effect on the longitudinal force X is recognizable only when the attack angle α is over ± 5 degrees.

IV. Hydrodynamic Derivatives

A method to estimate linear hydrodynamic derivatives is proposed by Ueno [5]. These linear hydrodynamic derivatives correspond to those defined at a steady horizontal advancing condition as a reference condition. The most basic condition as a reference condition is such as the attack angle, the main and tail wing angles are all zeros. In this case linear hydrodynamic derivatives for the vertical force Z and pitch moment M is written as follows.

$$\begin{cases} Z_w = Z_w^{<h>} - \frac{1}{2}\rho U_0 (S_w \frac{\partial C_{Lw}}{\partial \alpha}\Big|_0 + S_t \frac{\partial C_{Lt}^*}{\partial \alpha}\Big|_0) \\ Z_q = Z_q^{<h>} + \frac{1}{2}\rho U_0 (x_{Cw} S_w \frac{\partial C_{Lw}}{\partial \alpha}\Big|_0 + x_{Ct} S_t \frac{\partial C_{Lt}^*}{\partial \alpha}\Big|_0) \\ M_w = M_w^{<h>} + \frac{1}{2}\rho U_0 (S_w x_{Cw} \frac{\partial C_{Lw}}{\partial \alpha}\Big|_0 + S_t x_{Ct} \frac{\partial C_{Lt}^*}{\partial \alpha}\Big|_0) \\ M_q = M_q^{<h>} - \frac{1}{2}\rho U_0 (S_w x_{Cw}{}^2 \frac{\partial C_{Lw}}{\partial \alpha}\Big|_0 + S_t x_{Ct}{}^2 \frac{\partial C_{Lt}^*}{\partial \alpha}\Big|_0) \end{cases} \quad (3)$$

$$\begin{cases} Z_{\delta} = \frac{1}{2}\rho U_0{}^2 S \frac{\partial C_L}{\partial \alpha}\Big|_0 \frac{\partial \alpha}{\partial \delta_e}\Big|_0 \\ M_{\delta} = -\frac{1}{2}\rho U_0{}^2 S x_C \frac{\partial C_L}{\partial \alpha}\Big|_0 \frac{\partial \alpha}{\partial \delta_e}\Big|_0 \end{cases} \quad (4)$$

In Eq. (3) the variable U_0 is for the velocity at the reference condition and asterisk * stands for values taking into consideration the downwash effect of the main wings on the tail wings. The terms with superscript <h> in Eq. (3) stand for the hull components. Equation (4) is applicable both to the main and tail wings by adding subscripts *w* or *t* properly.

The lift curve slopes of main and tail wings are estimated by the following equations [9].

$$\begin{cases} \frac{\partial C_L}{\partial \alpha}\Big|_0 = \frac{2\pi}{(1+2/\Lambda)} \\ \frac{\partial C_{Lt}^*}{\partial \alpha}\Big|_0 = \frac{\partial C_{Lt}}{\partial \alpha}\Big|_0 \{1 - \frac{\partial C_{Lw}}{\partial \alpha}\Big|_0 /(\pi \Lambda_t)\} \end{cases} \quad (5)$$

The effective aspect ratio is calculated for a pair of main wing and a single tail wing since the main wings have almost no gap between the wing root and the hull while the tail wings have gaps as shown in Fig. 3. The coordinates of aerodynamic centers x_{Cw} and x_{Ct} in Eq. (3) are assumed to be equal to the coordinates x_{wa} and x_{ta} in Table I respectively. The ratio of attack angle to elevator angle $\partial\alpha/\partial\delta_e$ in Eq. (4) is assumed to be 1.

Estimated linear hydrodynamic derivatives for the vertical force *Z* and pitch moment *M* are shown in Table III together with those obtained by tank test data analysis. Prime " ' " in Table III means nondimensional values divided by $0.5\rho L^2 U^2$ for force terms or $0.5\rho L^3 U^2$ for moment terms. Note that the estimates are for the *H*/*L*=0.75 condition and that the estimated values Z_w, Z_q, M_w and M_q for the *H*/*L*=0.75 condition include the hull component obtained by tank test data analysis.

It is confirmed that the hull components are not negligible. This is because the hull volume is large comparing to wings area, which is a quite different feature of the SSS form airplanes.

TABLE III
LINEAR HYDRODYNAMIC DERIVATIVES.

	Tank test	Tank test	Tank test	Tank test	Tank test	Estimate
H/L	0.03371	0.10	0.20	0.30	0.75	0.75
$Zw^{<h>}{}'$	N/A	N/A	N/A	N/A	-0.02566	N/A
$Zq^{<h>}{}'$	N/A	N/A	N/A	N/A	0.01696	N/A
$Mw^{<h>}{}'$	N/A	N/A	N/A	N/A	0.01127	N/A
$Mq^{<h>}{}'$	N/A	N/A	N/A	N/A	-0.00065	N/A
Zw'	N/A	N/A	N/A	N/A	-0.17101	-0.12697
Zq'	N/A	N/A	N/A	N/A	-0.00330	0.00748
Mw'	N/A	N/A	N/A	N/A	0.00124	0.00180
Mq'	N/A	N/A	N/A	N/A	-0.00408	-0.00302
$Z_{\delta ew}'$	0.06506	0.10876	0.09951	0.09493	0.09128	0.08727
$M_{\delta ew}'$	0.00404	0.00507	0.00320	0.00286	0.00257	0.00393
$Z_{\delta et}'$	0.01311	0.01517	0.01463	0.01459	0.01505	0.01404
$M_{\delta et}'$	0.00475	0.00542	0.00501	0.00497	0.00494	0.00555

Differences between the estimated and analyzed values of Z_q, M_w and $M_{\delta ew}$ are relatively large. As mentioned in the previous section concerning Fig. 11, Z_q and M_w are small by their nature. $M_{\delta ew}$ is also small by its nature since the effect of main wing angle δ_{ew} on the pitch moment *M* is small because the main wing rotation axis is close to the midship. These are the reason why the differences of derivatives Z_q, M_w and $M_{\delta ew}$ between the estimated and experimental values are large. Other linear derivatives seem to be estimated properly. Differences between the estimated and analyzed values of other derivatives are within ±26% of analyzed ones.

V. CONCLUDING REMARKS

A prototype of SSS consisting of a hull, a pair of main and tail wings and a bridge deck is proposed. The cross sections and profile of the hull part are represented by mathematical formulae.

A model of the prototype SSS is made and hydrodynamic characteristics are investigated using tank tests. The effects of towing velocity, submerged depth, main and tail wings angles, vertical velocity and pitch rate on the longitudinal and vertical forces and pitch moment are clarified by the circular motion test.

The linear hydrodynamic derivatives with respect to the vertical force and pitch moment are analyzed using the tank test data. These hydrodynamic derivatives are also estimated and compared with the analyzed ones. It is confirmed that the estimate method provides proper values of these hydrodynamic derivatives.

The data of hydrodynamic forces and moment acting on the prototype SSS in vertical motion as well as the estimate method for the linear hydrodynamic derivatives are considered to be useful for estimating the dynamics of a SSS having same kind of configuration.

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