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A prototype of submersible surface ship and its hydrodynamic characteristics

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ABSTRACT

The submersible surface ship (SSS) is a new concept ship that avoids rough seas by going underwater using downward lift of wings and keeping residual buoyancy for safety. A prototype of SSS consisting of a hull, a pair of main wings, and a pair of horizontal tail wings is proposed, where mathematical formulae represent the forms of main hull and bridge deck. The circular motion test clarified the characteristics of hydrodynamic forces and moments acting on a model of the prototype SSS in vertical and lateral motions. The tank tests revealed how the main and the tail wing angles affect the total hydrodynamic forces and moments as well as how their performance interact each other. The test data also tell the variation of hydrodynamic characteristics of different submerged depth and different longitudinal position of the bridge deck. Comparisons of the estimated linear hydrodynamic derivatives with those obtained by the test data analysis validate the estimation method. A mathematical model is presented to describe the observed phenomenon that the aileron angle in lateral motion induces the vertical force and pitch moment, which leads a coupled vertical and lateral motion of the prototype SSS.

1. Introduction

The concept of submersible surface ship (SSS) is a ship submersible to the shallow but sufficient depth to avoid rough seas that might induce cargo damage, arrival time delay, seasickness, and so on. The configuration in the early concept of the SSS, proposed by Hirayama et al. (2005a), consists of a hull, a pair of main wings, and a pair of tail wings. In calm and moderate seas the SSS goes on the surface just like conventional ships, and in rough seas it goes underwater using downward lift of wings with keeping the residual buoyancy for its safety.

A research team of the Yokohama National University studied the feasibility of SSS where they used a SSS model (YNU-model) of which the lower hull form was a conventional container ship's one. Hirayama et al. measured the resistance and downward lift acting on the YNU-model (2005a) and proposed a modified YNU-model, which had its bow flare potion cut off (2005b). Although the modified YNU-model has improved downward lift characteristics, its form is not yet practical one because it has some long parts of angular corner and no bridge deck. Moreover, they have not investigated the hydrodynamic characteristics of the SSS in lateral motion that is crucial to investigate the six-degree of motion of the SSS.

Mori et al. (1988) proposed a high-speed semi-submersible vehicle (HSV) of which objective was to reduce the wave making resistance by submerging to the shallow depth with wings, which is the same mechanism as the SSS though the depth is shallower than the SSS. However, the hydrodynamic characteristics of lateral forces and moments were outside the scope of their research.

Although researchers have reported hydrodynamic characteristics of underwater vehicles including submarine (Gertler, 1950; USAF, 1968; Maeda et al., 1988; Evans and Nahon, 2004; Watt and Bohlmann, 2004; Jagadeesh et al., 2009), there is not sufficient information applicable to the SSS because the SSS cruises both on the surface and underwater, which is a different feature from the ordinary underwater vehicles. Therefore, the authors consider that the feasibility study of the SSS needs a proposal of its practical form and configuration, and research on its hydrodynamic characteristics including those of lateral forces and moments to clarify the property of six-degree of motion when submerged.

In this paper, the authors propose, from a practical point of view, a configuration and a form of prototype SSS consisting of a hull, a pair of main wings, a pair of tail wings, and a bridge deck. Mathematical formulae represent the cross sections and profiles of the main hull, while both the main and the tail wings' plans are trapezoids. The main wings work both as elevators and as aileron while the tail wings as elevators.

The circular motion test (Ueno et al., 2009) reveals the characteristics of six kinds of orthogonal forces and moments

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acting on a mode of the prototype SSS in the vertical and lateral motions. The tank test parameters are the longitudinal velocity, the vertical and lateral velocities noted as the attack angle and the drift angle, respectively, the pitch and yaw rates, the submerged depth, the main elevators and aileron angles, the tail elevators angle, and the longitudinal position of bridge deck.

The tank test data analysis and the theoretical estimation method proposed by Ueno (2010) provide the linear hydrodynamic derivatives of the prototype SSS for the vertical and lateral motions, and wing angles; the comparison validates the method. A mathematical model is presented for describing an unexpectedly observed phenomenon that the aileron angle in lateral motion induces the vertical force and the pitch moment, which might trigger the coupled vertical and lateral motion of the SSS.

2. Prototype of submersible surface ship

The basic configuration of the prototype SSS is a hull of conventional ship's lower and streamlined upper forms, horizontal main wings working as the main elevators and aileron, horizontal tail wings as the tail elevators. The principal objective of the main wings is to produce the downward lift, and of the tail wings to align the hull.

Fig. 1 shows the coordinate system of the SSS of which the origin is the cross point of the center plane, the midship section, and the water plane when the SSS is on the surface. The coordinates x, y, and z point forward, starboard, and downward, respectively. The variables u, v, and w represent translational velocity components; p, q, and r rotational velocity components; X, Y, and Z forces; K, M, and N moments. The variables of control surfaces δ_{ew} and δ_a represent the main elevators and aileron angles, respectively; δ_{et} tail elevators angle; δ_r rudder angle.

The prototype SSS, whose overview is shown in Fig. 1, has a bridge deck or a sail like a submarine and horizontal main and tail wings like an airplane, though the wing area, relative to the hull, is smaller than airplanes. Fig. 2 shows the main hull's body plan where the lower hull form is of the container ship that the YNU research team used (Hirayama et al., 2005a). Most of the underwater and all above-water cross sections are expressed by the Lewis form (Lewis, 1929); while several cross sections at the fore and aft ends, and the profile of hull shown in Fig. 3 are by the combinations of elliptic arcs and lines represented by the following formula.

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

Eq. (1) is a kind of the error function representing S-shape lines in $\xi\eta$-plane where s is an arbitrary value proportional to the slope at origin, p_+ and p_- are the asymptotic values of η for the positive and negative infinity of ξ,respectively. Each portion of the sectional shape or profile to which these lines are applied determines the range of ξ. The depth of prototype SSS is equal to that of the parent container ship.

Fig. 3, the horizontal and vertical plans of the prototype SSS, gives the idea of wings; the main wing has a tapered leading edge, and the tail wing has symmetrically tapered leading and tailing edges. The main wings' installation height is at the waterline of 105% displaced volume of the prototype SSS on the surface, while the tail wings' is below the main wings 10% the mean aerodynamic chord of the main wing to avoid the downwash effect from the main wings in submerged conditions. The aerodynamic centers of the main and tail wings are on their rotating axes that are perpendicular to the centerline. The bridge deck has a tapered shape with horizontal cross sections represented by the two identical face side line of NACA-6521 wing section set to each other, where its thickness is multiplied by 1.26. The rudder and propeller are same as the parent container ship, its hydrodynamic characteristics is out of scope of this report. Table 1 shows the dimensions of the prototype SSS. The length between perpendiculars is assumed 175 m in ship scale, same as the parent container ship. This structural design including how to fold or house the wings for the surface going is beyond this paper and should be discussed separately.

3. Tank test

3.1. Tank test model

The model length of prototype SSS between perpendiculars is 0.8 m as shown in Table 1. The main and tail wings of the model

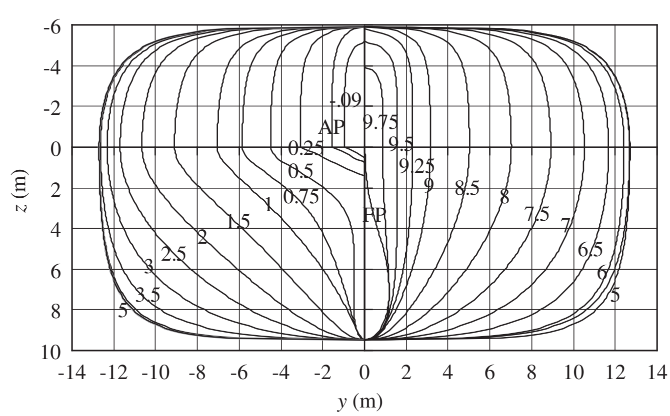

Fig. 2. Body plan of the prototype SSS.

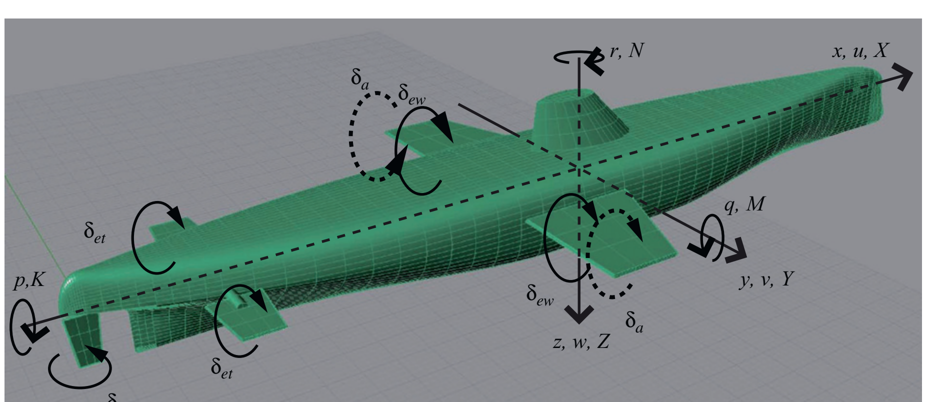

Fig. 1. Overview of the prototype SSS and coordinate system.