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Hydrodynamic derivatives and motion response of a submersible surface ship in unbounded water

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ABSTRACT

A submersible surface ship (SSS) is based on a novel concept that the SSS goes on surface like conventional ships in moderate seas but goes underwater in rough seas to the depth sufficient to avoid wave effects. The SSS has a wing system that produces downward lift to go underwater with preserving the residual buoyancy for its safety. The SSS is expected to be able to keep both safety and punctuality even if it encounters unexpected bad weather.

The motion of the SSS is studied. The equations of motion are formulated and the procedures for estimating hydrodynamic derivatives are presented. The hydrodynamic derivatives are estimated for a SSS having a configuration, a hull with a pair of main wings and a pair of horizontal tail wings. Using these estimated hydrodynamic derivatives, calculation of the SSS motion is carried out.

The calculation results show some specific aspects of the SSS especially for effects of the elevator of main wings and horizontal tail wings, aileron of main wings, rudder and propeller revolution. It is confirmed that the existence of static roll restoring moment and having large hull comparing with wing area play important roles in the motion of the SSS.

1. Introduction

The submersible surface ship (SSS) is a ship based on a novel concept, a ship that can avoid rough seas by going underwater, proposed by Hirayama et al. (2005a). The concept of SSS is new in the point that goes on surface like usual ships in calm and moderate seas but goes underwater in rough seas into the depth sufficient to avoid wave effects. In order to submerge the SSS uses wings producing downward lift. Even in submerged condition the SSS keeps residual buoyancy for its safety. The SSS is expected to be able to keep both safety and punctuality even if it encounters unexpected bad weather.

A SSS of which configuration is a hull with a pair of main wings and a pair of horizontal tail wings has been studied by a group of the Yokohama National University (YNU). Among researches necessary to realize a SSS are the dynamics, the structure and strength, the powering system for underwater cruising, the navigation and routing. Researches on the navigation and the wing performance of a SSS are in progress and are expected to be reported in the near future. From a viewpoint of the dynamics of a SSS related researches so far are as follows.

Hirayama et al. (2005a) carried out a trial tank test for a self-propelled SSS model made by modifying a conventional container ship model and obtained the basic information about the wing area necessary to submerge a conventional ship and its vertical motion control. Hirayama et al. (2005b) also clarified by a tank test the relation between the submerged depth, the downward lift and resistant acting on the SSS hull having modified bow shape. Koyama et al. (2006) simulated a submerging motion of the SSS model in waves and discussed its vertical stability. Hirakawa et al. (2007) studied the vertical motion control of the SSS model in the submerging and emerging motion by a tank test and simulation calculations. In order to clarify feasibility of the SSS, not only such studies concerning vertical motion done by YNU group but also studies concerning the lateral motions are needed.

Mori et al. (1988) proposed a high-speed semi-submersible vehicle with wings (HSV). The HSV submerges by using downward lift of wings, which is the same mechanism as the SSS. However, the objective of HSV is reducing the wave-making resistance by submerging into shallow depth, which is different from that of the SSS. Mori et al. confirmed that the HSV is successful in reducing the wave-making resistance but the reduction of frictional resistance still needed. Mori et al. (1991) showed using numerical calculation that the downward lift is effective in small submerged depth and that the nature of vertical motion is unstable but can be stabilized by controlling the main and tail wing angles. Although they studied vertical stability

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during submerged cruising, lateral motion such as sway and yaw motion of the HSV has not been investigated.

There are many reports concerning the dynamics of underwater vehicles. Ishidera et al. (1985) reported the equations of six-degree-of-freedom (6-DOF) motion for a remotely operated vehicle and the automatic depth and heading control system. Ura and Otsubo (1987) proposed a concept of unmanned autonomous gliding submersibles and analyzed its vertical motion. Maeda et al. (1988) reported the hydrodynamic characteristics of two types of unmanned untethered submersibles and estimated its stability derivatives. Towed vehicles are among proposed underwater vehicles (Muddie and Ivers, 1975; Dessureault, 1976; Ohkusu et al., 1987). Ohkusu et al. (1987) measured the hydrodynamic forces acting on a model of a depth-controlled vehicle towed by a long cable and discussed its vertical stability. Most of all these vehicles are statically stable in its steady advancing condition. That means the buoyancy is equal to the gravity in water.

On the other hand, a SSS using downward lift to balance with the residual buoyancy are considered to have common features with airplanes. The gravity of an airplane corresponds to the buoyancy of a SSS while the upward lift of an airplane corresponds to the gravity and the downward lift of a SSS. However, one difference is that a SSS generally feels static restoring moments for pitch and roll motion, because points of action for the gravity and the buoyancy are generally different from each other. Airplanes have nothing to do with that kind of static restoring moments. Another difference is that the volume-lift ratio of a SSS is larger than that of airplanes. That means the hydrodynamic effect of hull part of a SSS is relatively larger than that of airplanes. As long as the configuration of SSS proposed by YNU group is concerned, one more difference is that it has no vertical tail wing.

In this report, the equations of motion of a SSS in unbounded water are presented. The procedure to estimate hydrodynamic derivatives for the linear equations are also presented. This procedure is applied to the SSS configuration of YNU group and calculations of the motion are carried out for investigating the effects of the elevator of horizontal tail wings and main wings, aileron of main wings, rudder and propeller revolution. Results of these calculations show some aspects of the SSS dynamics, especially those due to the existence of static roll restoring moment and having large hull part.

2. Equations of motion

2.1. Configuration and coordinate systems

A SSS consisting of a hull, main wings and horizontal tail wings shown in Fig. 1 is supposed. The tail and main wings have elevators. The main wings have also an aileron. The hull is equipped with a propeller and a rudder as conventional ships.

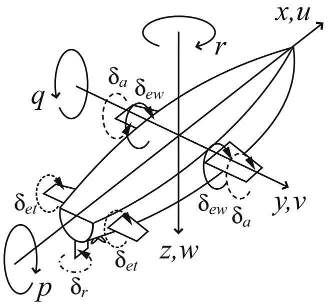

Fig. 1. General body-fixed coordinate system.

A general body-fixed coordinate system is shown in Fig. 1. The origin locates on the center plane at midship. x, y and z points forward, right and downward, respectively. u, v and w are translational velocities to x, y and z directions and p, q and r are angular velocities around x, y and z axes. In Fig. 1, δ_{ew}, δ_{et}, δ_a and δ_r show the positive direction of the main wing elevator angle, tail wing elevator angle, aileron angle and rudder angle. Note that the main wings work both as the elevator and the aileron. The elevator has symmetric angles and the aileron has anti-symmetric angles for the port side and the starboard side wings.

In the earth-fixed coordinate system O_e-$x_e y_e z_e$, $x_e y_e$-plane is horizontal and z_e-axis points vertically downward. The earth-fixed coordinate (x_e, y_e, z_e) and their time derivatives are related to those in the body-fixed one (x, y, z) by Eq. (1).

$$\begin{bmatrix} x & u \\ y & v \\ z & w \end{bmatrix} = [E] \begin{bmatrix} x_e & \dfrac{dx_e}{dt} \\ y_e & \dfrac{dx_e}{dt} \\ z_e & \dfrac{dx_e}{dt} \end{bmatrix} \tag{1}$$

Matrix E is defined by Eq. (2) in which ϕ, θ and ψ are Euler angles.

$$[E] = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \cos\phi\cos\theta \end{bmatrix} \tag{2}$$

Angular velocities p, q and r in the body-fixed coordinate system are related to Euler angles by Eq. (3).

$$\begin{cases} p = \dot{\phi} - \dot{\psi}\sin\theta \\ q = \dot{\theta}\cos\phi + \dot{\psi}\sin\phi\cos\theta \\ r = -\dot{\theta}\sin\phi + \dot{\psi}\cos\phi\cos\theta \end{cases} \tag{3}$$

Assuming the symmetry about xy-plane, the moment of inertias and products of inertias of the SSS have relations represented by Eq. (4).

$$I_{xy} = I_{yx} = 0, \quad I_{yz} = I_{zy} = 0 \tag{4}$$

2.2. Linear equations of motion

Let ρ, g, m and ∇ stand for the density of water, the gravitational acceleration, mass and displaced volume of the SSS, respectively. The center of gravity, $(x_g, 0, z_g)$ and the center of buoyancy $(x_b, 0, z_b)$ of the SSS are in the xz-plane in the body-fixed coordinate system.

A stability axis is employed as a body fixed O-xyz coordinate system after the example of airplane dynamics (Kato et al., 1982). The horizontal steady advancing condition is chosen as the reference condition, in which the velocity components are defined by Eq. (5).

$$u = U_0, \quad v = w = p = q = r = 0 \tag{5}$$

In Eq. (5), U_0 stands for the steady advancing velocity.

The general 6-DOF motion is described as deviation from the reference condition in which v, w, p, q and r stand for the deviations of velocity components. The longitudinal velocity component u is expressed by Eq. (6).

$$u = U_0 + \tilde{u} \tag{6}$$

In Eq. (6), $\tilde{u}$ stands for the deviation of longitudinal velocity component from U_0. For convenience the following expression, Eq. (7), is employed hereafter.

$$\tilde{u} \equiv u \tag{7}$$