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Available online at www.sciencedirect.com
ScienceDirect
Publishing Services by Elsevier
International Journal of Naval Architecture and Ocean Engineering xx (2016) 1—14
http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

# Experimental study on hydrodynamic coefficients for high-incidence-angle maneuver of a submarine

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Received 30 September 2015; revised 8 August 2016; accepted 24 August 2016
Available online ■ ■ ■

**Abstract**

Snap rolling during hard turning and instability during emergency rising are important features of submarine operation. Hydrodynamics modeling using a high incidence flow angle is required to predict these phenomena. In the present study, a quasi-steady dynamics model of a submarine suitable for high-incidence-angle maneuvering applications is developed. To determine the hydrodynamic coefficients of the model, static tests, dynamic tests, and control surface tests were conducted in a towing tank and wind tunnel. The towing tank test is conducted utilizing a Reynolds number of $3.12 \times 10^6$, and the wind tunnel test is performed utilizing a Reynolds number of $5.11 \times 10^6$. In addition, least squares, golden section search, and surface fitting using polynomial models were used to analyze the experimental results. The obtained coefficients are presented in tabular form and can be used for various purposes such as hard turning simulation, emergency rising simulation, and controller design.


*Keywords:* High-incidence-angle maneuver; Towing tank test; Wind tunnel test; Golden section search; High-order polynomial model

## 1. Introduction

Submarines are required to be stable during certain maneuvers such as steady turning, depth change, and emergency rising. A method for predicting the submarine behavior during such maneuvers is thus required for the design of the vehicle. A high-incidence-angle flow acts on a submarine during hard turning or emergency rising, resulting in excessive motion response of the vehicle. This makes it difficult to use a general dynamics model, which is suitable for linear motion, to predict the behavior of a submarine during such maneuvers. The conduction of a free running test is an accurate method for predicting the motions, but it is time consuming and costly. Alternative methods include simulation using the equations of motions and the utilization of a data base.

The simulation of submarine maneuver is generally based on Gertler and Hagen (1967)'s equations of motion. The utilized model was revised by Feldman (1979) to provide enhanced, unsteady, and nonlinear modeling for cross flow drag and sail vortex. Watt (2007) proposed an analytical method for estimating the added mass using incompressible potential flow theory and a damping term that is suitable for a high-incidence-angle flow. Many studies have been aimed at obtaining the coefficients of the maneuver model using captive model tests (Seol, 2005; Feldman, 1987, 1995; Nguyen et al., 1995; Quick et al., 2012, 2014; Roddy et al., 1995; Watt and Bohlmann, 2004). Planar Motion Mechanism (PMM) and Rotating Arm (RA) tests were generally used to determine the coefficients. The stability and control characteristics of a submarine have also been determined by RA and PMM tests

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Peer review under responsibility of Society of Naval Architects of Korea.

http://dx.doi.org/10.1016/j.ijnaoe.2016.08.003

(Feldman, 1987, 1995; Roddy et al., 1995). Researchers at the Defense Science and Technology Organization (DSTO) experimentally tested a generic submarine model in a wind tunnel (Quick et al., 2012, 2014). The wind tunnel tests were targeted at acquiring steady state aerodynamic force and moment data and investigating the characteristics of the flow field of a submarine. The standard submarine model was developed for a series of systematic hydrodynamic experiments jointly funded by Defense R&D Canada (DRDC) and the Royal Netherlands Navy (RNLN), and has been statically tested at different facilities (Mackay, 2003). A horizontal planar motion mechanism (HPMM) test was performed in a towing tank at the Seoul National University using various depths, and the horizontal dynamic stability of the submarine was analyzed using estimated coefficients (Seol, 2005). Most studies on the design of submarine control were concerned with the maintenance of depth in waves (Dumlu and Istefanopulos, 1995; Tolliver, 1982; Choi, 2006). The adaptive controller was designed by Dumlu and Istefanopulos (1995) to operate under various sea conditions. A mathematical model has been proposed for calculating the wave forces acting on the submarine, and a controller designed by PID has also been used to confirm the possibility of control through simulation (Choi, 2006). However, most previous experimental studies involved only static tests and, to the best of the authors' knowledge, there have been none that considered pitch/yaw. Studies that have considered controller design focused on vertical motions such as heave/pitch, and the developed controllers can therefore not be used to assure performance during 6-DOF motion.

This paper proposes a quasi-steady submarine dynamics model that is suitable for high-incidence-angle maneuvers such as hard turning and emergency rising. The model tests were conducted in the towing tank of Seoul National University and in the wind tunnel at the Agency for Defense Development. The goal of these tests was to obtain the hydrodynamic coefficients of the model. The towing tank test was conducted at a Reynolds number of $3.12 \times 10^6$, and the wind tunnel test was performed at a Reynolds number of $5.11 \times 10^6$. Resistance tests, static tests, and dynamic tests were conducted in the towing tank with a 1.3-m model by using the static test device and PMM device. The static test device was used to hold the model at a steady heading angle when resistance tests and static $\beta$ tests were performed. The static $\alpha$ test was also conducted with the static test device by rotating the submarine model by 90° onto its side. The static tests were conducted using angles ranging between −20° and +20°. The dynamic tests were comprised of the HPMM and vertical planar motion mechanism (VPMM) tests, which were performed with the PMM device. The PMM device only allowed the model to oscillate in the sway and yaw directions, and the VPMM was conducted by rotating the submarine by 90°. Because of the general complexity of the experiment and alignment issues related to the size of the model, the control surface efficiency tests could not be conducted in the towing tank. The static $\alpha$ test, the static $\beta$ test, the combined $\alpha/\beta$ test, and the control surface efficiency tests were all performed in the wind tunnel with a 1.92-m model. The resistance tests were used to measure the surge force at various speeds. Owing to the difficulty of obtaining uniform flow at low speeds in a wind tunnel, the resistance tests were conducted in only the towing tank. A three-axis potentiometer was used for the alignment of the combined $\alpha/\beta$ tests. Only the wind tunnel was equipped with the angle measurement system, and the combined $\alpha/\beta$ test could only be performed in the wind tunnel. Angles of attack ranging from −30° to +30° and drift angles ranging from −24° to +24° are used for the static tests in the wind tunnel. The static $\alpha$ tests and static $\beta$ tests results were used to validate the results of each facility test.

The list of towing tank and wind tunnel tests are given in Table 1.

## 2. Mathematical model

### 2.1. Overview

In this section, the equations of motion of a submarine are described. The coordinate system used in this study is shown in Fig. 1.

The origin of the body-fixed coordinates is located at the midship on the centerline. The six degrees of freedom equations of motion can be derived by Newton's second law, and they can be expressed as shown below:

$$
\begin{aligned}
& m\left[\dot{u} - vr + wq - x_G\left(q^2 + r^2\right) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})\right] = X \\
& m\left[\dot{v} - wp + ur - y_G\left(r^2 + p^2\right) + z_G(qr - \dot{p}) + x_G(qp + \dot{r})\right] = Y \\
& m\left[\dot{w} - uq + vp - z_G\left(p^2 + q^2\right) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})\right] = Z \\
& I_x\dot{p} + \left(I_z - I_y\right)qr - I_{xz}(\dot{r} + pq) + I_{yz}\left(r^2 - q^2\right) + I_{xy}(pr - \dot{q}) + m\left[y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp + ur)\right] = K \\
& I_y\dot{q} + \left(I_x - I_z\right)rp - I_{yx}(\dot{p} + qr) + I_{zx}\left(p^2 - r^2\right) + I_{yz}(qp - \dot{r}) + m\left[z_G(\dot{u} - vr + wq) - x_G(\dot{w} - uq + vp)\right] = M \\
& I_z\dot{r} + \left(I_y - I_x\right)pq - I_{zy}(\dot{q} + rp) + I_{xy}\left(q^2 - p^2\right) + I_{zx}(rq - \dot{p}) + m\left[x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)\right] = N
\end{aligned}
\tag{1}
$$

The equations assume that the submarine mass and mass distribution do not change with time. The terms on the right-hand side of Eq. (1) represent the external forces acting on the submarine. In this study, the following modular-type mathematical model is used to represent the external forces.