Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2015,27(1):68-75
DOI: 10.1016/S1001-6058(15)60457-7
www.sciencedirect.com/
science/journal/10016058

Numerical simulation of rotating arm test for prediction of submarine rotary derivatives*

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(Received June 18, 2013, Revised November 6, 2014)

Abstract: The numerical method is used for predicting the rotary-based hydrodynamic coefficients of a submarine. Unsteady RANS simulations are carried out to numerically simulate the rotating arm test performed on the SUBOFF submarine model. The dynamic mesh method is adopted to simulate the rotary motions. From the hydrodynamic forces and moments acting on the submarine at different angular velocities, the rotary derivatives of the submarine can be derived. The computational results agree well with the experimental data. The interaction between the sail tip vortex and the cross flow in the hull boundary layer is discussed, and it is shown that the interaction leads to the "out-of-plane" loads acting on the submarine.

Key words: submarine maneuverability, hydrodynamic coefficients, rotating arm test, dynamic mesh

Introduction

The rotary derivative of a submarine is one of the most important hydrodynamic parameters, and it significantly affects the maneuverability and the dynamic stability of the vehicle. The rotating arm experiment is an effective method to determine the rotating-related hydrodynamic coefficients. The submarine model is fixed to a rotating arm, while the radius of rotation and the angular velocity can be adjusted systematically. The transverse force and the yawing moment acting on the hull at different angular velocities are measured. Consequently, by analyzing these results, the rotary derivatives of the model can be derived. Moreover, it is believed that the rotary derivatives derived from the rotating arm test are generally more accurate than those from the planar motion mechanism (PMM) experiment.

With the advances of the computational fluid dynamics (CFD), much effort is put in the numerical simulations for manoeuvering purposes[1-6]. The CFD method can be considered as a "numerical rotating arm basin", which can be used to predict the forces and moments directly from the flow field around a submarine model. Gregory[7] put a deformed body in a rectilinear flow to investigate the flow separation over a body of revolution in a steady turning state. The total force on the curved body can account for the case of rotation within 5% of deviation. The results for the moments see a difference of 20% for $R/L=5$ and a difference of 100% for $R/L=3$. Sung et al.[8] simulated the flow around a turning submarine named ONR Body 1. The deviations between the computed forces and moments and those of experiments were within 20%. Zhang et al.[9] performed a computational study of the Series 58, SUBOFF and DRDC STR bare hulls undergoing steady turning maneuvering. They found that the rotation increases the lateral force and reduces the yawing moment relative to a hull in a pure translation at equivalent drift angles. Hu and Lin[10] computed the hydrodynamic coefficients of an autonomous underwater vehicle SMAL01 based on an added momentum source method.

In some investigations[8-10], the submarine rota-

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* Project supported by the National Natural Science Foundation of China (Grant No. 11272213).

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tion was considered in two ways: first, at the inlet of the computational domain, the incident flow varies linearly with the constant turning rate from the center of rotation, second, the Navier-Stokes (NS) equations were adjusted to a body-fixed frame of reference. In doing so, the unsteady flow can be treated as a steady problem. The vehicle could remain stationary in the control volume. It is convenient for meshing and numerical computations. But there are some drawbacks: both the NS equations and the turbulence models should be modified in a rotating coordinate system. Further, in the presence of the background rotation, the solid wall and far field boundary conditions should be treated carefully, which can significantly affect both accuracy and convergence. The gradients of the Cartesian velocity are set to zero, and the pressure is obtained by a non-reflecting condition as suggested by Sung[8]. Since in the physical experiment, the hull rotates through undisturbed fluid, it is intuitive to adopt the inertial frame of reference in solving the NS equations for the submarine motion. The artificial pressure gradient[11] is avoided in simulating the flow field in such a way, and results might be closer to the physical reality. The difficulty of this method lies in the moving boundary. To overcome this difficulty, the dynamic mesh method or the overset mesh method was purposed. Carrica et al.[12] simulated the flow field of a surface combatant in the steady turning state and the PMM test using an overset grid method. Pan et al.[13] applied the dynamic mesh method to simulate the PMM experiment performed on the SUBOFF submarine model.

The aim of the present study is to explore the possibility of developing a numerical method to predict the rotary derivatives of a submarine. The virtual rotating arm basin experiments are conducted using the unsteady RANS solver in an inertial reference system, and the moving boundary of the vehicle is taken into account by the dynamic mesh method. The resultant forces and moments are then post–processed to compute the rotating-related coefficients. The flow field around the rotating submarine is also discussed.

1. Numerical model

1.1 *Description of the model test*

The target studied in this paper is the SUBOFF model. The entity model is a body of revolution, without bow planes, with a sail, two horizontal planes and two vertical rudders, and a ring wing supported by four struts in an “X” configuration. The overall length of the SUBOFF model is 4.356 m, while the length between the perpendicular edges is 4.261 m, and the maximum diameter is 0.508 m.

Generally, the 6 DOF motion of the submarine is described using two coordinate systems. The first is a right-handed, body-fixed coordinate system, with its origin O at a point 2.013 m aft of the forward perpendicular edge on the hull centerline, which is prescribed as the center of the buoyancy (CB). The x-axis points upstream, the y-axis points starboard and the z-axis points downward.

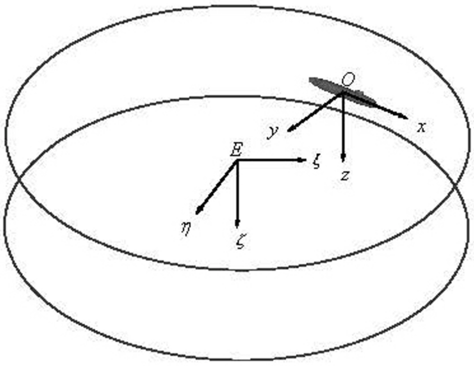

Fig.1 Principal earth-fixed and body-fixed coordinate systems

The second coordinate system, an inertial reference frame, is used to define the motions of the first coordinate system, as shown in Fig.1. In this earth-fixed coordinate system, the position of the vehicle’s CB is then expressed in ξ, η, ζ coordinates. The orientation of the body-fixed coordinate system is described by Euler angles ψ(yaw)), θ(pitch) , ϕ(roll) .

The origin E of the earth-fixed coordinate system is located at the center of the virtual basin, and the model is mounted to a virtual rotating arm which revolves about the axis $E\zeta$. In Fig.1, viewing from above, the model rotates clockwise with a steady angular velocity, r, that implies that the model turns to the starboard. The model’s y-axis coincides with the arm, while x-axis and z-axis are kept normal to the arm. Thus, the transverse velocity component of the model’s CB is always zero and the longitudinal velocity component is equal to its linear speed.

1.2 *Governing equations*

Numerical simulations are performed with the CFD software Ansys Fluent. The flow around the vehicle is modeled using the incompressible, Reynolds averaged Navier-Stokes (RANS) equations:

$$\frac{\partial(u_i)}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t}+\rho u_j\frac{\partial u_i}{\partial x_j}=\rho F_i-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j}-\rho\overline{u_i'u_j'}\right) \tag{2}$$

where t is the time, u_i are the time averaged velo-