Prediction of Hydrodynamic Derivatives of KCS Based on Computational Fluid Dynamics

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Abstract. Aiming at predicting the maneuverability of the ship in shallow water, KCS was selected as the research object. Static drift motion, pure sway motion, and pure yaw motion were performed to calculate the dimensionless hydrodynamic derivatives of KCS. A commercial software, STAR-CCM+ was used to simulate various kinds of movement conditions, by which the force and moment on the hull can be monitored. Then, through the curve fitting, hydrodynamic derivatives of KCS were predicted, and the maneuverability of KCS can be predicted.

Introduction

Ship maneuverability and stability play essential roles in the navigation of the ship. Ships with excellent maneuverability can maintain the direction of movement during straight-line navigation. They can change the course quickly when steering so that they can sail on a predetermined course. The stability of the ship refers to the ability of the ship to not overturn under limited action and to return to normal after the tilting force has disappeared.

Prediction of ship maneuverability has been discussed in recent years. In 1957, A. Goodman and Göttler first designed the Planar Motion Mechanism (PMM), which is mounted on the resistance mechanism of a conventional long-shaped pool to measure the hydrodynamic derivative of the ship. PMM test was initially been used for the testing of submarine models, and later extended to surface vessels, with satisfactory results, has become a routine test method.

In recent years, relevant scholars have estimated the hydrodynamics in the initial stage of ship design by establishing a series of databases. With the rapid development of computer science and technology and the accurate prediction of hydrodynamic maneuverability of ships by computational fluid dynamics (CFD) technology, it is an effective method to calculate linear hydrodynamic derivatives by commercial fluid mechanics software.

Based on the above background, this paper proposes a CFD-based fluid dynamic derivative identification method. In chapter 2, KCS model and calculation method will be introduced. In chapter 3, static drift motion, pure sway motion, and pure yaw motion will be performed. After obtaining the lateral forces and moments of different motions, dimensionless hydrodynamic derivatives can be calculated.

Ship Geometry and Method

Calculation Model

The research object of this paper is the KRISO Container ship with the scale ratio of 1:1. KCS is widely used as a research object. Therefore, many experiments using KCS as models are carried out. The physical model of KCS are shown in Figure 1.
Reference Coordinate System and Symbol Definition

In the study of ship motion, ships are generally considered to be rigid bodies with evenly distributed six degrees of freedom. The posture of the surface vessel in motion can be described as follows: surge, sway, heave, roll, pitch, and yaw, which is shown in figure 2.

Table 1. Parameters of KCS (actual model).

| Parameters                        | Value   |
|-----------------------------------|---------|
| Length between the perpendiculars | 230m    |
| Length of waterline               | 232.5m  |
| Depth                             | 19.0m   |
| Design draft                      | 10.8m   |
| Displacement                      | 52030 m³|
| Block coefficient                 | 0.651   |
| Froude number                     | 0.26    |
| Reynolds number                   | 2.1×10⁹ |

Table 2. The Symbol of Ship’s Six Degree-of-freedom.

| Degree of freedom | Force and moment | Velocity and angular velocity | Location and Euler Angle |
|-------------------|------------------|------------------------------|--------------------------|
| Surge             | X                | u                            | x                        |
| Sway              | Y                | v                            | y                        |
| Heave             | Z                | w                            | z                        |
| Roll              | K                | ρ                            | φ                        |
| Pitch             | M                | q                            | θ                        |
| Yaw               | N                | r                            | ψ                        |

Mesh Simulation

In the mesh simulation, the prism layer mesh is selected for meshing. The background extends to \(-2.0L_{WL} < x < 3.0L_{WL}, -1.5L_{WL} < y < 1.5L_{WL}, -0.5L_{WL} < z < 1.0L_{WL}\). The grids used are all unstructured grids, which are characterized by automatic generation by computer, saving the time taken by manually dividing the grid. The overall mesh distribution is shown in Figure 3.
Test Design and Calculation Results

PMM test exerts sway, surge, and yaw motion on the ship model, and it can be used to obtain the hydrodynamic coefficients of the ship. The simulation is based on the following working conditions: static drift movement, pure sway movement, and pure yaw movement.

Static Drift Movement

The ship's static drift motion is a uniform linear motion with the bow at a certain angle to the speeding direction of the ship. As shown in Figure 4, where $\beta$ represents the angle of drift movement.

$$
\begin{align*}
\psi &= 0 \\
r &= 0 \\
y &= a_0 \sin \omega t \\
v &= \dot{y} = a_0 \omega \cos \omega t \\
\dot{v} &= \ddot{y} = -a_0 \omega^2 \sin \omega t
\end{align*}
$$

(1)

Pure Sway Movement

In the test of pure sway simulation, the hull body is restricted to sway, and the other motions are restricted in simulation. And the diagram of pure sway motion is shown in Figure 5. By simulating sway motion and curve fitting at different oscillation frequencies, we can obtain dimensionless hydrodynamic derivatives $Y_v', N_v'$, $N_v''$ and $N_v'''$ at zero frequency.

$$
\begin{align*}
\psi &= 0 \\
r &= 0 \\
y &= a_0 \sin \omega t \\
v &= \dot{y} = a_0 \omega \cos \omega t \\
\dot{v} &= \ddot{y} = -a_0 \omega^2 \sin \omega t
\end{align*}
$$

(1)
Where, \( \psi \) is yaw angle in simulation, \( r \) is angular velocity of yaw in simulation, \( a_0 \) is the amplitude of simple harmonic motion, \( \omega \) is the frequency of simple harmonic motion.

When pure sway movement of the ship is simulated at a different frequency, the longitudinal velocity and the amplitude of the model in pure sway motion are all set as fixed values.

The Abkowitz maneuvering equations in the pure sway movement can be expressed as:

\[
\begin{align*}
Y &= Y_v + Y_{v\dot{v}} + Y_{vvv}v^3 \\
N &= N_v + N_{v\dot{v}} + N_{vvv}v^3
\end{align*}
\]

The dimensionless processing of each parameter is:

\[
\begin{align*}
Y' &= Y_v' / 0.5 \rho V L^2, \\
N' &= N_v' / 0.5 \rho V L^2
\end{align*}
\]

Substitute equation (1) into equation (2):

\[
Y = Y_v + Y_{v\dot{v}} + Y_{vvv}v^3 = Y_{c1} \cos \omega t + Y_{c2} \sin \omega t + Y_{c3} \cos 3\omega t
\]

\[
N = N_v + N_{v\dot{v}} + N_{vvv}v^3 = N_{c1} \cos \omega t + N_{c2} \sin \omega t + N_{c3} \cos 3\omega t
\]

Where, \( Y_{c1} = -\left(Y_{v\max} + \frac{3}{4} Y_{vvv\max}\right) \), \( Y_{c2} = Y_{v\max} '\), \( Y_{c3} = -\frac{1}{4} Y_{vvv\max} '\), \( N_{c1} = -\left(N_{v\max} + \frac{3}{4} N_{vvv\max}\right) \), \( N_{c2} = N_{v\max} '\), \( N_{c3} = -\frac{1}{4} N_{vvv\max} '\).

**Pure Yaw Movement**

As for pure yaw motion, the surface vessel superimposes lateral low frequency oscillatory motion and periodic tilt angle changes when moving longitudinally. By simulating pure yaw movement at different frequencies, \( Y_v' \), \( Y_{v\dot{v}}' \), \( N_v' \) and \( N_{v\dot{v}}' \) are finally predicted.

\[
\begin{align*}
y &= y \sin \omega t \\
v &= \dot{y} = a \omega \cos \omega t \\
\dot{v} &= \ddot{y} = -a \omega^2 \sin \omega t
\end{align*}
\]

Where, \( a \) is the amplitude of lateral movement during pure yaw motion. And \( \omega \) is the angular frequency of pure yaw motion. Moreover, the law of corresponding harmonic motion for yaw angle \( \psi \) is shown as follows:

\[
\begin{align*}
\dot{\psi} &= \psi_0 \cos \omega t \\
\dot{r} &= \psi_0 \sin \omega t \\
\dot{\psi} &= -\omega \psi_0 \cos \omega t
\end{align*}
\]

\( \psi_0 \) is yaw angle, and \( r \) is the angular velocity in pure yaw motion.

The amplitude of lateral movement in pure yaw motion is fixed at \( a = 10 \text{ m} \), and the frequency of yaw movement is taken as follows: 0.02Hz, 0.05Hz, 0.08 Hz, and 0.10 Hz. In pure yaw motion, the ship's hydrodynamic equation can be represented as:

\[
\begin{align*}
Y &= Y_v + Y_{v\dot{v}} + Y_{vvv}r^3 \\
N &= N_v + N_{v\dot{v}} + N_{vvv}r^3
\end{align*}
\]
The dimensionlessness of the obtained hydrodynamic derivative is expressed as:

\[
\begin{align*}
Y'_\ell &= Y_\ell / 0.5 \rho V L, \\
Y'_r &= Y_r / 0.5 \rho L^2, \\
Y''_m &= Y''_m / 0.5 \rho V^{-1} L^3, \\
N'_r &= N_r / 0.5 \rho V L^2, \\
N''_r &= N''_r / 0.5 \rho V^{-1} L^6.
\end{align*}
\]

After all the simulation performed, hydrodynamic derivatives of KCS were obtained.

Table 3. The results of Hydrodynamic derivatives in static drift simulations (x e-3).

| Drift Angle | Lateral Force CFD | Lateral Force EFD | Yaw Moment CFD | Yaw Moment EFD |
|-------------|------------------|------------------|---------------|---------------|
| 0           | 0.01             | 0.005            | 0.02          | -0.03         |
| 2           | 0.14             | -                | 0.13          | -             |
| 4           | 0.32             | -                | 0.27          | -             |
| 6           | 0.57             | 0.61             | 0.38          | 0.34          |
| 8           | 0.88             | -                | 0.51          | -             |
| 10          | 1.23             | -                | 0.60          | -             |
| 12          | 1.61             | 1.64             | 0.73          | 0.75          |

Table 4. Hydrodynamic derivatives in pure sway simulations (x e-3).

| Derivatives | CFD   | EFD   | Deviation% |
|-------------|-------|-------|------------|
| \( Y'_r \)  | 0.14  | 0.136 | 2.9%       |
| \( N'_r \)  | 0.063 | 0.060 | 5%         |
| \( Y'_r \)  | -4.0  | -4.1  | 2.5%       |
| \( N'_r \)  | -2.1  | -     | -          |

Table 5. Hydrodynamic derivatives in pure yaw simulations (x e-3).

| Derivatives | CFD   | EFD   | Deviation% |
|-------------|-------|-------|------------|
| \( Y'_r \)  | -0.075| -0.026| 188%       |
| \( N'_r \)  | -0.11 | -0.06 | 83%        |
| \( Y'_r \)  | 0.052 | 0.084 | 38%        |
| \( N'_r \)  | 0.023 | 0.056 | 59%        |

**Conclusion**

The prediction of ship hydrodynamic derivative is of vital importance for ship maneuverability. In this paper, the CFD method is used to predict the dimensionless hydrodynamic derivatives from static drift movement, pure sway movement, and pure yaw movement.

The results of CFD are constant with the results in EFD (HHI) in static drift and pure sway motion, which indicates that RANS simulation has shown good results in ship motion simulation and maneuverability analysis. As for pure yaw movement, significant deviations are found between simulation and test results. However, due to the limited number of the differences observed between the test data, their reliability may be uncertain.
In general, the results are convincing enough to show that CFD simulation has considerable development space in ship maneuverability prediction.

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