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Investigation of the hydrodynamic model test of forced rolling for a barge using PIV

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Abstract: In order to study the physical details of viscous flow in ship roll motions and improve the accuracy of ship roll damping numerical simulation, the application of the Particle Image Velocimetry (PIV) technique is investigated in model tests of forced ship rolling in calm water. The hydrodynamic force and flow field at the bilge region are simultaneously measured for barges at different amplitudes and frequencies in which the self-made forced rolling facility was used. In the model test, the viscous flow variation with the time around the bilge region was studied during ship rolling motion. The changes in ship roll damping coefficients with the rolling amplitude and period were also investigated. A comparison of the model test results with the Computational Fluid Dynamics (CFD) results shows that the numerical ship roll damping coefficients agree well with the model test results, while the differences in the local flow details exist between the CFD results and model test results. Further research into the model test technique and CFD application is required.

Key words: Particle Image Velocimetry (PIV); Computational Fluid Dynamics (CFD); ship roll motion; roll damping coefficients; flow field measurements

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0 Introduction

Ship roll motion is a key index to indicate the navigation performance of ships sailing in waves. At present, International Maritime Organization (IMO) is developing the second generation intact stability criteria [1] in which ship roll motion with large amplitude is arising widespread concerns in shipbuilding industry for its influence on three dynamic stability problems in waves, including parametric rolling, dead ship stability and excessive acceleration. The roll damping is a significant factor influencing the ship roll motion while its accurate estimation has become one of crucial problems in the hydrodynamics study due to the complicated fluid vortex effect. However, the traditional hydrodynamic model test of ship rolling is often concerned with the quantitative acquisition of the roll damping coefficients, while ignoring the qualitative observation of physical details of disturbance flow.

With the development of flow display technology, Particle Image Velocimetry (PIV) technology has been widely used in tank test for its competent monitoring performance in fine flow field. The technology can also be applied in the hydrodynamic tests of ship roll damping to monitor the physical phenomena

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closely related to ship roll performance such as flow separation and vortex escape from the bilge of the hull, which has become an important technology researching the physical characteristics of hydrodynamic force and assisting numerical modeling.

At abroad, PIV has enjoyed an earlier development and wide application in tank test. Bassler et al.[2] conducted the hydrodynamic tests of forced ship rolling at large amplitudes for the midship section of DTMB 5699, and studied the hydrodynamic damping law of ship roll motion during the process of large amplitudes through the tests of hydrodynamic load at bilge keel region and fine flow field of PIV at bilge region. Kawata and Obi[3] obtained the velocity information of the turbulent field by PIV system, and studied the velocity-pressure correlation. Irkal et al.[4] carried out a free attenuation roll test on a rectangular cross-section of a hull in the tank. In this experiment, PIV was introduced to test the viscous flow field at the bilge region during the ship rolling, and to study flow field characteristics under bilge keel in different sizes and configurations. The results are compared with those of the CFD simulation.

In China, PIV technology has been applied in the research of hydrodynamic flow field relatively late, but it has developed rapidly in recent years. For example, Li et al.[5] demonstrated the feasibility of PIV technology in this field by successfully carrying out the propeller test research in a large cavitation tunnel under uniform flow. Based on PIV technology, Qie et al.[6] studied the vortex field characteristics around different forms of breakwater under the action of regular waves. Currently, the domestic introduction of the PIV technology in the ship model tank test has received little attention in literature, and by now there is no record about PIV in the hydrodynamic model test of flow field of ship rolling.

Nowadays, Computational Fluid Dynamics (CFD) technology has seen rapid development in the ship hydrodynamics research, which can provide physical information[7] of each location in the flow field, such as turbulence intensity, Reynolds number, vortex intensity and flow velocity vector. CFD makes it convenient to compare these results with those of the tank test so as to understand flow field characteristics better. Zhou et al.[8] used three-dimensional viscous flow analysis software to simulate the free attenuation roll motion of four different types of ships at zero speed. The numerical results were verified by model test, which indicated that CFD has a good applicability in ship roll damping prediction. Begovic et al.[9] adopted CFD technology to analyze the zero-speed free attenuation roll damping in the case of complete and broken DTMB 5415 standard model, and analyzed the sensitive factors such as grid, time step and turbulence model. Yildiz et al.[10] conducted a forced rolling hydrodynamic test for the midship section of S60 under limited water depth, and analyzed the accuracy of CFD results and the Ikeda empirical formula on the basis of the test data.

In this paper, the application of PIV technology is investigated in model tests of forced ship rolling, which is carried out in the towing tank of ship model in Harbin Engineering University. In this experiment, the physical information of the disturbance flow field is accurately measured by adopting the advanced PIV system, and the ship roll motion characteristics are investigated by processing the trace particle images to obtain the visual display of the flow separation and vortex escape from the bilge of the hull when the ship roll motion is being carried out. Qualitative and quantitative comparison of the results will be drawn by numerical simulation of commercial CFD software.

1 Working principle of PIV and its system composition

1.1 Working principle of PIV

PIV technology, combined with the research results of optical technology, image processing technology and computer technology, not only provides real-time physical information of full flow field by means of professional equipment to achieve the precise measurement of the entire flow field, but also offers a wealth of space information of flow field and flow information such as velocity vector, streamline and vortex.

The tests based on PIV technology mainly include:

1) The trace particles are evenly arranged in the flow field, whose movement reflects the movement of the fluid particles at the corresponding positions in the flow field.

2) The surface of the measured flow field is irradiated with a sufficiently strong natural light or laser light source. Particle images with 2 successive exposures or multiple exposures are recorded by a CCD camera or other imaging system due to the scattering effect of particles on light.

3) According to the distance and pulse time interval between the same particle in adjacent particle images, the velocity field of the whole monitoring do-

main is processed.

4) Information of flow field such as vorticity field can be obtained after the processing of the velocity field data.

1.2 PIV system composition

It can be seen from the above part that PIV system is mainly composed of trace particles, imaging system and image processing system.

1) Trace particles.

The following conditions need to be satisfied: uniform dispersion, good liquidity and tracking, good reflection, and equivalent particle weight and fluid density. Among them, "good liquidity and tracking" requires a small particle radius, and "good reflection" requires a relatively big particle radius. Therefore, various factors need to be taken into account when the particle that can achieve the best overall effect is selected.

2) Imaging system.

The system includes a dual pulse laser light sheet, a lens and a camera. When the beam generated by the laser is scattered through the lens to form a light sheet of about 1 mm into the area to be measured in the flow field, the CCD camera aligns the area from the direction perpendicular to the light sheet. Then two or more pulsed laser images of the particles can be recorded by trace particle's scattering effect on light so as to form two PIV films in the identical area but at different moments.

3) Image processing system.

The velocity field is extracted from the particle images which will be first divided into several small regions (query area). Then, the size and direction of the particle displacement in the query area are obtained by using the cross-correlation method or autocorrelation method. Since the pulse time interval of the pulsed laser light sheet is constant, the velocity vector of the particles can be calculated. In this way, the velocity vector field of the whole flow field will be obtained.

2 Conditions and content of hydrodynamic test of forced ship rolling

2.1 Test conditions and equipment

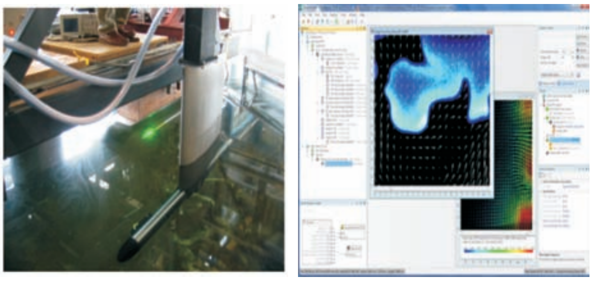
The test is carried out in the towing tank of ship model in Harbin Engineering University. The tank conditions and test equipment are shown in Figs. 1 and 2. The parameters of the test tank and the equipment of the PIV system are given as below.

(a) Towing tank

(b) Carriage

Fig.1 Towing tank and carriage in Harbin Engineering University

(a) Torque and angular displacement data collection system (left) and underwater PIV measuring system(right)



(b) Underwater PIV equipment (left) and Dynamic Studio Image data analysis software (right)

Fig.2 PIV equipment and data collection system

2.1.1 Conditions and main parameters of the test tank

1) The length, width and depth of the towing tank are 108 m × 7 m × 3.5 m.

2) The speed range of the carriage is 0.1–6.5 m/s, with an accuracy of 0.1%.

3) The system model used for data collection, analysis and processing is DEWE2010, with 16 bit precision.

The carriage equipped with sensor and data acquisition system can collect the data such as angular displacement, force and torque of the ship model in the roll test, which, after being processed, will help to produce the roll damping coefficients of the ship model at each frequency and amplitude.

2.1.2 PIV system equipment and the main technical indicators

In the hydrodynamic model test of forced rolling of the ship model, the flow field near the bilge of the hull is monitored by the vehicle-mounted PIV system, and details of the flow field such as the velocity field and vorticity field are obtained. The equipment and its main technical indicators are as follows.

1) CCD camera resolution: 2 048 × 2 048 pixels;

2) Maximum pulse energy of laser: 1 200 mJ;

3) Laser beam duration: 4 ns;

4) Laser wavelength: 532-1 064 nm;

5) Light sheet thickness: 0.6 mm;

6) Measurement area size: 400 mm × 400 mm;

7) PIV trace particles: polyamide trace particles (PSP-50 μm);

8) Data analysis equipment for PIV wave-making measurement experiment: Dynamic Studio (Smart Software for Imaging Solutions).

2.2 Test objects and parameters

The test object is a glass-steel barge model. In order to simplify the influence of the ship model, the cross-section of the barge is rectangular, the draft and the width remain unchanged along the length direction of the ship, and the light-ship mass is 56.1 kg. The principal dimensions of the ship model after ballast trimming are shown in Table 1.

Table 1 Principal dimensions of ship model

Items	Model size
Ship length L/m	3
Molded breadth B/m	0.4
Draft T/m	0.20
Moulded depth H/m	0.4
Displacement D/kg	244.8
Axis location of roll motion(away from the baseline of the ship model) z_0 /m	0.15

The test roll amplitudes are 0.06, 0.11 and 0.24 rad, and the forced roll test is carried out at the main possible frequencies. The results of the test are processed to obtain the damping coefficients under different amplitudes and frequencies, as well as the velocity vector and vorticity contours of the flow field under each working condition.

2.3 Test process

The test of forced ship rolling in calm water is a basic test to evaluate the roll performance of a ship. The hydrodynamic characteristics of the ship rolling and the nonlinear damping coefficient at large rolling can be measured over the entire oscillation frequency range. In the test, the ship model is placed in a balanced manner, and the self-developed forced rolling device is adopted to enable the ship for simple harmonic roll motion in the given amplitude and oscillation frequency around the fixed shaft.

The form of the forced roll motion of the ship model is:

$$\theta = \theta_0 \sin(\omega t) \tag{1}$$

where θ_0 stands for the forced roll amplitude of the ship model; ω is the roll circular frequency.

The data acquisition in this experiment is divided into two parts that are carried out at the same time. The first part is the flow field information collection, which will be completed by PIV system; the second part is the measurement of roll angle and torque, which will be completed by vehicle sensors and data acquisition system.

Fig. 3 presents the schematics for forced roll motion equipment, and Fig. 4 shows the PIV viscous flow field measurement system for forced roll motion. The forced roll motion equipment consists of a fixed device (1), a control and drive device (2), a crank guide mechanism (3), a rod drive mechanism (4), a force measuring and torque balance (5). PIV pulsed laser light sheet is located on one side of the ship model, measuring the flow of the flow field through continuous emission of laser. In the test, the trace particles are scattered in the flow field, and the flow field near the bilge of the ship model is irradiated with the pulsed laser light sheet. The particles are recorded on the CCD camera negatives by two continuous exposures. The sequence of frames in the region is extracted, and the time interval between two adjacent images is recorded. Then, the image correlation analysis is carried out by using Dyanmic Studio software in Fig. 2 to obtain the particle images so as to get velocity contour near the bilge of the ship model. The vorticity contour near the bilge of the ship model is calculated using the TECPLOT post-processing software based on the velocity contour obtained from the Dynamic Studio analysis. The laser pulse interval for the hydrodynamic model test of forced rolling is 0.135 s.

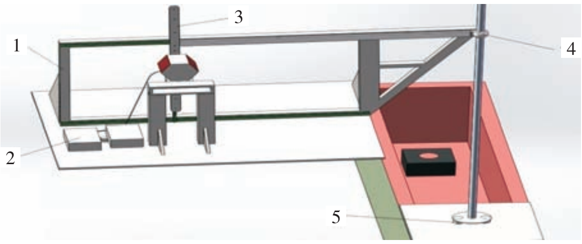


Fig.3 Schematics for forced roll motion equipment

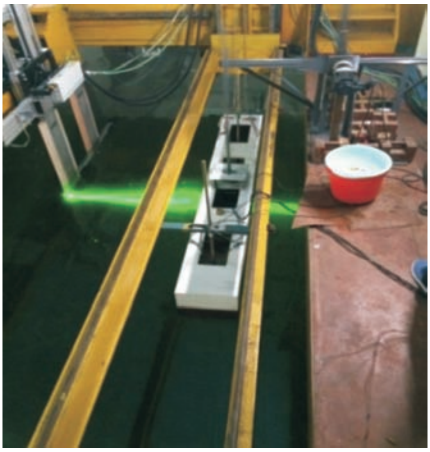


Fig.4 PIV viscous flow field measurement system for forced roll motion

3 Results and discussion

According to the hydrodynamic data obtained by aforementioned test, the damping coefficient can be calculated. Meanwhile, it is compared with the CFD results to verify the accuracy of the CFD method. Finally, the comparison between the flow field information of the two will be drawn.

3.1 Tank test results

This section will give the results of the hydrodynamic roll motion and flow field information, and then penetrate into deep analysis. Fig. 5 presents the roll damping coefficients of the ship model under three roll amplitudes based on the tank test data, in which the ordinate B_{44} is the non-dimensional roll damping coefficient.

As seen from the figure, when the roll angle is constant, the non-dimensional roll damping coefficient increases with the increase of roll frequency of the ship model on the whole. The increased rate is determined by the roll angle, and the larger the roll angle, the greater the damping coefficient. This phenomenon is consistent with the actual experience that the greater the angle and the speed of the ship rolling are, the more obvious the damping effect of the fluid becomes. During the test process, restricted by the mechanism design, this paper does not carry out roll damping test over 0.24 rad (about 13.75°). At large amplitudes of ship rolling, as ship roll damping is influenced by the processes of water entry and water exit at the bilge area and free surface effect, the hydrodynamic damping coefficient is more complicated with the fluctuation of the amplitude and oscillation frequency, whose specific rules need further model test and theoretical analysis. It should be noted that the analysis conclusion drawn from Fig. 5 does not apply to the larger amplitude situation that is not discussed in this paper.

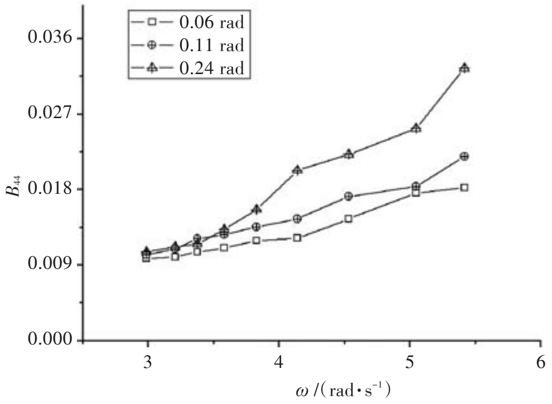
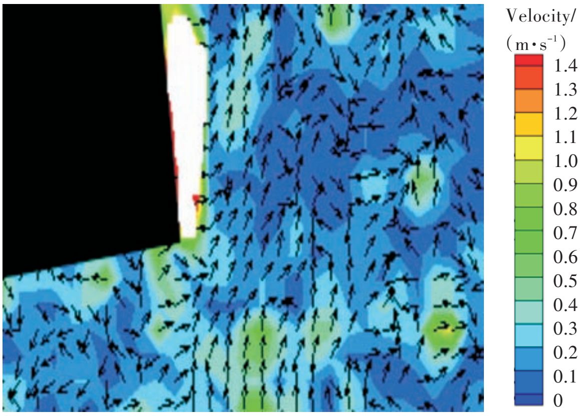


Fig.5 Variation of non-dimensional roll damping coefficients with respect to roll frequencies and amplitudes

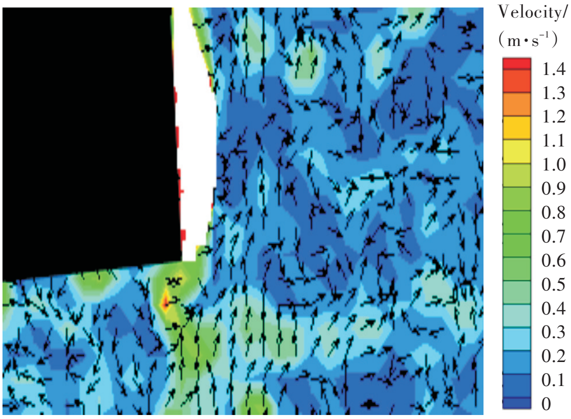
Fig. 6 shows the velocity vector of the flow field near the cross section of the hull measured by PIV. The selected test parameter is the roll amplitude of 0.06 rad with the roll period of 1.24 s.

In the velocity contour, the arrows indicate the velocity direction of the flow field at the fluid position where the particles are located, and the colors differ in the size of the velocity. From the velocity contour of t = 0.27 s to t = 1.08 s (the left side in Fig. 6), it can be seen that as the ship rolls to different angles, the phenomenon of flow separation emerges in the flow field near the bilge of the hull and a vortex appears at the bilge of the hull, which is reflected in the more irregular and vortex-like velocity vector near the bilge compared with those around the bilge. Moreover, it can be recognized from the velocity contour that the color of the velocity in the flow field near the bilge is deeper than that of the other areas, that is, the velocity is larger, which proves that the flow velocity should be relatively faster near the bilge in roll motion.

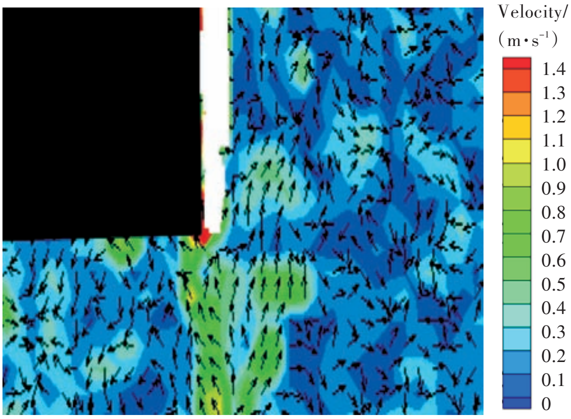
Through the observation of PIV flow field information diagram, it is found that the flow velocity at the



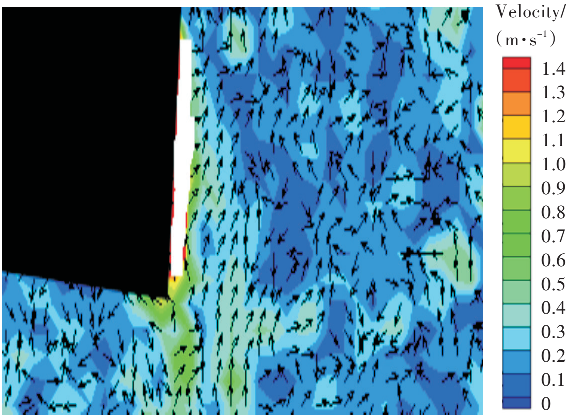
(a) t=0.27 s



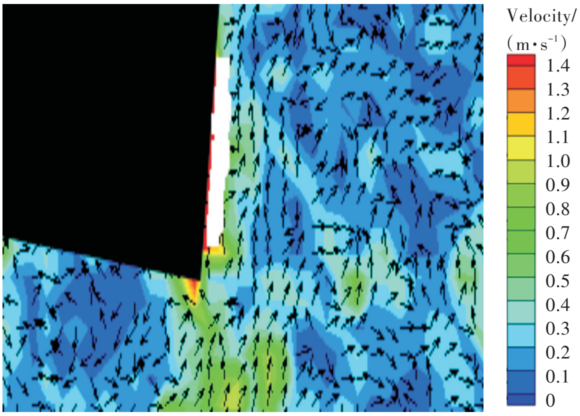
(b) t=0.405 s



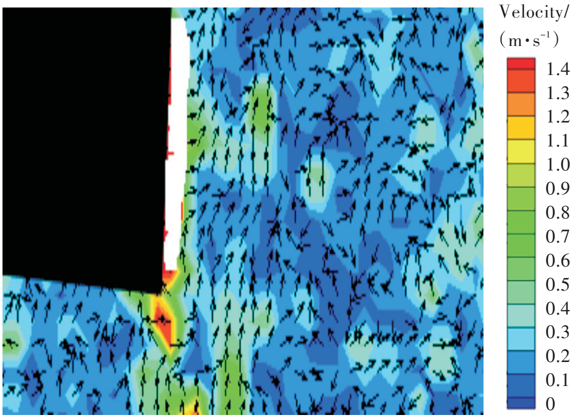
(c) t=0.54 s



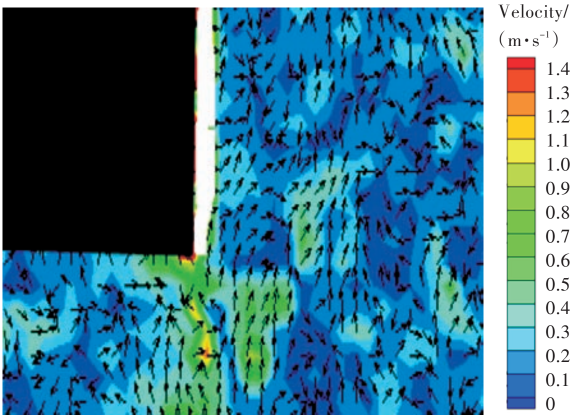
(d) t=0.675 s



(e) t=0.81 s



(f) t=0.945 s



(g) t=1.08 s

Fig.6 Flow velocity contours near the ship model's bilge at different time within one period

bilge is larger than that of other parts during a period of motion, and the obvious vortex appears near the bilge; the vortex shedding phenomenon mainly concentrates in the corner. With the roll motion proceeding, the vortex at the corner gradually produces, separates, and then falls off, which continues alternately. In addition, it is also noted in Fig. 6 that there are some blank spaces in the flow field information of ship bilge, and the reason is that during the model test, the phenomenon of light reflection emerges on the surface of the hull, which affects the local area particle image test results and the subsequent analysis of velocity flow field, leading to the distortion in the region test flow field, thus the relevant information is wiped. An effective solution to this problem is to perform more efficient painting operations on the hull surface, and the relevant model test techniques will be studied in subsequent experiments.

3.2 CFD numerical simulation results

Firstly, the hydrodynamic coefficients of the ship rolling obtained by the tank test and the CFD method are compared to quantitatively verify the effectiveness of the CFD method.

The basic principle of calculating the damping coefficient of the forced rolling of the ship model by the CFD method is presented in brief as follows.

For the two-dimensional numerical simulation of single-degree-of-freedom forced rolling, the form of the forced roll motion is the same as that of the model test, as shown in Eq. (1).

Through the UDF compiler, the dynamic pressure p_{d} is integrated along the hull surface after the gravity effect is eliminated from the numerical hydrodynamic field of forced rolling, thus the forced roll torque M_{d} is obtained.

M_{d} is decomposed into inertia term and damping term, namely:

$$M_{\mathrm{d}} = -A_{44}\ddot{\theta} - B_{44}\dot{\theta} \tag{2}$$

where A_{44} is additional mass coefficient of the ship rolling.

The additional mass coefficient of the ship rolling A_{44} and non-dimensional roll damping coefficient B_{44} can be obtained by the forced roll torque M_{d} that is calculated based on the CFD. The methods include Fourier series expansion method, least squares fitting of hydrodynamic load time history, etc. However, it should be noted that the obtained numerical results of roll additional mass coefficient and damping coefficient will be varied as data processing method changes, even for same load time history. In particular, the processing method will have stronger effect on the processing result of damping coefficient with relatively small magnitude in the time history of hydrodynamic load.

The method used in this paper belongs to the least squares fitting in the time history of hydrodynamic load. To minimize the error that would occur in the data processing process, the results of multiple roll periods within the time period when the CFD simulation is more stable are selected to simulate the roll damping coefficient in the specific data fitting process.

The specific form of the data fitting of the roll torque M_{d} obtained by the numerical simulation is as follows:

$$M_{\mathrm{d}} = M_0 \sin(\omega t + \gamma) \tag{3}$$

where M_0 is the amplitude of the roll torque; ω and γ are frequency and phase angle respectively. The variation period of the roll torque is consistent with the roll period.

By comparing Eq. (2) with fitted Eq. (3), it can be obtained that:

$$\begin{aligned} A_{44} &= M_0 \cos\gamma / \theta_0 \omega^2 \\ B_{44} &= -M_0 \sin\gamma / \theta_0 \omega \end{aligned} \tag{4}$$

According to the above principles, viscous flow simulation of forced rolling based on Renault Average Navier-Stokes (RANS) can be carried out to calculate the roll damping coefficient by taking into consideration the reasonable division of the flow field grid, and the definition of turbulence model, the number of grids, boundary conditions and initial conditions. This part will not be discussed in detail and readers can refer to Reference [11], which describes the simulation details of the two-dimensional forced roll test in the FLUENT software and performs the validation of numerical simulation.

Fig. 7 presents the comparison of non-dimensional roll damping coefficients between CFD numerical simulation and experimental results. It can be seen from the figure that the two are in good agreement with each other, which indicates that CFD numerical simulation is an effective method for hydrodynamic damping analysis of ship roll motion.

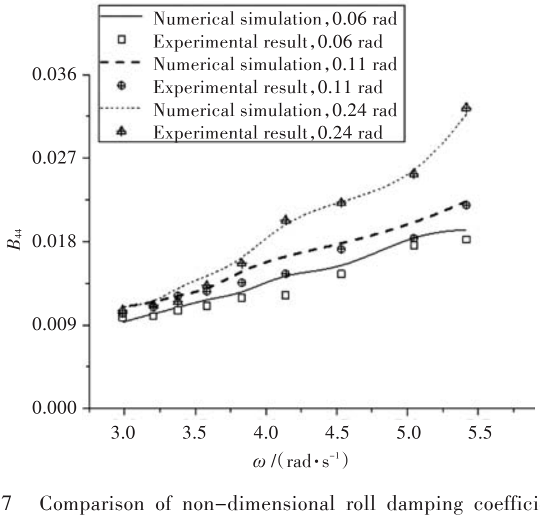
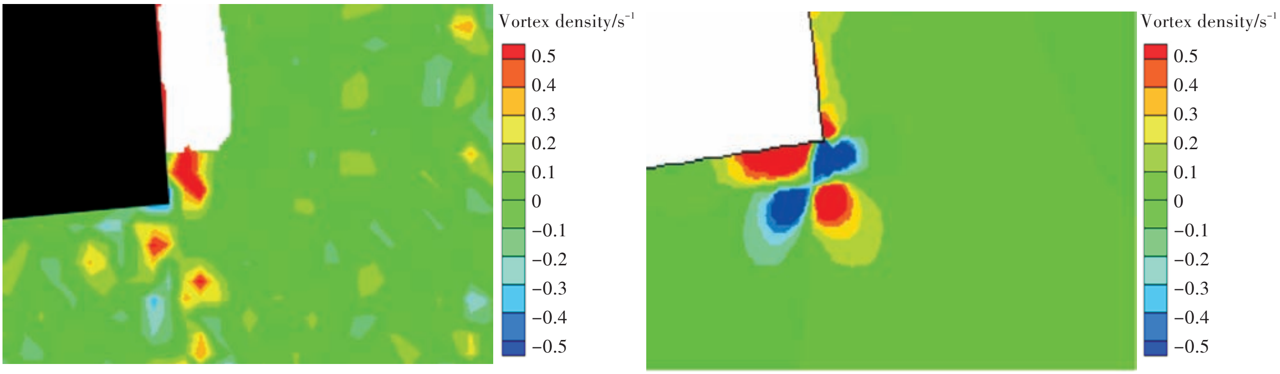
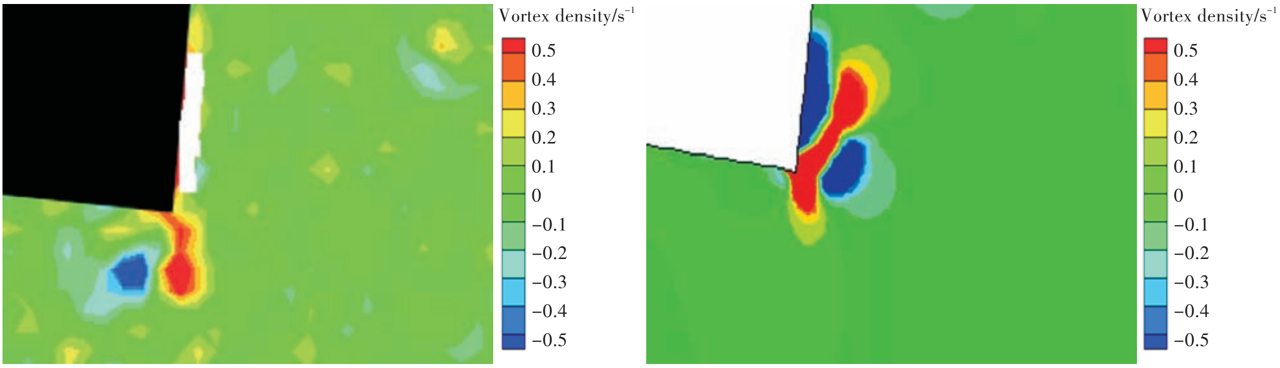


Fig.7 Comparison of non-dimensional roll damping coefficients between CFD numerical simulation and experimental results

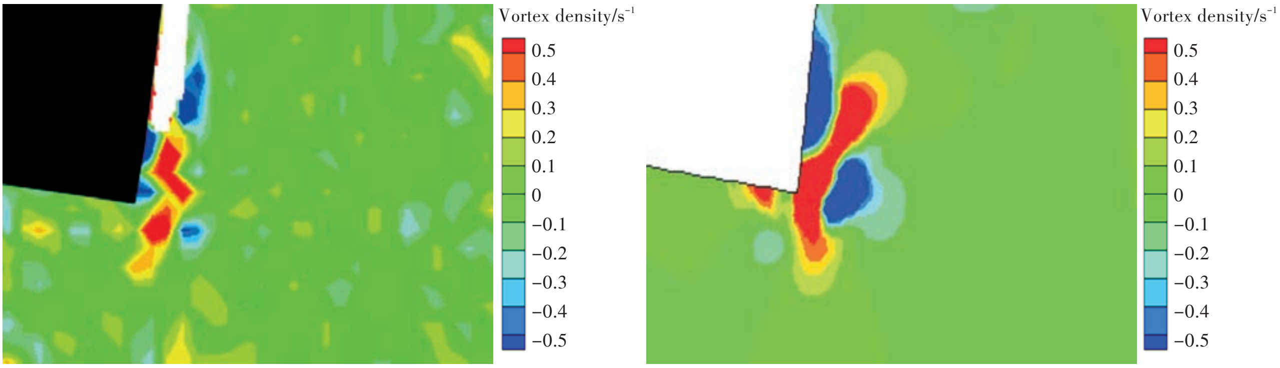
Fig. 8 shows the comparison of vorticity contours between PIV measurement and CFD simulation. It can be seen from the figure that the numerical results also capture the flow separation and vortex escape from the bilge of the hull, which is similar but not completely consistent with that of the test flow field. In this paper, a detailed comparison of the numerical flow field and the details of the test flow field is carried out for the multiple test conditions in model test. In general, the numerical simulation results have certain gaps with the model test results in the flow field details at the bilge of ship. The coinci-



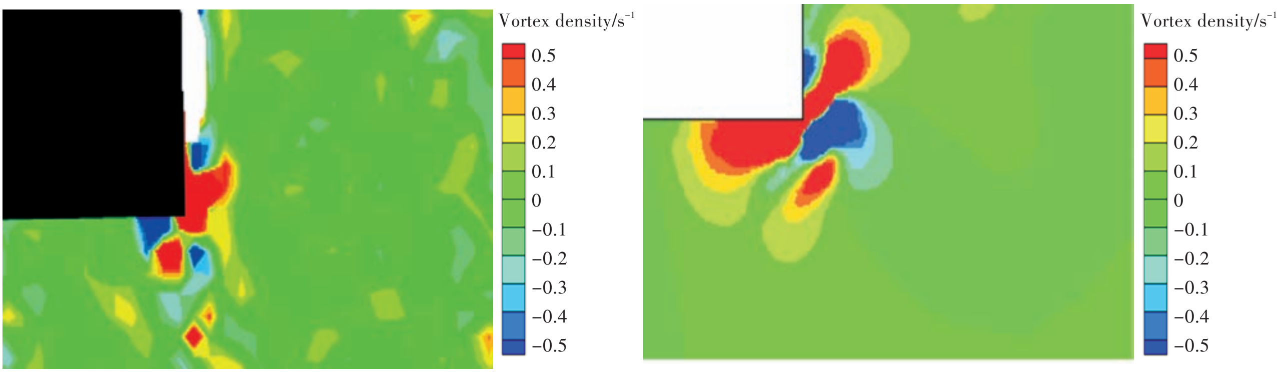
(a) t=0.27 s



(b) t=0.81 s



(c) t=0.945 s



(d) t=1.08 s

Fig.8 Comparison of vorticity contours between PIV measurement (left) and CFD simulation (right) dence degree is inferior to that of the comparison results shown in Fig. 7. There is more than one reason responsible for this phenomenon according to analysis, such as fine degree of viscous flow field simulation with CFD turbulence model at the bilge of ship, repeatability verification of model test flow field and transient change characteristics of unsteady rolling flow field, and thus further study is needed.

4 Conclusions

In this paper, the PIV flow field test technology is applied to the analysis of hydrodynamic fine flow field test of ship roll motion at large amplitude. In the hydrodynamic model test of forced rolling conducted in towing tank, roll hydrodynamic damping coefficient and the flow field details of the bilge in the hull are obtained. The relative results are horizontally compared with those of the CFD numerical simulation, and the main conclusions are as follows:

1) Based on PIV test, the viscous flow field of the forced rolling in the bilge is obtained. The flow velocity distribution and the generation and shedding of vortex during the oscillation period are presented, and the local characteristics of the hydrodynamic flow field are revealed, which can be used to verify CFD numerical simulation results.

2) For the zero-speed barge, the CFD numerical simulation of the roll damping coefficient and the model test results are compared within the largest test amplitude of 13.75°. The results show that the two are in good agreement, which indicates that CFD simulation technique can effectively capture the hydrodynamic viscosity effect in the process of rolling on the whole.

3) Through comparison between CFD simulation and PIV test result for local details of viscous flow field of forced rolling for a barge in the bilge region, it can be found that certain differences exist between them on the whole, which shows that the fine simulation of local details of viscous flow field of ship roll motion is more difficult than the overall simulation of viscous damping. In order to achieve more consistent results between CFD simulation and PIV test, further research is needed on the basis of turbulence model selection and model test techniques.

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PIV技术在某驳船模型强迫横摇水动力测试中的应用

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摘　要:[**目的**]为研究船舶横摇过程中粘流场细节以提高横摇阻尼数值模拟精度,[**方法**]开展了粒子图像测速(PIV)技术在静水强迫横摇水动力测试中的应用研究。首先,采用自制的强迫横摇装置在水池中开展某驳船在不同摇幅和振荡周期下船舶横摇水动力与舭部流场的同步测试。观测舭部粘流场在船体振荡过程中的变化规律,研究横摇阻尼系数随摇幅和周期的变化规律。然后,将模型试验测试结果与计算流体动力学(CFD)软件模拟结果进行对比。[**结果**]结果表明,CFD预报船舶横摇整体阻尼系数精度较好,但预报的局部流场细节与模型试验测试结果间存在一定的差异,[**结论**]需在模型试验技术和CFD预报技术上开展进一步研究。

关键词:粒子图像测速; CFD; 横摇运动; 横摇阻尼系数; 流场测量

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新概念高速穿梭艇系列船型及其直航性能

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摘　要:[**目的**]为了将高速与高耐波性能相结合,上海交通大学开发了高速穿梭艇系列复合船型,目前已发展出单体、双体和三体船型。[**方法**]介绍高速穿梭艇系列船型的新进展和船型设计特点,并通过数值水池实验对高速穿梭艇系列船型在静水中的直航性能进行研究。数值水池通过求解URANS方程和采用重叠网格技术来预报船体受力和运动。[**结果**]数值水池实验结果表明,高速穿梭艇系列船型具有优良的快速性和航行姿态,船体兴波和飞溅随船型的不同而有所差异。[**结论**]展示了多种创新的船舶设计方案,可为研究人员提供定量和定性的参考。

关键词:高速穿梭艇; 船型开发; 高性能船舶; 直航性能; 数值仿真