Numerical analysis of bilge keels effects on the rolling motion of a ship

Tian Luo, Decheng Wan*

Dtate Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration
Shanghai,China
* Corresponding author: dcwan@sjtu.edu.cn

ABSTRACT: It is a huge challenge to accurately simulate rolling motions of ships due to the tremendous effect of viscosity. In this paper, the simulations for rolling motions of the 3D ship models DTMB5512 with and without bilge keels were carried out by naoe-FOAM-SJTU solver based on OpenFOAM. The naoe-FOAM-SJTU solver utilized the Reynolds Averaged Navier Stokes (RANS) method. The results of free decay rolling motions were compared with the experimental data to ensure the reliability of the calculations, and the results showed that the bilge keels increased the natural period and reduced the roll angle for free decay rolling motions. For forced rolling motion, the results showed that bilge keels reduced the maximum of the damping moments.

KEY WORDS: Rolling motions; RANS; naoe-FOAM-SJTU solver; bilge keels.

INTRODUCTION

Simulations of ship motions is of great importance to the ship design and researches. However, it is difficult to accurately predict ship rolling motions. The viscosity exerts a great influence on rolling motions, resulting in lots of non-linear terms in the calculations. Thus, the traditional potential theory can't be utilized to predict rolling motions. The damping coefficient is a key factor in the description of ship rolling motions. Generally speaking, rolling damping coefficient is added up by: (1) friction damping coefficient, (2) wave damping coefficient, (3) vorticity damping coefficient, (4) lift damping coefficient, (5) bilge keels damping coefficient (Subrata, 2001)[1]. To generate the damping coefficient into five separated coefficients is convenient to analyze the relationship between rolling motion parameters and damping coefficients. These five separated coefficients are assumed to be in a linear correlation.

In order to simulate ship rolling motions and calculate the damping coefficient, several experiments had been carried out to develop the empirical formulas before. In 1977[2] and 1978[3], Ikeda presented individual empirical formulas for the five damping coefficients. However, the efficiency of experiment was low and these formulas could only be applied in similar ship models as the prototype in the experiment. With the high development of computer technology, Computational Fluid Dynamics (CFD) method[4] is extensively applied in the ship researches. Many methods deriving from CFD also have been developed to simulate roll motions of ships and ship-like structures. CFD method is mature enough for 2D ship models. Nonetheless, researchers are still engaged in developing appropriate CFD models to simulate rolling motions in 3D ship models. Wilson and Stern[5] used the SFDSHIP-IOWA solver to simulated free decay and forced rolling motions for the ship model DTMB5512 at multiple forward speeds. Luca and Stefano[6] simulated roll motions of the monohull, catamaran and SWATH with different rolling frequencies by the CFD method. Yang[7] accurately calculated the damping coefficients of free decay roll motions and forced rolling motions for the ship model Series 60. The accurate predictions in these studies have demonstrated the reliability of CFD methods.

This paper simulated free decay and forced rolling motions of ship models DTMB5512 by applying the RANS method. The comparison between the free decay rolling motions and experimental data was utilized to ensure the reliability of the computational meshes and the solver. In addition, the comparisons between the bare hull (BH) and the hull with bilge keels (BK) were conducted in both rolling motions to study the effect of bilge keels. This paper applied naoe-FOAM-SJTU solver[8] based on OpenFOAM (Open Field Operation and Manipulation) to simulate the ship roll motions and the flow field around the hull. The solver was based on the RANS method, and the VOF method was used to capture the free surface. A moving-mesh technique and a 6DoF (Six Degree of

Freedom) motion solver were employed to simulate ship motions. In addition, the PISO (Pressure-Implicit Split-Operator) algorithm was used to solve the coupling of the velocity and the pressure in the incompressible N-S momentum equation. Furthermore, a predictor-corrector approach was associated to promote computational efficiency. This solver can be applied to simulate the complex flows in ship, offshore and ocean engineering, resistance and wave-making of fully appended ship, green water and slamming, motion response and air gap in floating platform and so on. With the naoe-FOAM-SJTU solver, Zha et al.[9], Cao et al.[10] and Shen et al.[11,12] accurately simulated varies of ship motions and waves. These researches showed that the naoe-FOAM-SJTU solver could accurately predict the ship motions and waves.

NUMERICAL METHODS

RANS Method

The governing equations of the viscous flow around ship are composed of the continuity equations and incompressible RANS equations. The VOF method is used to capture the water-air interface, and the FVM is utilized to discretize the equations. The momentum and continuity equations are coupled by the PISO algorithm, which uses a predictor-corrector method to solve the equations by applying the continuity equation. The detailed calculation can be referred by reference 9.

Damping Coefficient

The methods to calculate damping coefficients of free decay rolling motions and forced rolling motions are different.

Free Decay Roll

In free decay rolling motions, the damping coefficient and the natural period are two key factors to describe the rolling motions. In this paper, they are used to compare with the experimental data to ensure the reliability of the calculations. The damping coefficient $\mu_{\phi\phi}$ [13] can be calculated from the history curve of rolling angle shown in Fig. 1:

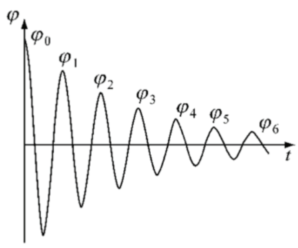


Fig. 1 The history curve of rolling angle

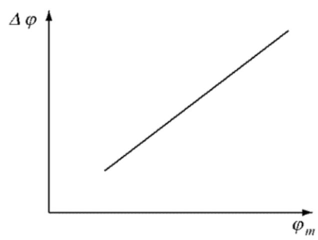


Fig. 2 The curve of damping coefficient

Then Fig. 2 can be drawn in which the horizontal axis is $\varphi_m = (\varphi_k + \varphi_{k+1})/2$ and the vertical axis is $\Delta\varphi = \varphi_k - \varphi_{k+1}$ .The damping coefficient of free decay roll can be described as:

$$\mu_{\phi\phi} = \Delta\varphi / \pi \cdot \varphi_m \tag{1}$$

Forced Roll

For forced rolling motions, the damping coefficient can be calculated by the moment $\boldsymbol{M_0}$ when the roll angle is 0:

$$B_{eq} = \frac{\boldsymbol{M}_0}{\theta_0 \omega} \tag{2}$$

From Eq. 4, it can be concluded that the damping coefficient is in accordance with the moment and thus the moment can be divided into five parts. In order to analyze the results visually, the moment will be mainly analyze instead of the damping coefficient. With the naoe-FOAM-SJTU solver, $\boldsymbol{M}_p$ and $\boldsymbol{M}_f$ are obtained respectively. $\boldsymbol{M}_p$ is the pressure part of roll motion relative with the vorticity, wave and bilge keels parts while $\boldsymbol{M}_f$ is the shear part relative with the friction and bilge keels parts. The sway motions of ship are not taken into consideration and all the calculations are carried out with viscous effects in the paper, thus the lift part is ignored and the wave part is not calculated separately. According to the linear correlation among the four parts, the correlation among the moments can be presented as:

$$\begin{cases} \boldsymbol{M}_p = \boldsymbol{M}_{pw} + \boldsymbol{M}_{pe} + \boldsymbol{M}_{pb} \\ \boldsymbol{M}_f = \boldsymbol{M}_{ff} + \boldsymbol{M}_{fb} \\ \boldsymbol{M} = \boldsymbol{M}_p + \boldsymbol{M}_f \end{cases} \tag{3}$$

where $\boldsymbol{M}_{pw}$, $\boldsymbol{M}_{pe}$, $\boldsymbol{M}_{pb}$ are the pressure part of the moment caused by the wave, vorticity and bilge keels respectively, $\boldsymbol{M}_{ff}$, $\boldsymbol{M}_{fb}$ are the friction part of the moment caused by the bare hull and bilge keels.

GEOMETRY AND COMPUTATIONAL MESH

A modern naval combatant model DTMB 5512 used in experiments was simulated to ensure the reliability of the results and analyze the effect of bilge keels. The simulation was performed with two ship model configurations: the bare hull (BH) and bare hull with bilge keels (BK). The main geometry properties of the bare hull are presented in Table 1 and the models are shown in Fig. 3.

Table 1 The main geometry properties of DTMB5512 ship model

Geometry properties	Left Column
L_{pp}	3.048 m
Beam	0.409 m
Draft	0.132 m
Mass	83.06 kg
C_b	0.506
Wetted Area	1.398 m^2
COG	(1.524 0 0.03)

(a) BH (b) BK

Fig. 3 The DTMB5512 ship models

The meshes in this paper were dynamic meshes generated by a mesh generation utility in OpenFOAM, named snappyHexMesh. The computational domain was $-1.0L \le x \le 3.0L$, $-2.0L \le y \le 2.0L$, and $-1.0L \le z \le 0.5L$. It is acknowledged that CFD results are affected by the mesh quantity and quality, so the convergence study would be carried out next. The mesh information is shown in Table 2 and Fig. 4:

Table 2 The mesh information of convergence study

	Mesh 1	Mesh 2	Mesh 3
The number of meshes	97.8 W	232 W	646 W

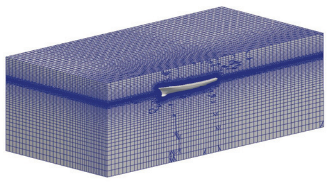


Fig. 4 Mesh distribution for DTMB5512 ship model

VALIDATION

In order to ensure the reliability of the computational mesh and the results, roll motions of the BH model was simulated in the same conditions as the experiment. The parameters of this condition is shown in Table 3:

Table 3 The condition for free decay roll

Condition	Motion	Froude Number	Initial Angle
BHLS	Free decay roll	0.138	10°

At first, the convergence study was carried out with the BH model. The result is presented in Table 4 and Fig. 5:

Table 4 The validation results for free decay roll

Condition	Natural Period			Damping Coefficient		
	Experimental Data	CFD	Deviation	Experimental Data	CFD	Deviation
Mesh 1	1.584	1.69	6.7%	0.0745	0.0657	11.8%
Mesh 2		1.65	4.2%		0.0703	5.6%
Mesh 3		1.64	3.5%		0.0711	4.6%

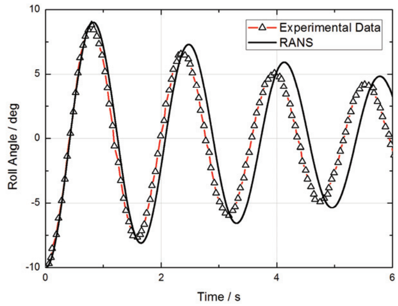
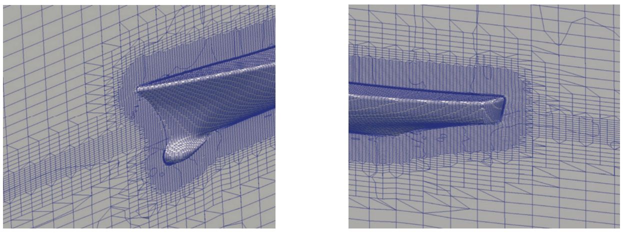


Fig. 5 Validation result for Mesh 2

As shown above, the deviations for Mesh 2 and 3 are less than 6%, which indicates that the Mesh 2 and 3 with the naoe-FOAM-SJTU solver can provide reliable results. Although in Mesh 3 the deviation is smaller, the number of meshes and the computing time are both larger than Mesh 2. Thus Mesh 2 is computed in the next work and the details of the mesh distribution for Mesh 2 is shown in Fig. 6:



(a) The stem meshes (b) The stern meshes

Fig. 6 Mesh distribution for Mesh 2

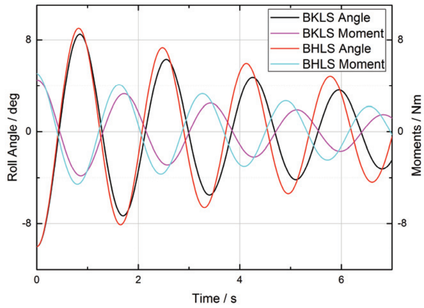
RESULTS

In order to demonstrate the effect of bilge keels on the rolling motions, the free decay and forced rolling motions of two models (BH and BK) were simulated in this work. The conditions are described in Table 5:

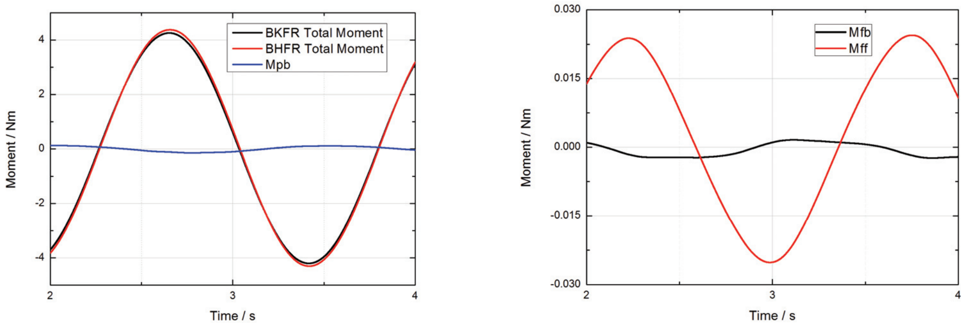
Table 5 The condition for free decay roll

Condition	Appendage	Motion	Froude Number	Frequency	Initial Angle
BHLS	——	Free Decay Roll	0.138	——	10°
BKLS	Bilge Keels				
BHFR	——	Forced Roll	0.28	0.654	5°
BKFR	Bilge Keels				

Fig. 7 presents the time history curve of moments and Fig. 8 presents the vorticity contours at representative time:

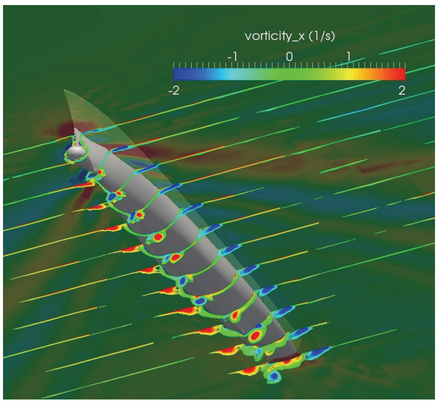


(a) Free decay roll

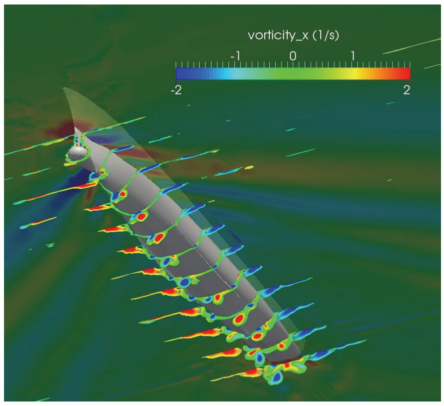


(b) Forced roll

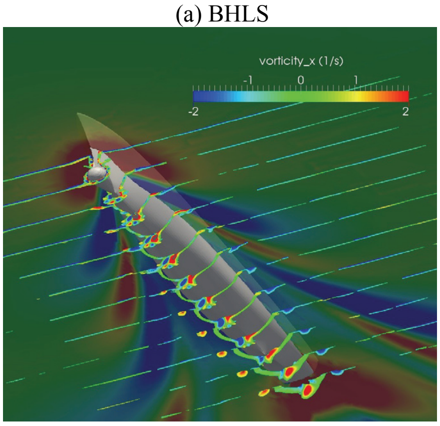
Fig. 7 The time history curve of moments



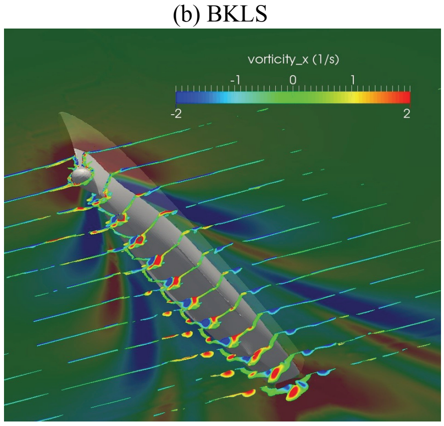
(a) BHLS



(b) BKLS



(c) BHFR



(d) BKFR

Fig. 8 The vorticity contours

As shown in the Fig. 7, it can be concluded that the bilge keels reduce the maximum of moments for both rolling motions and M_{fb} is fairly small. And Fig. 8 shows the bilge keels increase two sets of vorticity and have little effect on the free surface. Fig. 9 shows one reason for the decrease of moments:

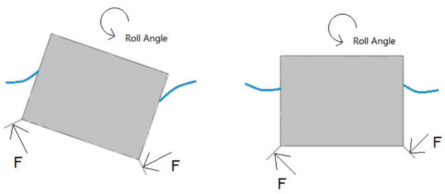


Fig. 9 Effect of bilge keels

The moment reaches the maximum when the ship rolls to maximum roll angle, then the main moments caused by wave and vorticity forces the ship to roll back to the equilibrium state. At the same time, according to Fig. 8, the force on the bilge keels makes the ship farther outside equilibrium state and thus leads to the moment in an opposite direction. In addition, according to Fig. 7, the bilge keels generate two additional sets of vorticity changing the pressure around the ship but the number and the value of the vorticity are small. As a result, bilge keels reduce the maximum of moments. For free decay roll, the effect of bilge keels is great. The decrease of moments leads to the increase of the natural period and the decrease of the roll angle, which can accord with the experimental results. For forced roll, the effect of bilge keels is small. Fig. 6 shows that M_f affected by the wetted area occupies a small part of the total moment, and the wetted area of bilge keels is much smaller than that of bare hull. Thus the effect of M_{fb} can be ignored. Fig. 6 also shows that M_{pb} is much smaller than M_{pw}+M_{pe} .

CONCLUSIONS

The paper applied naoe-FOAM-SJTU solver based on RANS method to simulate free decay and forced rolling motions of ship models DTMB5512. For free decay roll, the comparison with experimental data was carried out, and the deviation was less than 6%, which ensures the reliability of the computational meshes and the solver. Then the comparisons between the bare hull (BH) and the hull with bilge keels (BK) were conducted to study the effect of bilge keels. As the results showed, the bilge keels reduced the maximum of damping moments. Thus the natural period increased and the roll angle decreased in free decay rolling motions. And the effect of bilge keels was small in forced rolling motions. The friction part affected by the wetted area of bilge keels could be ignored since the area was much smaller than that of the bare hull. In addition, for both rolling motions, the bilge keels generate two sets of vorticity changing the pressure around the ship.

In order to achieve a greater understanding of rolling motions in viscous flow field, in the further research, the parameters of rolling motions will be changed to study the relationship between the parameters and the five damping coefficients. In addition, the sway motion will be taken into consideration to study the effect of lift on rolling motions.

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REFERENCES

[1] CHAKRABARTI S, Empirical calculation of roll damping for ships and barges [J]. Ocean Engineering, 2001, 28: 915-932.

[2] IKEDA Y, HIMENO Y, TANAKA N. On eddy making component of roll damping force on naked hull [J]. Journal Soc. Naval Arch, 1977, Japan, 142: 54-64.

[3] IKEDA Y, HIMENO Y, TANAKA N. A prediction method for ship roll damping [J]. Report of Department of Naval Architecture, 1978, University of Osaka Prefecture, No 405.

[4] ALESSANDRINI B, DELHOMMEAU G. Fully coupled Navier-Stokes solver for calculation of turbulent incompressible free surface flow past a ship hull [J]. International Journal for Numerical Methods in Fluids, 1999, 29(2): 125-142

[5] WILSON R, STERN F. Unsteady RANS CFD method for naval combatant in waves [C]. The 22th Symposium on Naval Hydrodynamics, 1998, Washington, DC, August: 532-549.

[6] BONFIGLIO L, BRIZZOLARA S. Influence of viscosity on radiation forces: a comparison between monohull, catamaran and SWATH [C]. Proceedings of the Twenty-third (2013) International Offshore and Polar Engineering, 2013, Anchorage, Alaska, USA, June 30–July 5: 718-725.

[7] YANG CL, ZHU RC, MIAO GP, FAN J Numerical simulation of rolling for 3-D ship with forward speed and nonlinear damping analysis [J]. Science Direct, 2013, 25(1): 148-155.

[8] ZHA RS, YE HX, SHEN ZR and WAN DC. Numerical computations of resistance of high speed catamaran in calm water [J]. Journal of Hydrodynamics, Vol. 26, No. 6, 2014: 930-938.

[9] CAO H, WAN DC. RANS-VOF solver for solitary wave run-up on a circular cylinder[J]. China Ocean Engineering, 2015, 29: 183–196.

[10] SHEN Z, WAN DC. The Manual of CFD solver for ship and ocean engineering flows: naoe-FOAM-SJTU[R]. Technical Report No. 2012SR118110, 2012, Shanghai Jiao Tong University.

[11] SHEN Z, WAN DC. An irregular wave generating approach based on naoe-FOAM-SJTU solver[J]. China Ocean Engineering, 2016, 30: 177–192.

[12] YANG B, SHI AG, WU M, Calculation of Ship Roll Damping Coefficient Based on CFD [J]. Navigation of China, 2012, 35(3): 76-80.