A Study on Applicability of CFD Approach for Predicting Ship Parametric Rolling

Yao-hua, Zhou, *School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China,* E-mail: yhzhou@ccs.org.cn

Ning, Ma, *State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China,* E-mail: ningma@sjtu.edu.cn

Jiang, Lu, *China Ship Scientific Research Center, Wuxi 214082, China*

Xie-chong, Gu, *State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*

ABSTRACT

New criteria for Parametric Rolling (PR) are considered in the development of 2nd generation intact stability criterion, by the International Maritime Organization (IMO). As it is well known, estimation methods of the roll damping affect the prediction of parametric rolling significantly, and most estimation approaches for roll damping are based on experiment data or Ikeda's empirical formula. When the new criteria are applied in the design stage of ship, the accuracy of estimation approach for roll damping will be a key aspect of the validity of prediction. In this research, a hybrid method is proposed that 3D CFD approach is utilized to calculate the roll damping, while potential theory method is adopted for predicting parametric rolling motion. Furthermore, direct simulation is also investigated for PR of containership based on CFD approach. Comparative study is carried out for these two methods and potential method whose roll damping is estimated by simplified Ikeda’s method and experimental data. According to the results, the CFD approach could achieve satisfactory agreements with the experiment for both roll damping and roll amplitude of PR. Therefore, CFD approach may be suitable to be utilized for PR analysis especially at the early design stage when lack of experiment data.

Keywords: *Parametric rolling; Roll damping; CFD;*

1. INTRODUCTION

Due to the lack of experiment data in the initial design stage, the roll damping is usually obtained by semi-empirical method such as simplified Ikeda’s method, so the prediction of PR will be doubtful, because the roll damping has not yet been determined. Considering the significant effect of roll damping on parametric rolling, the estimation method of roll damping needs further investigation.

Fully nonlinear CFD approach could be a good choice for this purpose, and it is preferable to directly obtain the roll damping by CFD approach for numerical prediction model of PR. In this study, a hybrid method is developed based on 3D CFD approach and potential method. The parametric rolling is simulated and validated for containership C11. Good agreement has been achieved. Furthermore, numerical study also has been carried out to investigate the applicability of direct CFD prediction for parametric rolling.

2. HYBRID METHOD FOR PREDICTING PARAMETRIC ROLLING

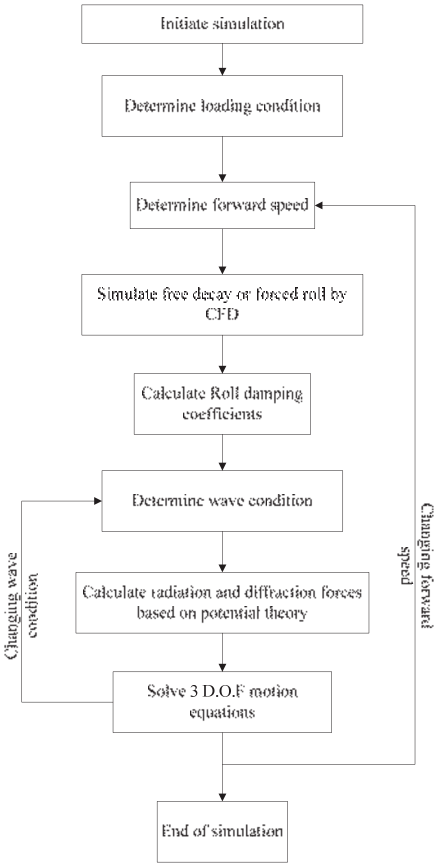


Figure 1 Conceptual scheme of hybrid method for assessment

The hybrid method is developed based on non-linear 3D CFD approach and 3D potential method. CFD approach is utilized for calculation of roll damping and potential method is adopted for calculation of radiation and diffraction forces. The method follows process shown in Figure 1.

2.1 Numerical models

The hybrid method adopts a 3 D.O.F weakly nonlinear model (roll, heave and pitch) for the simulation of ship motion. Such kind of models that considering the time delay effect and nonlinearity of Froude-Krylov forces has been successfully applied for the simulation of parametric rolling (Turan, 2008, Chang, 2008.). Motion equations are shown in Eqn (1) (Zhou, 2010).

$$
\begin{aligned}
&(M+\mu_{33})\ddot{\eta}_3+\int_0^t K_{33}(t-\tau)\dot{\eta}_3 d\tau+\mu_{35}\ddot{\eta}_5\\
&+b_{35}\dot{\eta}_5+\int_0^t K_{35}(t-\tau)\dot{\eta}_5 d\tau=F_3^{IS}+F_3^{D}-Mg\\
&(I_{xx}+\mu_{44})\ddot{\eta}_4+\int_0^t K_{44}(t-\tau)\dot{\eta}_4 d\tau\\
&=F_4^{IS}+F_4^{D}+F_4^{v}\\
&(I_{yy}+\mu_{55})\ddot{\eta}_5+\int_0^t K_{55}(t-\tau)\dot{\eta}_5 d\tau+c_{55}\eta_5\\
&+\mu_{53}\ddot{\eta}_3+b_{53}\dot{\eta}_3+\int_0^t K_{53}(t-\tau)\dot{\eta}_3 d\tau=F_5^{IS}+F_5^{D}
\end{aligned}
\tag{1}
$$

Where F^{IS} is the composition force of Froude-Krylov force and restore force which are calculated based 3D pressure integration method for the instantaneous wetted hull; diffraction forces F^{D} are predicted by 3D frequency domain potential method; radiation forces are calculated based on impulse response theory in the motion equation to considering the memory effect (as shown in Eqn (2)).

$$K_{jk}(\tau)=\frac{2}{\pi}\int_0^{\infty}(B_{jk}(w_e)-b_{jk})\cos w_e\tau dw_e \tag{2}$$

Where $B_{jk}(\omega_e)$ is wave making damping that calculated by frequency domain potential theory method. μ_{jk} is added mass or moment of inertia, which is calculated for mean wetted surface by solving boundary problem.

F_4^{v} is moment due to roll damping, and is simplified as shown in Eqn (3).

$$F_4^{v}=-(A\cdot\dot{\eta}_4+C\cdot\dot{\eta}_4^{\,3}) \tag{3}$$

Where A and C are roll damping coefficients that calculated by CFD approach.

The Roll damping coefficients are calculated based on motion or moment data of numerical simulations for free decay or forced roll of scaled model. The simulation is carried out by 3D RANSE solver ISIS-CFD (Deng, 2010). This flow solver uses the incompressible unsteady Reynolds-averaged

Navier Stokes equations (RANSE), which is based on the finite volume method to build the spatial discretization of the transport equations. The face-based method is generalized to three-dimensional unstructured meshes for which non-overlapping control volumes are bounded by an arbitrary number of constitutive faces. The flow solver deals with multi-phase flows and moving grids.

2.2 Validation and Discussions

The well-known Container ship C11 (Lu, 2011) is utilized for numerical simulation to validate the hybrid method.

2.2.1 Estimation of roll damping by CFD simulation

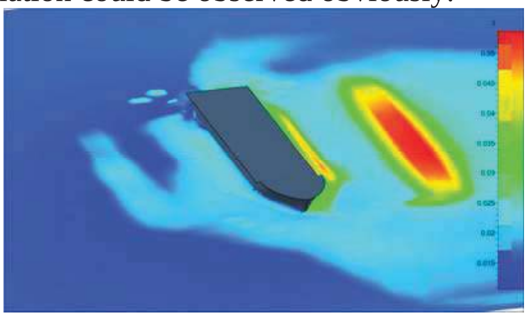
First, four ship models of different types are utilized for validating numerical simulation method, including S175, 3100TEU container ship, Warship and Concept Trimaran. S175 is a public experimental model, without bilge keel or rudder. 3100TEU is commercial ship that still in service, with bilge keels and rudder installed in the model. The experiments of these container ships are conducted by Shanghai Jiao Tong University. Warship is a model of combatant published by RINA (RINA, 1980), and installed with bilge keels, rudders and stabilizer fins. The Concept Trimaran is a Concept ship for research purposes that developed by Harbin Engineering University (Zhou, 2010). Table 1 shows the principal dimensions of the four models. Figure 2 shows the model of 3100TEU.

Figure 2 the model of 3100TEU container ship

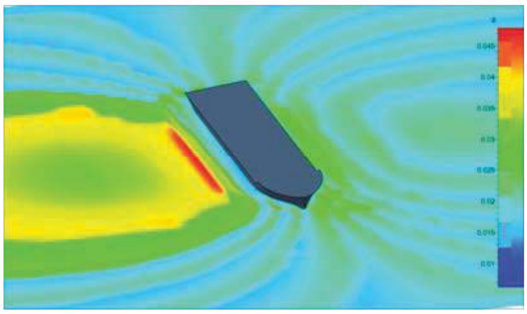
Table.1 Principal Dimensions

		S175	3100TEU	Warship
Length Lpp	(m)	3.034	3.120	6.000
Breadth B	(m)	0.440	0.469	0.654
Draft T	(m)	0.165	0.173	0.204
GM	(m)	0.017	0.013	0.028
		Trimaran		
Length L_{WL} (main hull)	(m)	3.120		
Breadth B_{WL} (main hull)	(m)	0.240		
Draft T (main hull)	(m)	0.116		
GM	(m)	0.140		

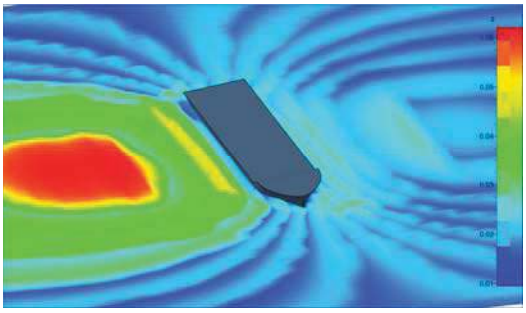
All of the predictions are procured on 0.79~1.2M grid. Figure 3 shows the free surface around 3100TEU model in free decay test simulation. The generation and propagation of wave trough and crest in wide area due to radiation could be observed obviously.



(a) T=8.1s



(b) T=8.7s

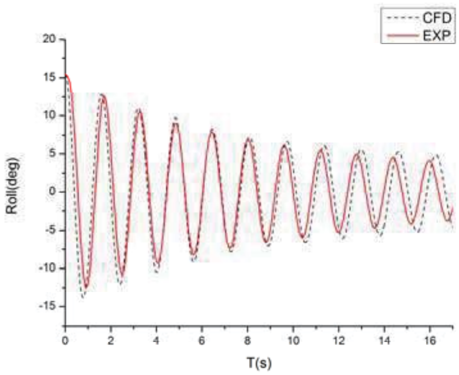


(c) T=9.0s

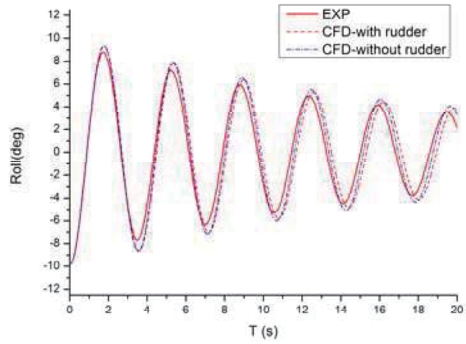
Figure 3 Free surface height around 3100TEU model

Figure 4 shows the roll decay curves of S175 and 3100TEU, including the comparisons between the experimental data and simulations. Figure 5 shows the CFD simulation results of Warship and Trimaran.

As shown in Figure 4 and Table 2(a), good accuracy could be achieved for the natural roll period. Moreover, with the increase in the number of rolling cycles, errors of the time history due to cumulative error are inevitable. By fitting the extinction curve, it could be found that, the CFD method is able to ensure the simulation of roll damping to achieve a satisfactory accuracy, even if there are certain errors for the amplitude and phase of roll. The comparisons of B_{44} and 2μ show that (Table 2(b)), the CFD method proposed by this study could achieve good agreement for the simulation of free decay in calm water at zero velocity, and the errors are acceptable.

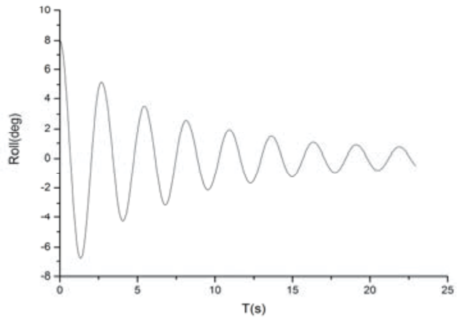


(a) S175

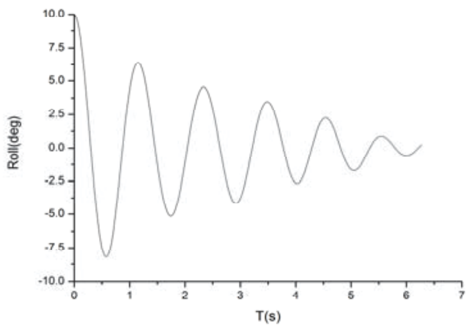


(b) 3100TEU

Figure 4 The time histories of free rolling of S175 and 3100TEU (Fn=0)



(a)Warship



(b)Trimaran

Figure 5 the time histories of free rolling of Warship and Trimaran (Fn=0)

Table 2 (a) The natural roll periods T_{roll}

		CFD (s)	EXP (s)
S175		1.635	1.600
3100TEU	with rudder no rudder	3.610 3.570	3.600
Warship		2.735	2.66

Trimaran	1.108	1.100

Table 2 (b) The extinction/damping coefficients

	$\hat{B}_{44}$ (0~15degs) / 2μ	CFD	EXP
S175	$\hat{B}_{44}$	4.34E-4~3.59E-3	4.86E-4~4.25E-3
3100TEU	$\hat{B}_{44}$ (with rudder)	2.03E-3~8.13E-3	2.27E-3~7.32E-3
	$\hat{B}_{44}$ (no rudder)	2.05E-3~6.10E-3	
Warship	2μ	0.0878	0.094
Trimaran	2μ	0.117	0.123

For the estimation of roll damping for C11, the scale of CFD simulation is taken as the same scale of model test. All of the predictions are procured on 1.44M grid (as shown in Figure 6).

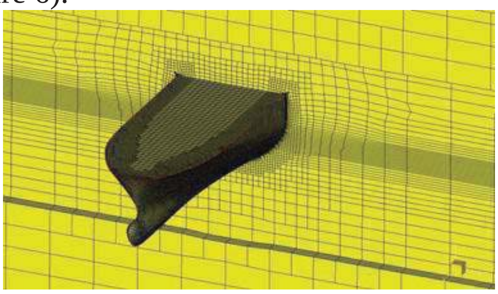


Figure 6 Meshes of typical section of C11

For blind simulation of parametric rolling, the initial heel angle or forced roll amplitude is difficult to determine for estimation of roll damping. Therefore, these two values are taken as 20 degrees for both CFD simulations. Figure 7 and Figure 8 show the simulations of forced roll and free decay at Fn=0.0, 0.05 and 0.1. Then roll damping coefficients A and C are estimated for further parametric rolling prediction.

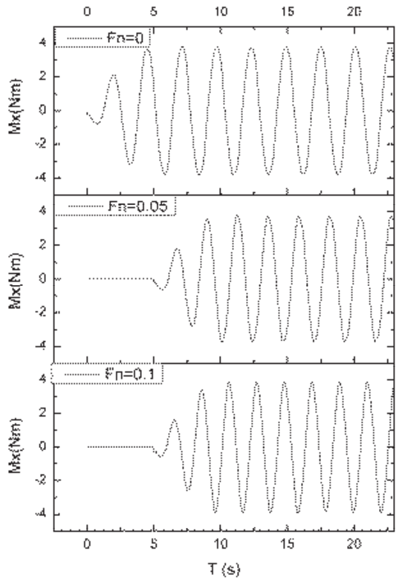


Figure 7 Time history of roll moment for forced roll simulation of C11

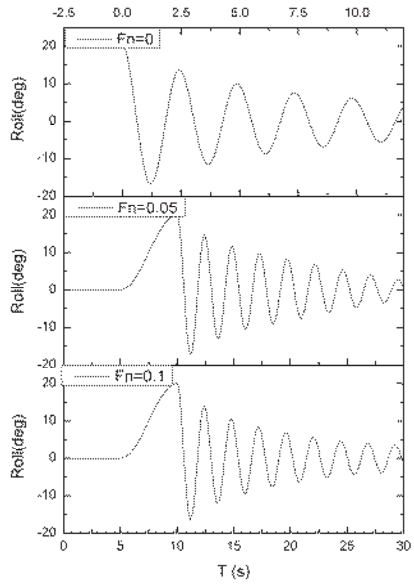


Figure 8 Time history of free decay simulation of C11

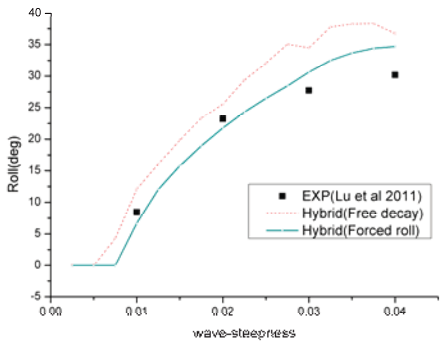
Table 3 The damping coefficients of C11 (full scale)

	Fn	A	C
Free decay	0.0	3.68E+08	5.59E+10
	0.05	2.82E+08	4.28E+10

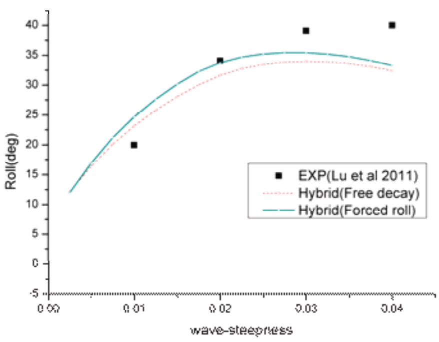
	0.1	2.53E+08	8.25E+10
Forced roll	0.0	6.22E+08	6.92E+10
	0.05	3.18E+08	2.99E+10
	0.1	2.60E+08	3.63E+10

2.2.2 Validation and analysis of parametric rolling results

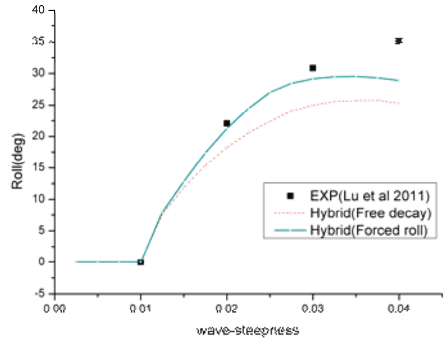
Figure 9 shows the predictions of parametric rolling for C11 by hybrid method. Two options of estimating roll damping coefficients were compared with experiment data. According to prediction results, the hybrid method (with forced roll damping) could successfully predict parametric roll for different speeds and wave-steepness. For cases those amplitudes around and less than 27~33 degrees could achieve satisfactory accuracy.



a) Fn=0.0



b) Fn=0.05



c) Fn=0.1

Figure 9 Roll amplitudes prediction for PR

The initial heel angle or forced roll amplitude plays an important role on obtaining the roll damping characteristic such as equivalent damping coefficients (Hashimoto, 2010). In this study, the initial heel angle and forced roll amplitude are both taken as 20 degrees for estimation of roll damping coefficients. Thus, the agreement is not good for cases with large amplitudes. Therefore, how to determine the initial heel angle or forced roll amplitude for blind simulation of PR by hybrid method still needs further study in the future. These values could be taken as 20 degrees temporarily to be consistent with IMO's Level 2 criteria.

According to the president results of C11, it is appropriate to adopt the hybrid method (forced roll), and this method could bring great advantage in the initial design stage especially in the lack of experiment data for a new design.

3. STUDY ON APPLICABILITY OF DIRECT CFD METHOD FOR PREDICTING PARAMETRIC ROLLING

In order to improve the forecasting precision of PR for optimal design, in theory the best way is to carry out good simulation for encountered wave surface accounting the action of ship, highly nonlinear restoring forces and hydrodynamic forces, and large roll-heave-pitch resonance. Different from traditional potential methods, fully nonlinear CFD approach could be a good choice for state of the art method for this purpose. Thus, it is also necessary to carry out comparative study for hybrid method with “state of the art” methods such as 3D direct CFD approach.

The direct CFD prediction method utilizes the same RANS solver as in the estimation of roll damping. Most of parameter settings and mesh generation also follow the same principles. All of the predictions are procured on 2.77M grid. As shown in Figure 10, cylindrical computational domain is created with sliding grid for simulating near filed flow of ship.

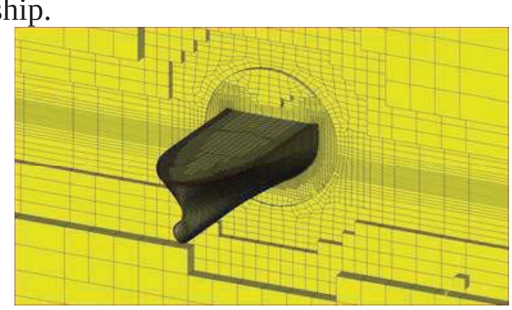
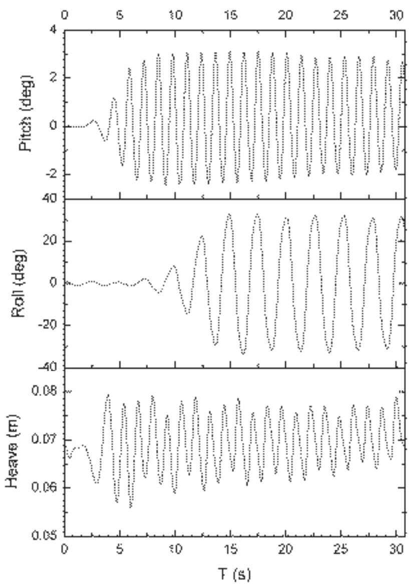
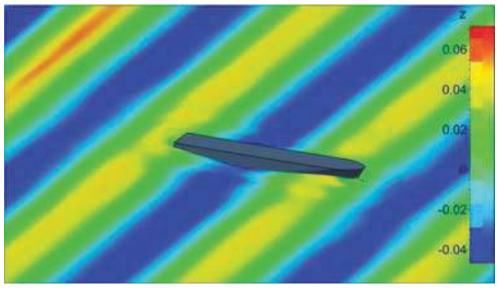


Figure 10 Refined meshes of typical section of C11

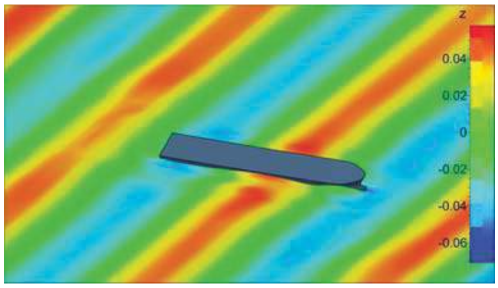
3 D.O.F motions (roll, pitch and heave) are free for simulation of PR. Sway and yaw are limited and neglected.



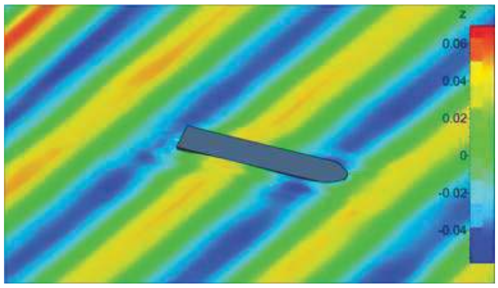
a) Time history of motion responses



b) Simulation of PR (t=16.704s)



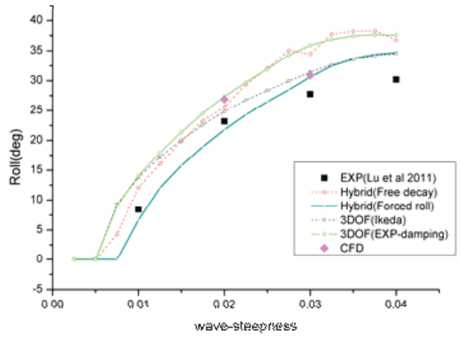
c) Simulation of PR (t=17.052s)



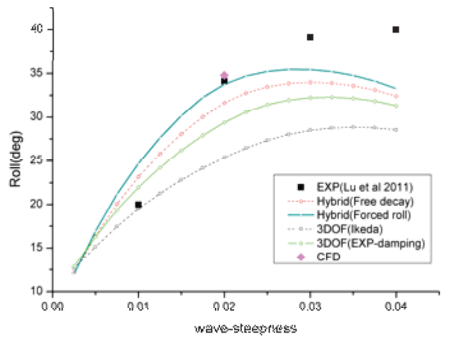
d) Simulation of PR (t=17.4s)

Figure 11 Simulations of Parametric Rolling (Fn=0, wave-steepness 0.03)

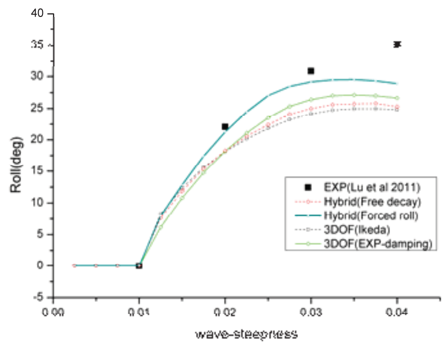
Figure 11 shows the time histories of motion responses and interactions between fluid field and ship at Fn=0. Figure 12 shows the comparisons of roll amplitudes predicted by different methods, including Hybrid method, direct CFD method and potential theory method whose roll damping is estimated by simplified Ikeda’s method and experimental data (3 D.O.F(Ikeda) and 3 D.O.F(EXP-damping)).



a) Fn=0.0



b) Fn=0.05



c) Fn=0.1

Figure 12 Comparisons of roll amplitudes for PR

In Figure 12, results show the influence of four estimating methods of roll damping on PR amplitudes. Roll amplitudes of hybrid method (Free decay) is very close to 3 D.O.F (EXP-damping), It indicates roll damping estimated by free decay based on CFD simulation achieved good accuracy for prediction of PR, and can be a good option to replace free decay tests which are currently carried out in initial design stage.

On the whole, Hybrid method and direct CFD prediction method could achieve good accuracy for prediction of PR. These two methods are considered to be more appropriate as options for numerical models of direct stability assessment of PR.

4. CONCLUSIONS

The research results show that, the CFD approach has good applicability in simulating parametric rolling, and has positive significance for the development of direct stability assessment criteria of PR. Overall, hybrid method needs less computational resource, and is more suitable for engineering application comparing to direct CFD method. It is suggested to pay enough attentions to the application of CFD approach in the study and development of guideline of direct stability assessment criteria in the future.

5. ACKNOWLEDMENTS

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