Validation of One Numerical Method for Parametric Roll Criteria with Experiments

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ABSTRACT

The numerical methods for the direct stability assessment of parametric roll are currently under development at the International Maritime Organization (IMO) for the second generation intact stability criteria. For providing a numerical method for parametric roll with sufficiently simple and enough reliable, firstly, heave and pitch motions obtained by a strip theory applied to an upright hull is used to determine the simultaneous relative position of the ship to waves in time domain; secondly, the nonlinear Froude-Krylov component of roll restoring variation is calculated by integrating wave pressure up to wave surface with the heave and pitch motions; secondly, the dynamic effect which consists of radiation and diffraction components is taken into account. Finally, the proposed numerical method is validated by four ships with four experiments.

Keywords: *Parametric roll, second generation intact stability criteria, dynamic stability, stability in waves*

1. INTRODUCTION

The numerical methods for direct stability assessment of parametric roll are under development at the International Maritime Organization (IMO) for the second generation intact stability criteria (IMO SDC.3, 2016). Parametric roll in head seas is a nonlinear phenomenon involving dynamic heave and pitch motions, and it is still difficult to be predicted accurately in head seas. IMO is also calling for the validation of numerical methods or guidelines for finalization of second generation intact stability with samples.

Several successful predictions of parametric roll in following waves have been reported (Munif and Umeda, 2000) due to the fact that coupling with dynamic heave and pitch is not important while the wave induced added resistance is generally small in following waves.

Although the accurate prediction of head-sea parametric roll is difficult at this stage due to the fact that the coupling with heave and pitch is significant and the added resistance as well as the resulting speed loss cannot be simply ignored, the effect of dynamic heave and pitch motions on parametric roll has been investigated so far by many researchers and found that restoring arm variation in head waves depends on dynamic heave and pitch motions (Taguchi, et al., 1995). The effect of surge motion, with added resistance taken into account, on parametric roll was investigated by some researchers (Umeda, et al.,2008;Umeda & Francescutto,2008; Lu, et al., 2010,2011,2012), but an experimental study with and without surge was not conducted in the above investigations. The partially restrained experiments with the surge motion restrained and free running experiments with the surge motion free were conducted in the reference (Lu, et al., 2016).

In a linear seakeeping theory the roll motion of a symmetric hull has no effect on heave and pitch motions, the coupling from parametric roll to heave and pitch is not taken into account in above studies. Rodriguez et al. (2007) observed subharmonic components in heave and pitch motions when parametric roll occurs in their experiments. Neves et al. (2009) using their nonlinear heave-pitch-roll mathematical model numerically subsequently revealed an interesting bifurcation structure of heave and pitch motions together with parametric roll. Later Lu et al (2013,2016) also observed subharmonic components in pitch motion and heave displacement together with parametric roll in their free-running model experiment and half restrained model experiment, but failed to reproduce this phenomenon with a coupled heave-roll-pitch mathematical model based on a nonlinear strip theory (Hashimoto & Umeda, 2012).

Many prediction methods for parametric roll ignore the radiation and diffraction effects on restoring variation but some methods do not. Boroday (1990) and Umeda & Hashimoto (2006) took into account the radiation and diffraction effects using a strip theory on the restoring variation. Hashimoto et al. (2007) reported that radiation and diffraction effects on the restoring variation could result in larger parametric roll amplitude, which improves accuracy for a car carrier. The effect of radiation and diffraction forces on restoring variation for parametric rolling still remains open which requires further experimental and numerical studies with more examples as mentions in the reference (Lu, et al., 2016).

As mentioned in the reference (Lu, et al., 2016), there are several issues should be discussed to finalize the guidelines in this respect and IMO is also calling for conducting more examples to finalize the guidelines of parametric roll with sufficiently simple and enough reliable methods. Therefore, the authors carry out the first step to validate the uncoupled numerical models by conducting four free running experiments with a post Panamax C11 class containership, a pure car carrier, a passenger ship and a 4250TEU containership, respectively.

2. MATHEMATICAL MODEL

The uncoupled roll model (Hashimoto et al. 2007, Umeda, et al.,2008) which has been used for estimating parametric roll for many years is expressed as (1) and called as 1 DOF approach. Although this model is a 1 DOF of rolling model, heave and pitch motions are taken into account to estimate restoring variation. Restoring moment in waves is calculated as a sum of two components. One is the nonlinear Froude-Krylov component, which is calculated by integrating wave pressure around the instantaneously wetted hull surface with heave and pitch motion obtained by a strip theory applied to an upright hull. The other is the hydrodynamic effects which result from radiation and diffraction components that are extrapolated nonlinearly with regards to roll angle (Lu, et al., 2011, 2012).

Since the prediction accuracy of restoring moment in head seas could be improved if the dynamic component is included. The dynamic effect is calculated by applying a strip theory to different heeled hulls with regards to simultaneous roll angle while it is assumed a linear relationship with the wave height. This effect is considered as an additional effect on GZ by dividing calculated dynamic roll moment with a ship displacement.

$$\ddot{\phi} + 2\mu\dot{\phi} + \gamma\dot{\phi}^3 + \frac{W}{I_{xx} + J_{xx}} GZ(t, X_G, \zeta_G, \theta, \phi) = 0 \quad (1)$$

where: ϕ: roll angle, μ: linear roll damping coefficient, γ: cubic roll damping coefficient, W: ship weight, Ixx: moment of inertia in roll, Jxx: added moment of inertia in roll, GZ: righting arm, t: time, ζ_G: heave displacement and θ: pitch angle, X_G: instantaneous ship longitudinal position.

3. SUBJECT SHIPS

The principal particulars of the post Panamax C11 class containership, the pure car carrier, the passenger ship and the 4250TEU containership used for this research are shown in Tables 1 -4 .

Table 1 Principal particulars of the C11 containership

items	ship	model
length: L_{pp}	262.0 m	4.0m
breadth: B	40.0 m	0.611m
Depth:D	24.45m	0.373m
mean draught: T	11.5 m	0.176m
block coefficient: C_b	0.560	0.560
Pitch radius of gyration: κ_{yy}	0.24Lpp	0.24Lpp
metacentric height: GM	1.928 m	0.029m
natural roll period: T_φ	24.68 s	3.05s

Table 2 Principal particulars of the car carrier

items	model
length: L_{pp}	4.2m
breadth: B	0.624m
Depth:D	0.774m
mean draught: T	0.197m
block coefficient: C_b	0.646
Pitch radius of gyration: κ_{yy}	0.25Lpp
metacentric height: GM	0.019m
natural roll period: T_φ	3.45s

Table3 Principal particulars of the passenger ship

items	model
length: L_{pp}	3.0m
breadth: B	0.514m
Depth:D	0.239m
mean draught: T	0.127m
block coefficient: C_b	0.515
Pitch radius of gyration: κ_{yy}	0.24Lpp
metacentric height: GM	0.023m
natural roll period: T_φ	2.865s

Table 4 Principal particulars of the 4250TEU containership

items	model
length: L_{pp}	4.0m
breadth: B	0.511m
Depth:D	0.307m
mean draught: T	0.20m
block coefficient: C_b	0.643
Pitch radius of gyration: κ_{yy}	0.30Lpp
metacentric height: GM	0.026m
natural roll period: T_φ	2.7s

4. EXPERIMENTS

The four free running experiments were conducted in the seakeeping basin (length: 69m, breadth: 46m, depth: 4m) of China Ship Scientific Research Center, which is equipped with flap wave makers at the two adjacent sides of the basin. The ship model was driven by a propeller in the free running experiment. The pitch and roll amplitudes were measured by a MEMS (Micro Electro-Mechanical System)-based gyroscope placed on the ship model and the wave elevation was measured by a servo-needle wave height sensor attached to the towing carriage.

Figure 1: The C11 containership model in the free running experiment

Figure 2: The pure car carrier model in the free running experiment.

Figure 3: The passenger ship model in the free running experiment.

Figure 4: The 4250TEU containership model in the free running experiment.

5. RESULTS AND DISCUSSIONS

5.1 The C11 Containership

The head-sea parametric roll of C11 containership in the free running experiments is recorded. Although the Froude number of the forward speed is limited to 0.15 due to the length of the seakeeping basin, the forward speed in not limited in the simulations. In the results, the minus Froude numbers mean the forward speed in following seas while the positive Froude numbers mean the forward speed in head seas. FK means only Froude-Krylov components of roll restoring variation are considered while FK+R&D means the radiation and diffraction components of roll restoring variation are also considered.

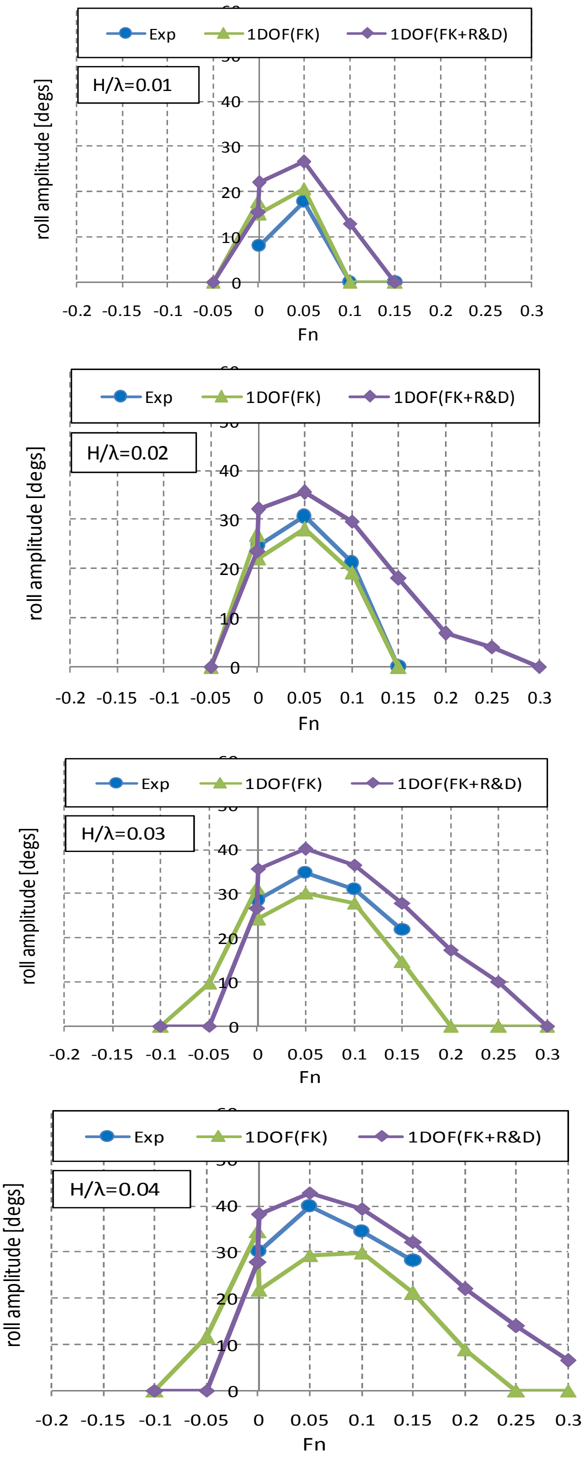
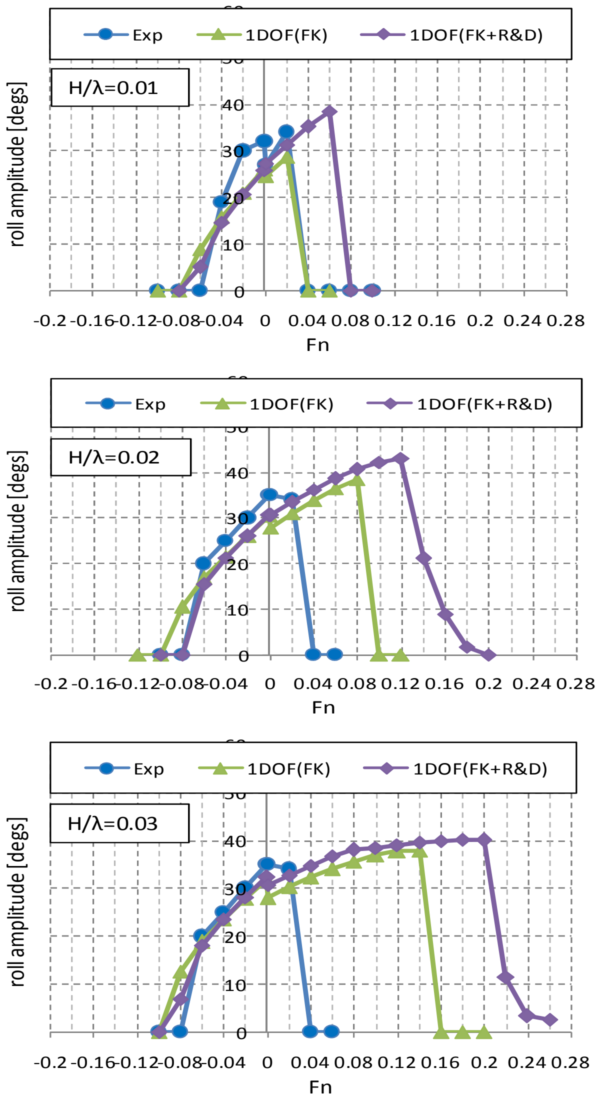


Figure 5: Comparisons of parametric roll between experiments and simulations, under the condition of λ/L_{pp}=1.0, χ=0^0 and 180^0.

The prediction of head-sea parametric roll in the 1 DOF approach with Froude-Krylov, radiation and diffraction components is generally larger than that in the experiments while the prediction of head-sea parametric roll with the Froude-Krylov on its own is generally smaller than that in the experiments except for H/λ=0.01 as shown in Fig. 5. The speed range of parametric roll with the 1 DOF (FK+R&D) is larger than that in the experiments while the speed range of parametric roll with the 1 DOF (FK) is more close to that in the experiments in head seas. The above conclusions are not always fit for parametric roll in following seas. The difference between the simulations with the 1 DOF (FK) and the 1 DOF (FK+R&D) is not so larger and the simulations with the 1 DOF (FK) is more conservative than that with the 1 DOF (FK+R&D) in following seas, and the radiation and diffraction effects on restoring variation could be ignored in following seas.

5.2 The Pure Car Carrier



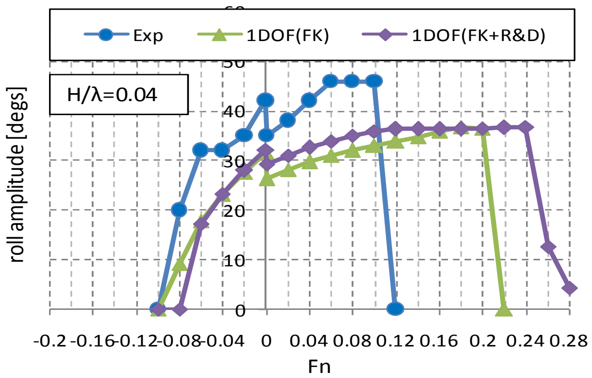
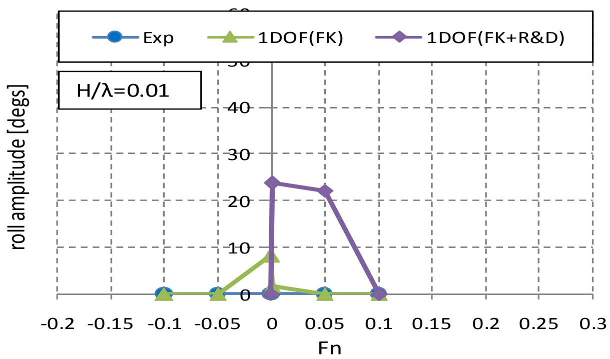
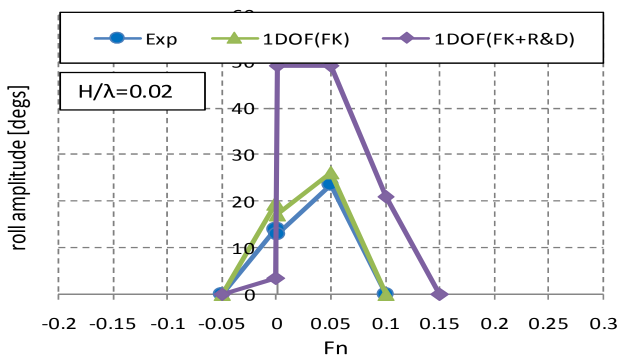


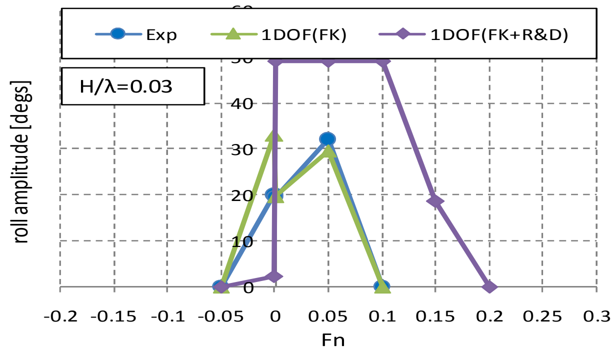
Figure 6: Comparisons of parametric roll between experiments and simulations, under the condition of λ/L_{pp}=1.0, χ=0^0 and 180^0.

The prediction of head-sea parametric roll in the 1 DOF (FK+R&D) is generally larger than that in the 1 DOF (FK) while this conclusion is not always fit for parametric roll in following seas. Both simulations overestimate the speed range of parametric roll and underestimate the maximum roll amplitude corresponding to the maximum roll in the experiments in head seas. Both simulations have a good agreement with the experiments in following seas, and the radiation and diffraction effects on restoring variation could be ignored in following seas.

5.3 The Passenger Ship







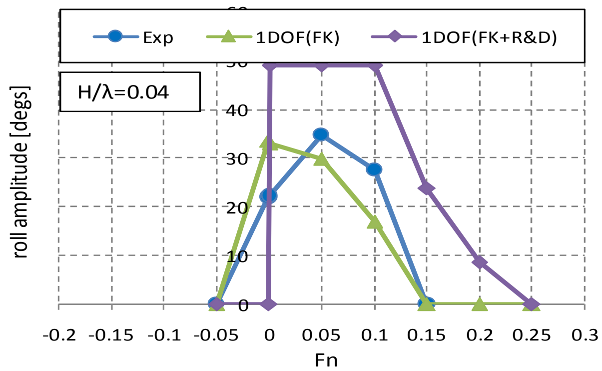
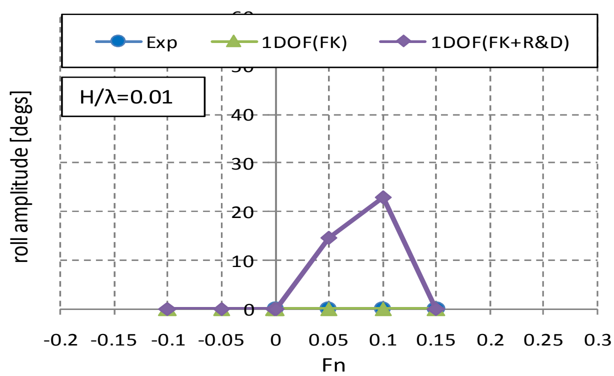


Figure 7: Comparisons of parametric roll between experiments and simulations, under the condition of λ/L_{pp}=1.0, χ=0^0 and 180^0.

The prediction of head-sea parametric roll in the 1 DOF (FK+R&D) overestimates the speed range and maximum angles of parametric roll while the prediction of following-sea parametric roll in the 1 DOF (FK+R&D) underestimates the speed range and maximum angles of parametric roll. The prediction of parametric roll with the 1 DOF (FK) is more close to experiments than that with the 1 DOF (FK+R&D). The radiation and diffraction effects on restoring variation could be ignored in following seas and that in head seas should be further studied for this kind ship.

5.4 The 4250TEU Containership



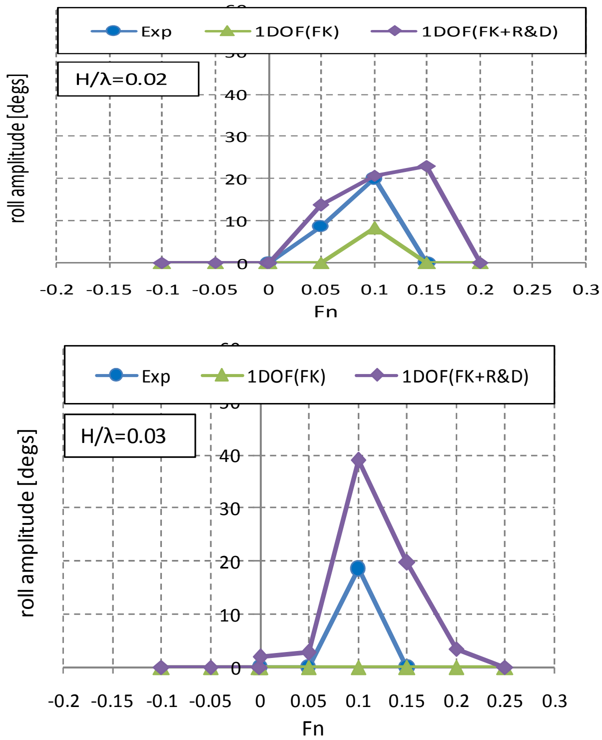


Figure 8: Comparisons of parametric roll between experiments and simulations, under the condition of λ/L_{pp}=1.0, χ=0^0 and 180^0.

The prediction of head-sea parametric roll in the 1 DOF (FK+R&D) overestimates the speed range and maximum angles of parametric roll while the 1 DOF (FK) fails to predict parametric roll at some points because the 4250 TEU containership is not vulnerable to parametric roll and parametric roll is diapeared while wave height increase. The simulations cannot accurately agree with that in the experiments, but the simulations can also prove that the 4250 TEU containership is not vulnerable to parametric roll.

Parametric roll is a nonlinear phenomenon due to the roll restoring force variation and involve dynamic heave and pitch motions in head seas. As examined by above four ships, it is still difficult to predict parametric roll accurately in head seas. However, the 1 DOF approach can predict parametric roll successfully for the post Panamax C11 class containership, and can also identify vulnerable ships of parametric roll successfully.

6. CONCLUSIONS

On the basis of validating the 1 DOF approach by conducting four free running experiments with a post Panamax C11 class containership, a pure car carrier, a passenger ship and a 4250TEU containership, respectively, the following remarks can be made:

1) The effect of radiation and diffraction component on restoring variation should be taken into account in head seas if a conservative prediction of parametric roll in direct stability assessment is required.

2) The effect of radiation and diffraction component on restoring variation could be ignored in following seas if a simplified prediction of parametric roll is required.

3) One method could not be fit for all kind of ships for predicting parametric roll, and the 1 DOF approach can be recommended for parametric criteria at this stage due to its simple application.

A universal method should be found for most kind of ships for parametric roll criteria in future and this kind of ships whose parametric roll disappears with the wave height increase should be pay attention and more examples with experiments and numerical simulations should be conducted to finalize the guidelines of parametric roll criteria.

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