Experimental and Numerical Investigation on Parametric Roll of a Large Container Ship

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Abstract — Parametric roll may cause serious safety issues of ships, particularly large container ships. The International Maritime Organization (IMO) has been working on developing the second generation of the intact stability criteria, parametric roll as a kind of stability failure mode is causing increasing concern to academics. This paper focuses on the prediction of the occurrence of parametric roll and the factors which influence it, a series of tests are conducted in a towing tank with varying speed, wave height, wave frequency, with and without wave excitation. In addition, the trend of the roll response amplitude of the parametric roll is also discussed. Finally, the nonlinear 3-D Rankine panel method is used to predict the parametric roll in the head sea for a full-scale ship, the results of which agrees well with the experimental results.

Keywords - Parametric roll; Container ship; Model experiment; Rankine panel

I. INTRODUTION

A variety of motions happen when the ship is sailing in waves and roll is the most dangerous and common motion [1-4]. When parametric roll happens in head and following seas, the periodical change of the GM causes the instantaneous variation of the wet area [7]. Roll angle increases rapidly in a few periods, which may lead to damage and great harm to the safety of the ship, its cargo and crew. Several incidents occurred in the container ship, it's prone to the phenomenon of parametric roll for the slim body and the complicated hull form of the bow. Today, with the extensive use of container shipping, how to improve the stability performance in waves and minimize the risk of entering in parametric roll resonance is causing increasing concern to academics. However, in order to incorporate parametric roll in ship design and its operation, a deeper understanding of the phenomenon is required.

The International Maritime Organization (IMO) is working on developing the second generation of the intact stability criteria [9], parametric roll, broaching, dead ship, pure loss of stability and the excessive acceleration of five kinds of stability failure mode as the future stability criterion specify the research object. Recently, the IMO and academics tend to use the hydrodynamic theory [16-19] to consider the second generation of the stability criteria, in order to improve the existing system intact stability criteria and reassess of the stability rules. In order to be able to develop and validate a numerical model, having the access to experimental data is of high importance. Therefore, it is expected to obtain reliable data on parametric roll hydrodynamic characteristics in the experimental research program, which can be compared with that of the numerical models.

II. EXPERIMENTS

A 8000TEU container ship in scale 1:80 has been tested in regular waves at the towing tank (length ×width ×depth=108×7×3.5) of Harbin Engineering University (see Fig.(1)). The towing tank is equipped with a flap type wave-maker and a wave height recorder on the other side. Sensors and data acquisition system are installed on the towing carriage. The data acquisition system has two heave-poles on it, the distance between them is 127.9mm, the bigger one was located in the center of gravity, and the other one was in the stern of the model, they can measure 6-DOF motion and avoid the yaw phenomenon occur in experiment (see Fig.(2)). The model was ballasted to correct draft, with the mass units located to obtain the required distribution for the roll and pitch radii of gyration, and a moment of inertia frame was used to measure and set the pitch radius of gyration. What's more, the model has bilge keels on it. The main information of the model is given in table I, while the ship geometry is presented in Fig.(3).

Fig.1 The Towing Tank of Harbin Engineering University

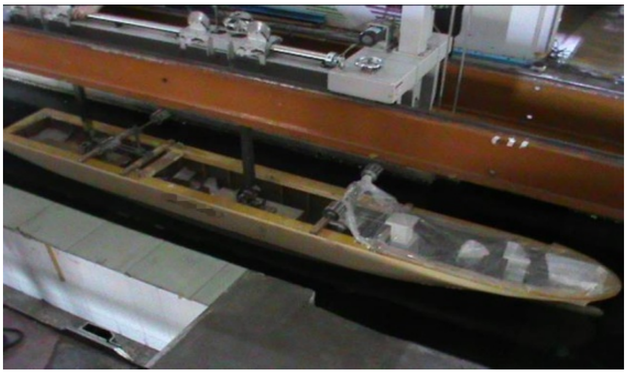


Fig.2 Two Heave-Poles fixed on the Model of the Containership

TABLE I. MAIN INFORMATION OF THE SHIP MODEL.

Displacement（∇）	222.8kg
Breadth（B）	0.50m
Length（L_{pp}）	4.00m
Draft（T）	0.16m
Longitudinal center of gravity（LCG）	1.75% L_{pp} m
Vertical position of the center of gravity（VCG）	0.2m
Pitch gyration radius（K_{yy}）	0.25 L_{pp} m
Metacentric height（GM）	0.05m
Natural roll period（T_n）	2.2s

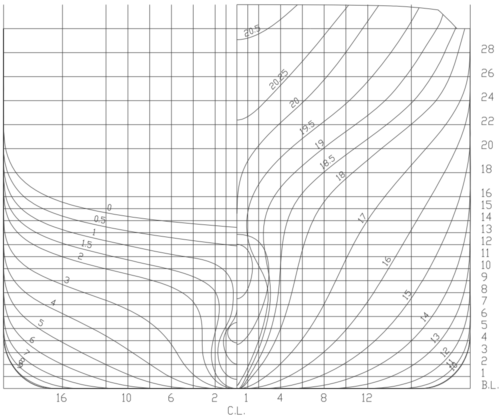


Fig.3 Body Plan of the Ship

In this study, the vessel is tested in regular waves with heading angle of 180 degree, and the model speed is designed according to the Froude number F_r=0, 0.1, 0.2. For the wave steepness S_w, which is the ratio between wave height and wavelength, is 1/20, 1/30, 1/50, 1/100. The roll natural period can be obtained from Eq. (1).

$$T_n = 2\pi\sqrt{\frac{J_{\varphi\varphi} + \Delta J_{\varphi\varphi}}{Dh}} \tag{1}$$

Here T_n is the natural period, $J_{\varphi\varphi}$ is the roll moment of inertia, $\Delta J_{\varphi\varphi}$ is the additional roll moment of inertia, D is the displacement, h is the metacentric height without taking the modification of the free surface into consideration. In a rough estimate, $r_{xx} = \frac{1}{3}B$ and $\Delta J_{\varphi\varphi}$ is about 20% $J_{\varphi\varphi}$。

Finally, there are ratios between the encounter period T_e and the roll natural period T_n, saying T_e/T_n, for which the instability occurs more easily. According to the principle of resonance, T_e/T_n = 0.45, 0.5, 0.55, 0.6. We can obtain the encounter frequency ω_e, the wave period and the wavelength form Eq. (2)

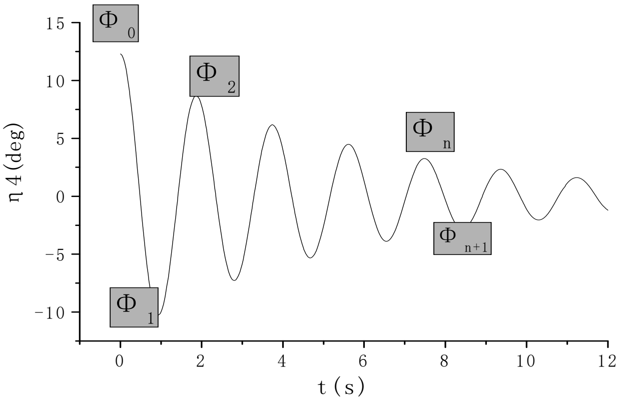
$$T_e = \frac{2\pi}{\omega_e}, \qquad \omega_e = \omega(1 - \frac{\omega V \cos\beta}{g}), \qquad T = \sqrt{\frac{2\pi\lambda}{g}} \tag{2}$$

T is the wave period, ω is the wave circular frequency, λ is the wavelength, V is the speed, and β is 180 degree.

A. *Roll damping*

The roll damping is a key design parameter for the avoidance of parametric roll. None of current State-of-the-art computational programs can claim to calculate the roll damping accurately for any given vessel including all roll damping devices.

Assuming the ship do free rolling in still water with an initial roll angle ϕ_0, energy dissipation for water damping. The roll angle changing with time is a gradual attenuation curve, ϕ_n is the amplitude of n time, then half a period is ϕ_{n+1}, $\Delta\phi = \phi_n - \phi_{n+1}$, the average amplitude of two adjacent sampling points $\phi_m = (\phi_n + \phi_{n+1})/2$, there is a linear relationship between $B(\dot{\phi})$ and $\dot{\phi}$ as the same case of $\Delta\phi$ and ϕ_m. Here, a and b are the attenuation coefficients, A and B are the damping coefficients.



$\Delta\phi = a\phi_m + b\phi_m^2$	$B(\dot{\phi}) = -2A\dot{\phi} - B\lvert\dot{\phi}\rvert\dot{\phi}$
$\Delta\phi = b\phi_m^2$	$B(\dot{\phi}) = B\lvert\dot{\phi}\rvert\dot{\phi}$
$\Delta\phi = a\phi_m$	$B(\dot{\phi}) = -2A\dot{\phi}$

Fig.4 Curve of Extinction (Up) and the Relationship between Attenuation and Damping (Bottom)

Energy method is used here to obtain the relationship between attenuation coefficients and damping coefficient. Reduction of potential energy is equal to the damping moment energy consumption as follows:

$$\begin{aligned}\Delta E &= \int_0^{\phi_n} Dh\phi d\phi - \int_0^{\phi_{n+1}} Dh\phi d\phi \\ &= \frac{1}{2}Dh(\phi_n^2 - \phi_{n+1}^2) \\ &= Dh\phi_n\Delta\phi\end{aligned} \tag{3}$$

$$W = -\int_{\varphi_n}^{\varphi_{n+1}} (A\dot{\varphi} + B\dot{\varphi}^2)d\varphi \tag{4}$$

$$W = \Delta E \tag{5}$$

$$\Delta\phi = -\frac{1}{\mathrm{Dh}}\left(\frac{n_\varphi\pi}{2}A\phi_n + \frac{4n_\varphi^2}{3}B\phi_m^2\right) \tag{6}$$

$$A = \frac{2Dh}{n_\varphi\pi}a, \qquad B = \frac{3Dh}{4n_\varphi^2}b \tag{7}$$

Where D is the displacement of the model, and h is the metacentric height, n_ϕ is the natural circular frequency, μ is the dimensionless attenuation derived from the least square method. $2\mathrm{v}_{\varphi\varphi}$ is the unit moment of inertia damping coefficient, and β is the unit square damping coefficient of the moment of inertia.

$$\mu = \frac{1}{\pi}(a + \mathrm{b}\phi_m), \qquad 2v_{\varphi\varphi} = \frac{4}{T_\varphi}a, \qquad \beta = \frac{3}{4}b \tag{8}$$

$$2v_{\varphi\varphi} = \frac{A}{I_{\varphi\varphi} + \Delta I_{\varphi\varphi}}, \qquad \beta = \frac{B}{I_{\varphi\varphi} + \Delta I_{\varphi\varphi}} \tag{9}$$

The roll attenuation curves with different speeds in still water are shown in Fig.(5), with the results of the roll damping shown in table II.

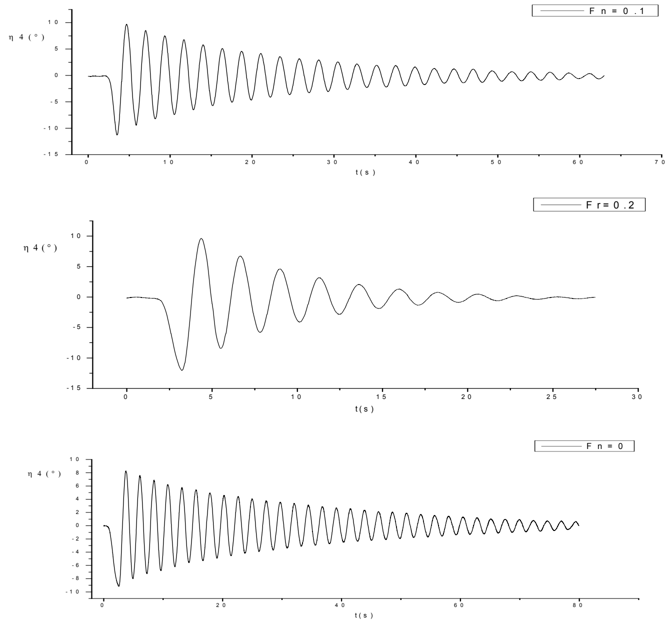


Fig.5 Roll Attenuation Curve under Different Speed in Still-Water

TABLE II. ROLL DAMPING RESULT IN DIFFERENT SPEEDRoll.

Froude number	Fr=0	Fr=0.1	Fr=0.2
The initial roll angle	9.16	11.26	12.02
a	1.92E-02	4.35E-02	0.16
b	3.97E-03	3.10E-03	7.48E-03
Linear damping coefficient N1	0.5	1.24	4.41
The square damping coefficient N2	5.05E-02	3.90E-02	9.20E-02
Dimensionless attenuation of the linear damping coefficient	0.033	0.074	0.27
Dimensionless attenuation of the square damping coefficient	0.0030	0.0023	0.0056
Dimensionless attenuation of the equivalent linear coefficient $2\overline{\mu}$	0.038	0.056	0.18

B. Influence factors of parametric roll

In this part, the analysis of experimental results main take account of the conditions for the occurrence of parametric roll, the influences of speed change, wave parameters (wave period, wavelength, wave height), and the wave excitation, which is also considered in this part. The experimental results are very meaningful to the numerical simulations in the future.

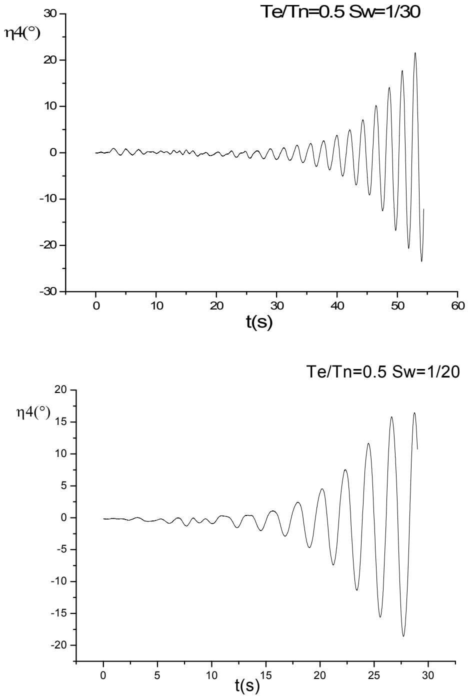


Fig.6 Fr=0.1, No Wave Excitation, the Wave Length-to-Ship Ratio λ/L is 0.78.

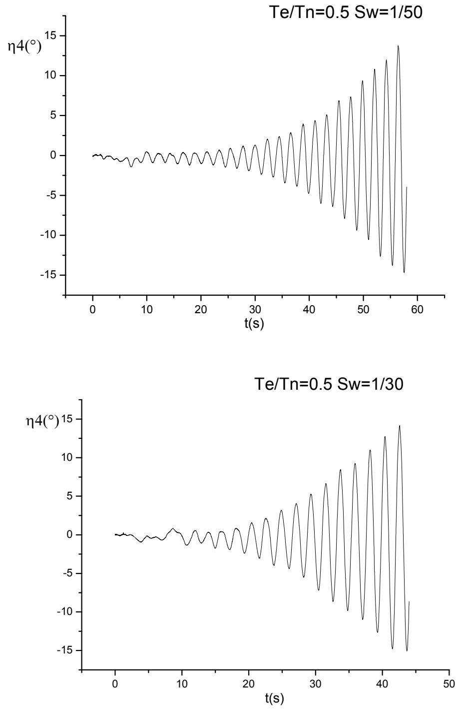


Fig.7 Fr=0.2, No Wave Excitation, the Wave Length-to-Ship Ratio λ/L is 1.05.

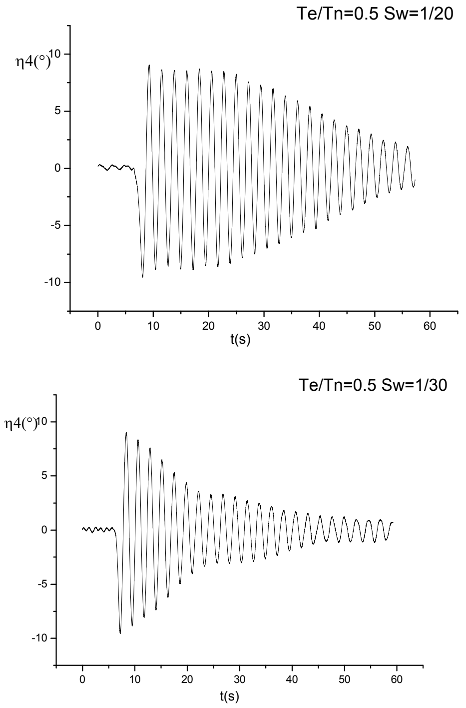


Fig.8 Fr=0, Wave Excitation, the Wavelength –to -Ship Ratio λ/L is 0.47.

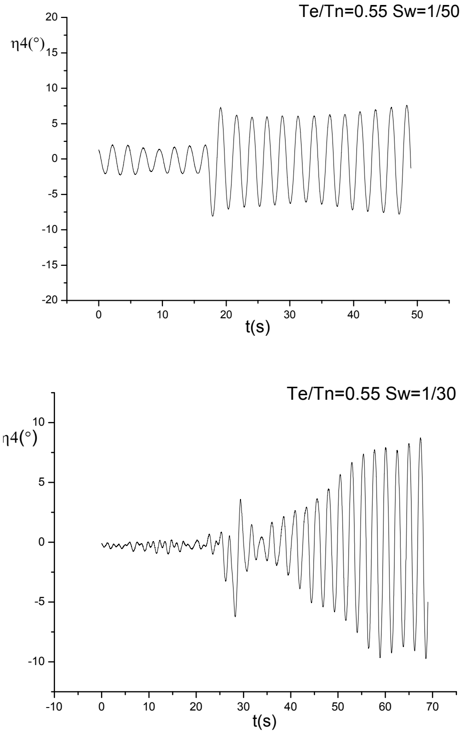


Fig.9 Fr=0.1, Wave Excitation, the Wavelength -to-Ship Ratio λ/L is 0.91.

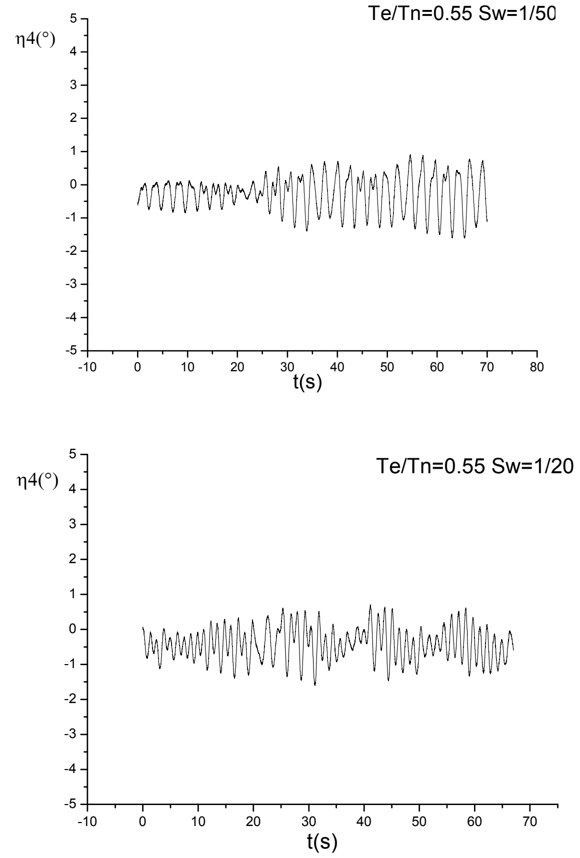


Fig.10 Fr=0.1, No Wave Excitation, the Wave Length-to-Ship Ratio λ/L is 0.91.

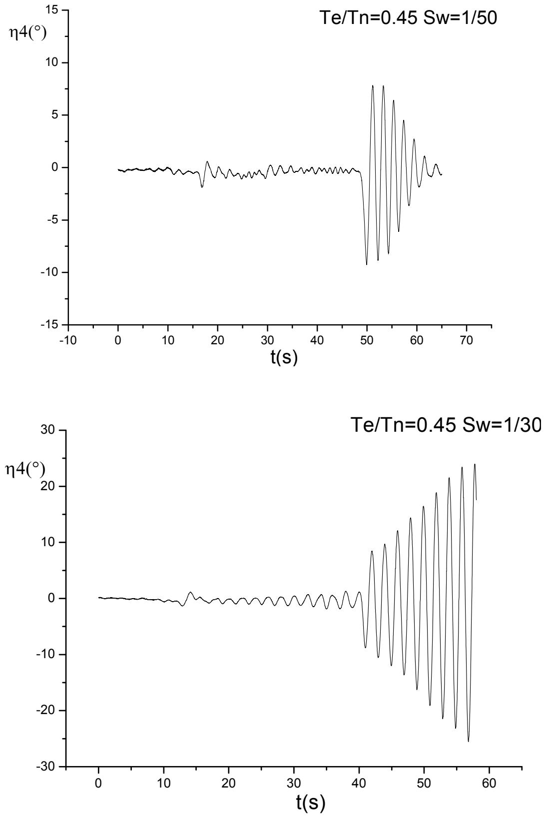


Fig.11 Fr=0.2, Wave Excitation, the Wavelength -to-Ship Ratio λ/L is 0.89.

When the ratio between encounter period and the roll natural period T_e/T_n is 0.5, parametric roll occurs easily (see Fig.(6) and Fig.(7)). As the wave height increases, the time of the phenomenon gets shorter, and the roll amplitude increases rapidly. Under the same wave condition, there is no parametric roll at zero speed, even though add wave excitation to the model, roll motion finally decay. When the ratio between encounter period and the roll natural period is not 0.5, it needs a long time for the phenomenon to start. Then, when adding a wave excitation, the parametric roll occurs. The initial angle is presented in the Figures which have a wave excitation (see Fig.(8), Fig.(9) and Fig.(11)).

TABLE III. ROLL EXCITATION INFLUENCE IN EXPERIMENT.

Fr	Te/Tn	λ/L	S_w	Roll excitation	Parametric roll(Yes/No)
0.1	0.55	0.91	1/50	√	Yes
0.1	0.55	0.91	1/50	×	NO
0.1	0.55	0.91	1/30	×	NO
0.1	0.45	0.66	1/30	√	Yes
0.1	0.45	0.66	1/20	×	Yes
0.1	0.45	0.66	1/50	√	NO
0.1	0.6	0.68	1/20	√	Yes
0.1	0.6	0.68	1/30	√	NO
0.2	0.45	0.89	1/50	√	NO
0.2	0.45	0.89	1/30	√	Yes
0.2	0.45	0.89	1/20	√	Yes
0.2	0.55	1.21	1/50	√	NO
0.2	0.55	1.21	1/30	√	NO
0.2	0.55	1.21	1/20	√	Yes
0	0.45	0.38	1/20	√	NO
0	0.55	0.57	1/20	√	NO

Fig.12 Serious Parametric Roll Phenomenon in Experiments

The influence of wave excitation can be seen in table III, the roll angle time history for each test in waves is examined and placed into one of two categories: parametric roll; no parametric roll, after the initial wave excitation the roll motion decayed. The wave excitation is made by using a bamboo pole press the side of the model leading a small roll angle (see the right of Fig.(12)).

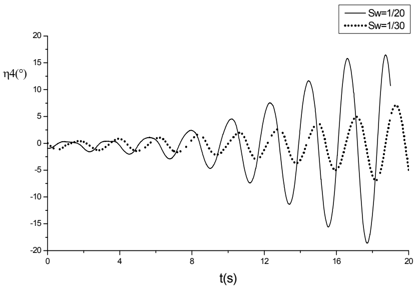


Fig.13 Fr=0.1,Te/Tn=0.5

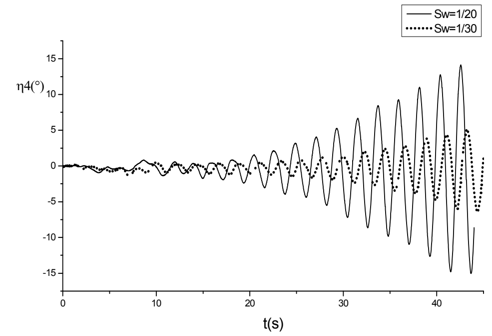


Fig.14 Fr=0.2,Te/Tn=0.5

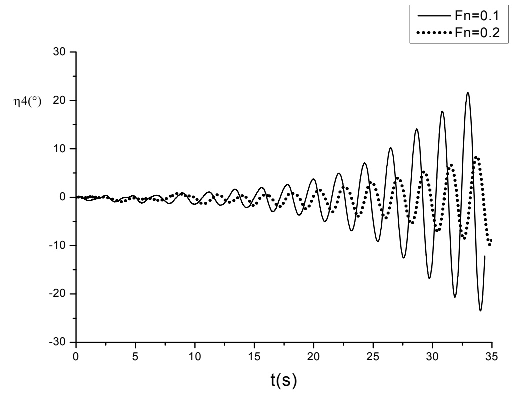


Fig.15 S_w=1/30, Te/Tn=0.5

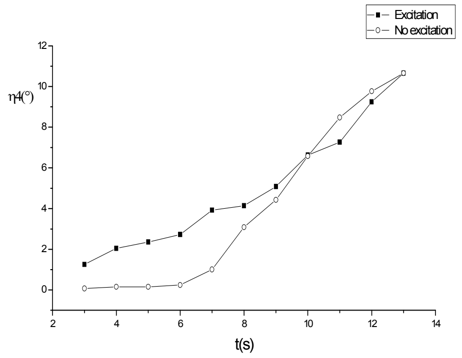


Fig.16 Final Roll Angle Influence of the Wave Excitation

Fig.(13) and Fig.(14) show the influences of wave steepness. With the same speed, roll angle increases with the increasing of the wave height. It's concerned that the increase of the wave height can increase the probability of occurrence of the parametric roll in a certain range until reaching the threshold. Fig.(15) shows when the wave steepness is identical, low speed may lead to serious parametric roll more easily. However, in complicated sea condition, wave excitation is an important issue for the parametric roll motion. Whatever, whether the wave excitation will affect the result of the final roll angle? It can be observed from Fig.(16) that the roll angle coincidence in the end.

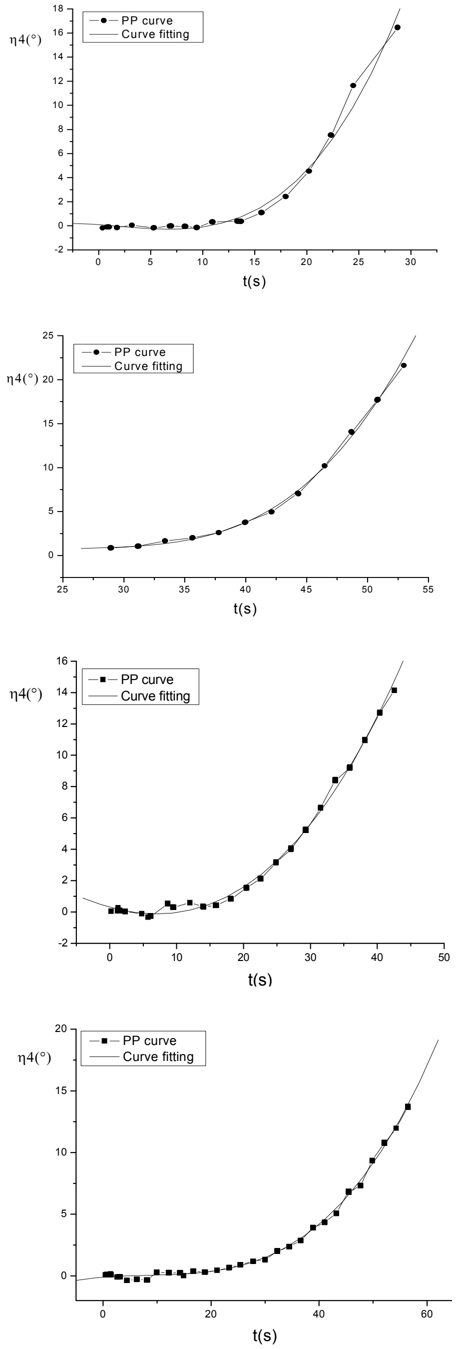


Fig.17 Cubic Fit with the Peak Point Curve

As we have known, when the ship encounter with parametric roll, the roll angle increase quickly in a short time, but the trend of roll angle has never been discussed before. Picking the peak point of roll curve from Fig.(6) and Fig.(7), a cubic polynomial fit has a good agreement with the peak point curve (see Fig. (17)).

III. THE VALIDATION OF NUMERICAL METHOD AND EXPERIMENTAL FOR THE FULL-SCALE SHIP

A. Numerical investigation of the nonlinear model in regular waves

Based on the 3-D linear potential flow theory, the definite conditions of velocity potential of the disturbance flow field around the ship with forward speed are established. Artificial numerical beach is introduced to absorb disturbance waves, keeping them from reflecting back. The radiation potential and the disturbance are solved by 3-D Rankine panel method. Taking the consideration of nonlinear factors due to the instantaneous position variation of the body surface, the nonlinear ship motion equation is established and solved in time domain.

The following nonlinear effects are included with the nonlinear option:

- Integration of Froude-Krylov and hydrostatic pressure over exact wetted surface.
- Quadratic terms in Bernoulli equation are included.
- Exact treatment of rotation angles in inertia and gravity terms.
- Quadratic roll damping.

A velocity potential φ_T can be used to describe the water velocity based on the basic assumptions that the sea water is incompressible, inviscid and the fluid motion is irrotational. Laplace equation can be derived:

$$\nabla^2\varphi_T = 0 \tag{10}$$

Dynamic boundary condition is:

$$\frac{\partial\varphi}{\partial t} = -g\zeta \quad , \quad z = 0 \tag{11}$$

Kinematic boundary condition is:

$$\frac{\partial\zeta}{\partial t} = \frac{\partial\varphi}{\partial z} \quad , \quad z = 0 \tag{12}$$

where ζ is the total disturbance free surface elevation.

The surface of the object S_B should satisfy the impenetrable condition:

$$\nabla\varphi \cdot n = V \cdot n - \nabla\varphi_I \cdot n \tag{13}$$

where n is the outer normal of S_B, V is the velocity.

The initial conditions are:

$$\varphi = 0 \quad , \quad \frac{\partial\varphi}{\partial t} = 0 \quad , \quad t = 0 \tag{14}$$

The incidence wave potential and wave height η are defined as:

$$\begin{cases} \varphi_I = \dfrac{gA}{\omega} e^{kz} \sin(kx - \omega t + \varepsilon) \\ \eta = \dfrac{gA}{\omega} e^{kz} \cos(kx - \omega t + \varepsilon) \end{cases} \tag{15}$$

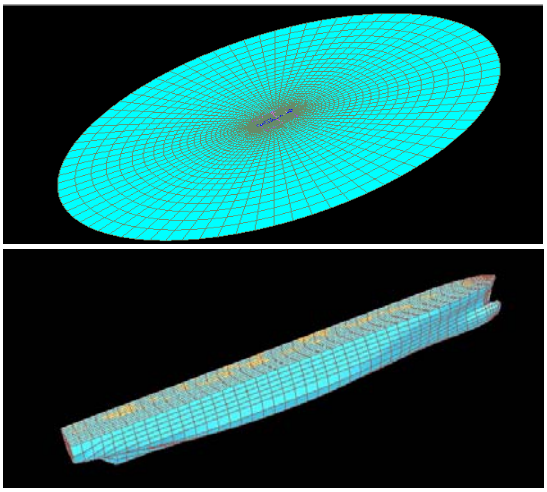


Fig.18 Hydrodynamics Mesh Model for the Container Ship

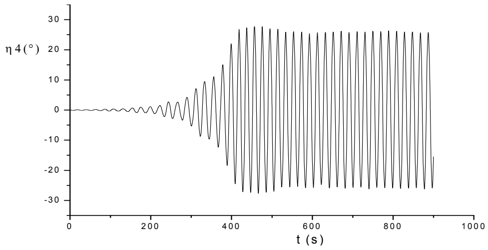


Fig.19 Fr=0.1,Te/Tn=0.5 S_w=1/30

Here, A is the wave amplitude and ε is the phase angle.

The equation of the motion is

$$\begin{cases} m\dfrac{dV}{dt} = F \\ I\dfrac{d\omega}{dt} + m\dfrac{d(r \times V)}{dt} = M \end{cases} \tag{16}$$

where m is the mass of the ship, F and M are the force and moment of the center of gravity. I is the moment of inertia matrix of the ship.

The force (moment) on the hull is:

$$F_T^{Nonlinear} = F_{RES}^{nonlinear} + F_{FK}^{nonlinear} + F_{HD}^{Linear} \tag{17}$$

where $F_{RES}^{nonlinear}$, $F_{FK}^{nonlinear}$, F_{HD}^{linear} are the restoring force(moment), Froude-Krylov force (moment) and the hydrodynamic force (moment) .

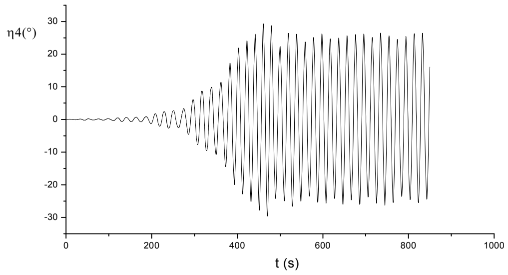


Fig.20 Fr=0.1,Te/Tn=0.5 S_w=1/20

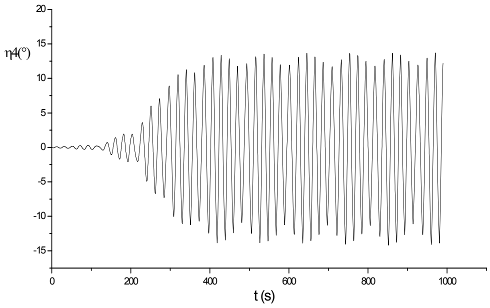


Fig.21 Fr=0.2,Te/Tn=0.5 S_w=1/50

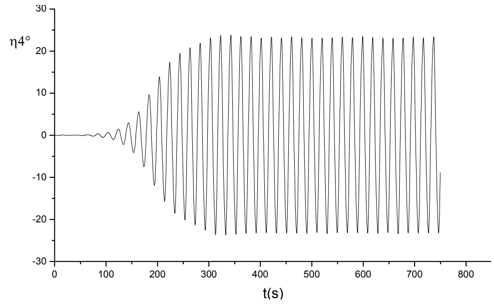


Fig.22 Fr=0.2,Te/Tn=0.5 S_w=1/30

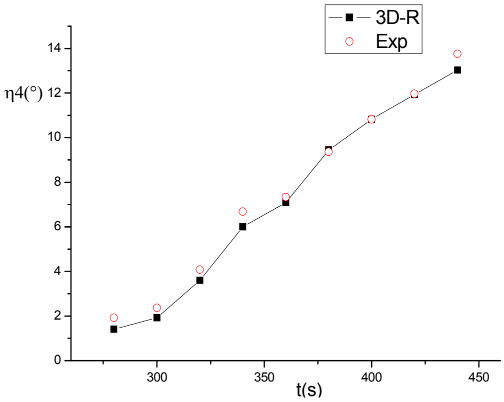


Fig.23 Fr=0.1,Te/Tn=0.5 S_w=1/30

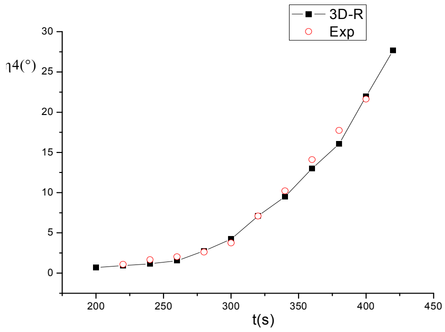


Fig.24 Fr=0.2,Te/Tn=0.5 S_w=1/50

From Fig.(19) to Fig.(22) are the numerical results of the container ship in head seas, and experiment and numerical results are presented in Fig.(23) and Fig.(24),which show that the numerical results and the experimental results agree well.

IV. CONCLUSIONS

In this paper, experimental and numerical results of the phenomenon of parametric roll resonance in a towing tank for a 8000TEU container ship in regular waves, have been presented. The data of the experiment have a crucial effect on promoting the development of the numerical simulation.

Roll damping is obtained by fitting the extinction curve, which is a accurate way in studies. By analyzing the effects that influence the parametric roll, it is concluded that the increase of wave height can result in an increase of the roll angle until reaching the threshold. Improving the speed appropriately can reduce the parametric roll moment. Wave excitation is an important issue to the parametric roll motion, but it will not affect the final roll angle. In addition, the trend of the roll angle is noted that a cubic polynomial fit has a good agreement with the roll peak point curve.

The 3-D Rankine panel method for the regular wave in head seas has a high agreement with the experiment. Considering the nonlinear factors, the method can predict the roll angle during the design phase and has further evidence of its reference value.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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