# Investigation of Susceptibility of Parametric Roll in Regular and Irregular Waves

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**ABSTRACT**

In the present study, the effect of consideration of wave length and ship speed in the procedure of the susceptibility check guide by ABS (2004) was investigated. A simple method was adopted for calculating hydrostatics. Some modifications were made to the original procedure in order to consider realistic wave condition and hydrostatic equilibrium. It was found that the modifications to the susceptibility procedure gave noticeable enhancing correlations between the susceptibility predictions and the numerical simulations in regular and irregular waves. A series of parametric roll simulations were conducted to investigate behavior of IPR (Index of Parametric Roll, Hong, 2009), which gives systematic identification of parametric roll in irregular sea ways.

**KEYWORDS**

Susceptibility; Parametric Roll; Index of Parametric Roll; Time-domain Simulation

## INTRODUCTION

Parametric roll motion of container carrier is one of the typical examples of Mathieu-type instability, which is caused by periodic change of restoring force/moment in waves. Recent noticeable increase of container carrier size resulted in typical post-panamax container hull form which has a large flared bow, stem overhang and wide beam. This kind of hull form is the a main source of vulnerability of post-panamax container carriers to unwanted large roll motion in head and following waves (France et al., 2003).

The change of roll restoring moment in waves is significant especially when the wave length is comparable with ship length. Roll motion induced under such situation when encounter wave frequency is double of roll natural period has been known as parametric roll (Kerwin, 1955; Paulling and Rosenberg, 1959). Recently there has been a number of systematic studies on parametric roll (Belenky et al, 1998, 2003, 2006; Francescutto and Bulian, 2002; Spyrou, 2005, 2008; Neves and Rodriguez, 2006). Most of previous studies have concentrated on analytical approach based on Mathieu-type nonlinear equation and heading angles are limited on head and following seas. In practice, however, parametric roll has been observed not only for the typical case in which wave length is the same as ship length and the encounter period is half of roll natural period but for wide range of wave periods, lengths and headings from numerical and experimental studies (Shin et al., 2004, Ikeda et al., 2005, Levadou and Gaillarde, 2003, Hong et al., 2009, Shigunov et al, 2009). Recent growth of time-domain ship motion simulation tools makes it possible to assess parametric roll for various wave conditions not limited to head and following regular waves.

Even though enhanced tools for simulation of parametric roll in time domain are available for design and analysis of container carriers, it is also important to assess parametric roll susceptibility by simple estimation of stability changes in waves, because the result of the susceptibility criteria gives an understanding of the overall trend of parametric roll occurrences and a guide to plan numerical and physical experiments matrix to identify and quantitatively evaluate parametric roll for avoiding parametric roll in service.

In the present study, the effects of consideration of realistic conditions in simplified susceptibility procedure are investigated, such as ship speed, wave length and heading angle rather than encounter frequency only with specific wave length. The prediction results are compared with those of nonlinear time-domain parametric roll simulation. In irregular wave conditions, a kind of operational effectiveness approach is conducted in which the correlations between encounter period, corresponding wave length, maximum roll angle and IPR (Index of Parametric Roll) suggested by Hong et al.(2009) are investigated simultaneously.

$$IPR = \int_{\omega_1}^{\omega_2} H(\omega) S_\zeta(\omega) d\omega / m_0$$
$$H(\omega) = S_{xy}(\omega) S_{yx}(\omega) / (S_{xx}(\omega) S_{yy}(\omega)) \qquad (1)$$
$$m_0 = \int_{\omega_1}^{\omega_2} S_\zeta(\omega) d\omega$$

## SUSCEPTIBILITY IN REGULAR WAVES

### *Consideration of Wave Length, Ship Speed and Heading Angles*

The susceptibility check procedure of ABS (2004) guide is considered in the present study. The following modifications were made and numerically implemented to investigate effects of wave length, ship speed and heading angle in the parametric roll susceptibility criteria. The ABS guide assumes that the wave length is same as the ship length, wave height is determined according to the wave length, which is very similar to design wave concept in structural design to give conservative estimation (Shin et al, 2004).

The modified form of wave elevation to calculate hydrostatics approximates the equilibrium of buoyancy and weight such that mean water line change due to wave profile is taken into account especially for long waves. The modified form uses weighting factor for the range of wave length ratio 0.5< $\lambda / L$ <1.5 where buoyancy change is drastic due to pitch motion.

(1) Original form (ABS Guide, 2004)

$$d(x_i, x_{Cj}) = d_m + 0.5 h_w \cos\left(\frac{2\pi(x_i - x_{Cj})}{L}\right) \qquad (2)$$

(2) Modified form

$$\begin{aligned} &d_1(x_i, x_{Cj}) = d(x_i, x_{Cj}) - h_m \\ &\qquad \text{if } \lambda \geq 1.5L \\ &d_2(x_i, x_{Cj}) = d(x_i, x_{Cj}) - h_m \left(\frac{\lambda - 0.5L}{L}\right) \\ &\qquad \text{if } 1.5\text{L} \geq \lambda \geq 0.5L \qquad (3) \\ &d_3(x_i, x_{Cj}) = d(x_i, x_{Cj}) \\ &\qquad \text{if } 0.5\text{L} \geq \lambda \\ &h_m = \frac{1}{N_C} \sum_{j=1}^{N_C} 0.5 h_w \cos\left(\frac{2\pi(x_i - x_{Cj})}{\lambda} \cos\beta\right) \end{aligned}$$

where, $d(x_i, x_{Cj})$ denotes instantaneous draft of $i$-th station with $j$-th position of the wave crest.

Typical examples of the difference between the original susceptibility procedure and the modified one are shown through Figs. 1 ~ 2. In Fig. 1, the left hand side figures show the parametric roll susceptibility predictions by the ABS original procedure while the right hand side ones are those by the modified form. In each figure, abscissa denotes wave heights, and the ordinate denotes encounter frequency. In the case of the modified procedure wave length is determined by heading angle, ship speed and wave frequency. Red dots (parametric roll occurs) and blue cross symbols (no parametric roll occurs) denote the simulation results by NLOAD3D (SAIC, 2008), green area represents susceptible parametric roll regions.

The ABS original procedure and the modified one both predict wider susceptible regions of parametric roll than simulations. In the original procedure, however, the susceptible encounter frequency moves to higher frequency as wave height and length increase while the simulations do not show such behaviors. The modified procedure shows better coincidences with the simulations in the region of long period and high waves due to consideration of wave length and hydrostatic equilibrium.

In Fig. 2, the parametric roll susceptibility regions for various heading angles are compared. Red regions denote susceptible conditions. It can be seen that the modified form captures nearly all cases predicted by the simulation for wade range of wave incidences and ship speeds, except in the case of extremely high waves in following sea.

There are three sub-regions of susceptible area as shown in Fig. 3. In region (A), the original procedure exaggerates stiffening effect as wave height increases so much, which misses possible parametric roll occurrence in high wave condition. In this region wave length is relatively longer than ship length up to two times or higher. The modified procedure accounts the hydrostatic equilibrium in longer wave region, which enhances prediction capability in that region. In region (B) where wave amplitude is relatively moderate, both methods overestimate susceptibility while NLOAD3D simulation gives less possibility as ship speed is increased. In regions (C) where wave length is relatively shorter than regions (A) & (B), parametric roll hardly occurs because the wave length is shorter than half of ship length. But the susceptibility criteria approximates that the restoring moment changes as one period even in shorter waves, which gives conservative predictions than real situation.

In summary, the original susceptibility criteria may miss important possible parametric roll regions. The assumption that wave length is equal to ship length does not always imply worst scenario. Consideration of realistic wave length in long period region gives more realistic estimation of parametric roll susceptibility. A suggestion for enhancement of susceptibility criteria is to account ship speed, heading and wave period simultaneously.

## SUSCEBTIBILITY IN IRREGULAR WAVES

### *Representation of Irregular Sea States*

Selection of critical sea states for prediction of parametric roll should be based on realistic operational scenario which considers involuntary ship speed reduction corresponding to sea states and heading angles. Here, an example of selection of sea states is given for three container ships of which main particulars are summarized in Table 1.

**Table 1: Main particulars of container ships**

| TEU | 6,250 | 10,000 | 13,000 |
|---|---|---|---|
| Lpp (m) | 286.3 | 321.0 | 366.0 |
| Breadth(m) | 40.3 | 48.4 | 57.0 |
| Height (m) | 24.1 | 27.2 | 27.2 |
| Draft (m) | 13.127 | 15.0 | 15.0 |
| GM (m) | 1.128 | 1.959 | 5.5 |
| T_roll (sec) | 30.7 | 28.8 | 22.2 |

For operational sea states scenarios, the following sea states were assumed.

- $H_{1/3}$: 1.88m, 3.25m, 5.0m, 7.5m, 11.5m
- $T_p(\equiv 5\sqrt{H_{1/3}}$ , ): 0.8 ~ 1.2 $T_p$
- Service ship speed: 25 knots

Operating ship speed was determined considering involuntary speed loss due to added resistance depending on heading and wave height (Table 2). In the case of no data on added resistance of the target ship, the reference value (Fig. 4, Lewis, 1989) can be used.

For given sea state conditions, encounter period contour could be drawn in which wave period variation is taken into account. Five cases of wave periods ( $T = 0.8T_p \sim 1.2T_p$ ) were considered to investigate variations of wave heights and corresponding wave periods.

**Table 2: Operating speeds ($V_s/V_{s0}$, $V_{s0}$=25knots)**

| H1/3(m) | Tp (sec.) | Heading Angle(degrees) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 180 | 165 | 150 | 135 | 120 | 105 | 90 | 75 | 60 | 45 | 30 | 15 | 0 |
| 1.88 | 7.5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3.25 | 8.8 | 0.9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 | 9.7 | 0.85 | 0.85 | 0.86 | 0.87 | 0.87 | 0.88 | 0.89 | 0.9 | 0.91 | 0.93 | 0.95 | 0.97 | 1 |
| 7.5 | 12.4 | 0.65 | 0.69 | 0.73 | 0.77 | 0.8 | 0.83 | 0.85 | 0.88 | 0.92 | 0.95 | 0.97 | 0.99 | 1 |
| 11.5 | 15 | 0.4 | 0.5 | 0.55 | 0.6 | 0.63 | 0.67 | 0.7 | 0.73 | 0.77 | 0.8 | 0.85 | 0.9 | 0.95 |

a)

b)

c)

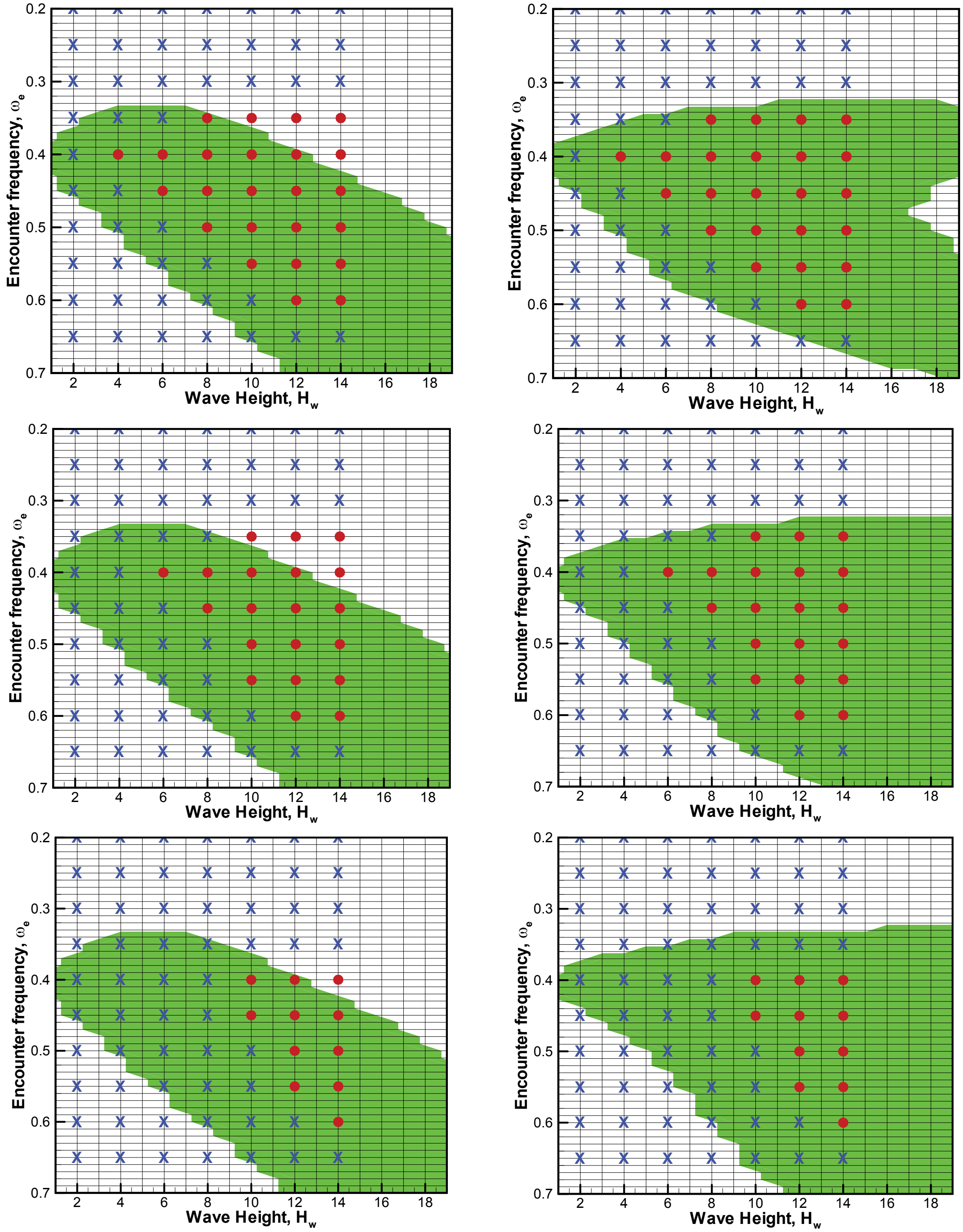


Fig. 1: Comparison of parametric roll susceptibility criteria between original form and modified form with NLOAD3D (symbol, red circle: true, blue X: false) for a 6250 TEU container ship in head sea (a) Vs = 5 kn (b) Vs = 12.5 kn (c) Vs = 17.5 kn

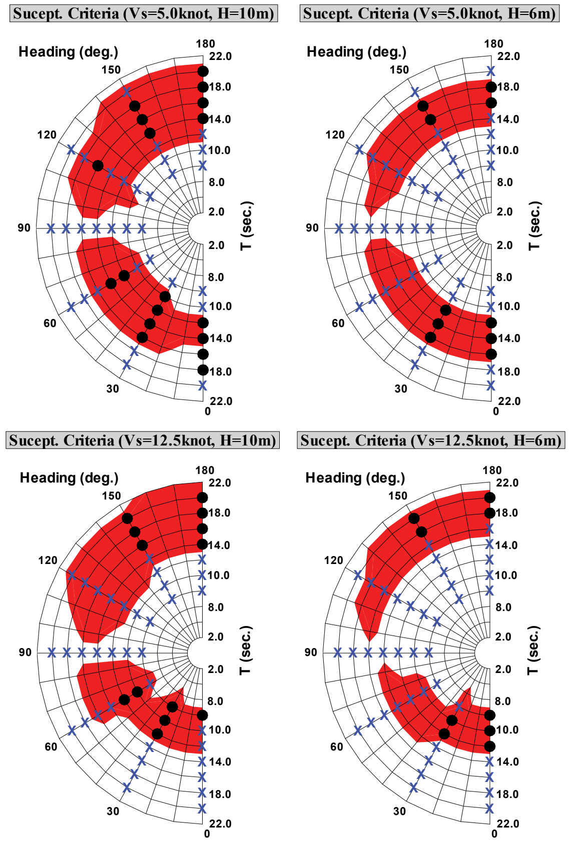


**Fig. 2: Comparison of parametric roll susceptibility criteria by modified form with NLOAD3D (symbol, circle: true, X: false)**

### *Identification of Parametric Roll in Irregular Waves*

Fig. 5 shows an example of simulation results for the conditions described in the previous section, The simulation duration is 0.5 hours. In the figure, the encounter period, corresponding effective wave length ratio ( $\lambda / L \cos\beta$ ), maximum roll angle and IPR are shown respectively as contours. From the top line to the bottom, effects of modal period changes are shown for the 6250 TEU container ship of which roll natural period is 30.7 seconds. In the present calculation, the possible encounter period of parametric roll lies between 10 to 18 seconds in regular waves according to the modified form. Highest level of maximum roll angle due to parametric roll appears at intersection range of encounter modal periods10 ~ 15 seconds and modal wave length ratio 1~2.5, which has a very close correlation with regular wave cases. It can be seen that IPR has very good correlations with highest roll due to parametric roll for various irregular sea states. In these simulations, IPR values less than 0.7 (green) indicates parametric roll.

The correlation factor between regular and irregular wave periods and lengths could be obtained through more systematic numerical tests, whatever those are zero-upcrossing, mean and modal periods.

Fig. 6 shows a case for 10,000 TEU and 13,000 TEU vessels when $T_p$=1.0 $T_p$. similar behaviors are observed for correlation between IPR and Max roll. In case of the 13,000 TEU container vessel, no critical parametric roll occurrence is observed.

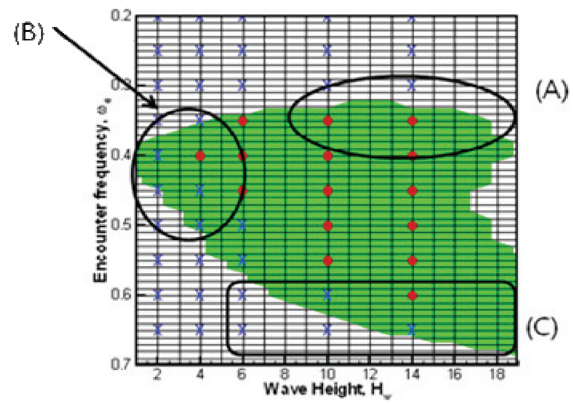


**Fig. 3: Categorization of susceptible region of parametric roll**

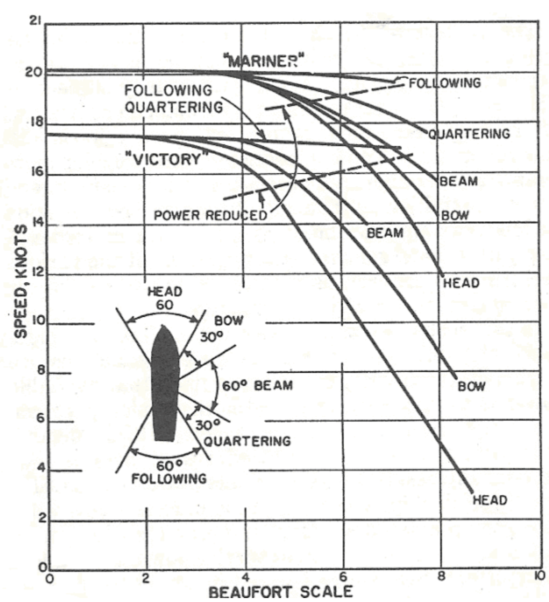


**Fig. 4: Attainable ship speed in different sea conditions for two classes of cargo ships (Lewis, 1989)**

## CONCLUSIONS

The realistic wave condition such as wave heading and ship speed, and weight-buoyancy equilibrium were accounted in estimation of hydrostatic change in assessing parametric roll susceptibility. Implemetation of the modified procedure noticeably enhances correlation with time-domain simulation reslts. In irregular sea conditions, a practical scenario for performance evaluation was proposed, which can gives a useful guide for route planning. A series of simulation results strongly supports the usefulness of IPR (Index of Parametric Roll) for identifying parametric roll in irregular seaways.

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## REFERENCES

ABS (2004) Guide for the Assessment of Parametric Roll Resonance in the Design of Container Carriers. (Updated June 2008).

Belenky, V. L., Weems, K. M., Lin, W. M. and J. R. Pauling, (2003), “Probabilistic analysis of roll parametric resonance in head seas” Proc. of 8th Intl Conf on Stability of Ships and Ocean Vehicles (STAB 2003), Madrid, Spain. pp325-340

Belenky, V. L., Degtyarev, A. B. and A. V. Boukhanovsky, (1998), “Probabilistic qualities of nonlinear stochastic rolling”, Ocean Engineering, Vol. 25, No. 1, pp1-25

Belenky, V., Yu, H.C., Weems, K. (2006). “Numerical procedures and practical experience of assessment of parametric roll of container carriers”, Proc of the 9th Intl Conf on Stability of Ships and Ocean Vehicles (STAB 2006), Rio de Janeiro, Brazil pp. 119–130.

France, W.N., Levadou, M., Treakle, T.W., Paulling, J.R., Michel, R.K., Moore, C. (2003). “An investigation of head-sea parametric rolling and its influence on container lashing systems”, Marine Technology, 40 (1), 1–19.

Hong, S.Y., Yu, H.C., Kim, S.E. and Sung, H.G. (2009), “Investigation of parametric roll of a container ship in irregular seas by numerical simulation”, Proc. 10th Intl Conf Stability of Ships and Ocean Vehicles (STAB 2009), St. Petersburg, Russia, pp 549-558

Ikeda, Y., Munif, A., Katayama, T., Fujiwara, T. (2005), “Large parametric rolling of a large passenger ship in beam sea and role of bilge keel in its restraint”, Proc. 8th Intl Ship Stability Workshop, Istanbul, Turkey, pp 1-11

Kerwin, J.E. (1955), “Notes on rolling in longitudinal waves”, Intl Shipbuilding Progress, Vol. 2, No. 16, pp597-614

Levadou, M., Gaillarde, G., 2003. Operational guidance to avoid parametric roll. Design and Operation of Container Ships, London, pp. 75–86.

Lewis, E., V. (Ed) (1989), Principles of Naval Architecture, Volume III: Motions in Waves and Controllability, SNAME

Neves, M.A.S., Rodriguez, C.A. (2006). “An investigation on roll parametric resonance in regular waves”, Proc of the 9th Intl Conf on Stability of Ships and Ocean Vehicles (STAB 2006), Rio de Janeiro, Brazil, pp. 99–108.

Paulling J. R. and Rosenberg R.M. (1959). “On unstable ship motions resulting from nonlinear coupling”, J. of Ship Research, Vol. 3, No 1, pp. 36-46.

SAIC (2008), NLOAD3D Nonlinear 3D Seakeeping and Load Prediction Program User Documentation, ver. 1.4.0, Apr. 2008

Shigunov, V., el Moctar, O., Rathje, H., (2010). “Operational guidance for prevention of cargo loss and damage on container ships”, Ship Technology Research 57 (1), 8–28.

Shin, Y. S., Belenky, V.L., Paulling, J.R., Weems, K.M., and W.M. Lin (2004), “Criteria for Parametric Roll of Large Containerships in Longitudinal Seas,” SNAME Trans. Vol. 112, pp. 14-47.

Spyrou, K.J.(2005), “Design criteria for parametric rolling”, Ocean Engineering Intl, Vol. 9, No. 1, pp 11-27

Spyrou, K.J., Tigkas, I., Scanferla, G., Pallikaropoulos, N. and Themelis, N.(2008), “Prediction potential of the parametric rolling behavior of a post-panamax containership”, Ocean Engineering, Vol. 35, No. 11-12, pp1235-1244

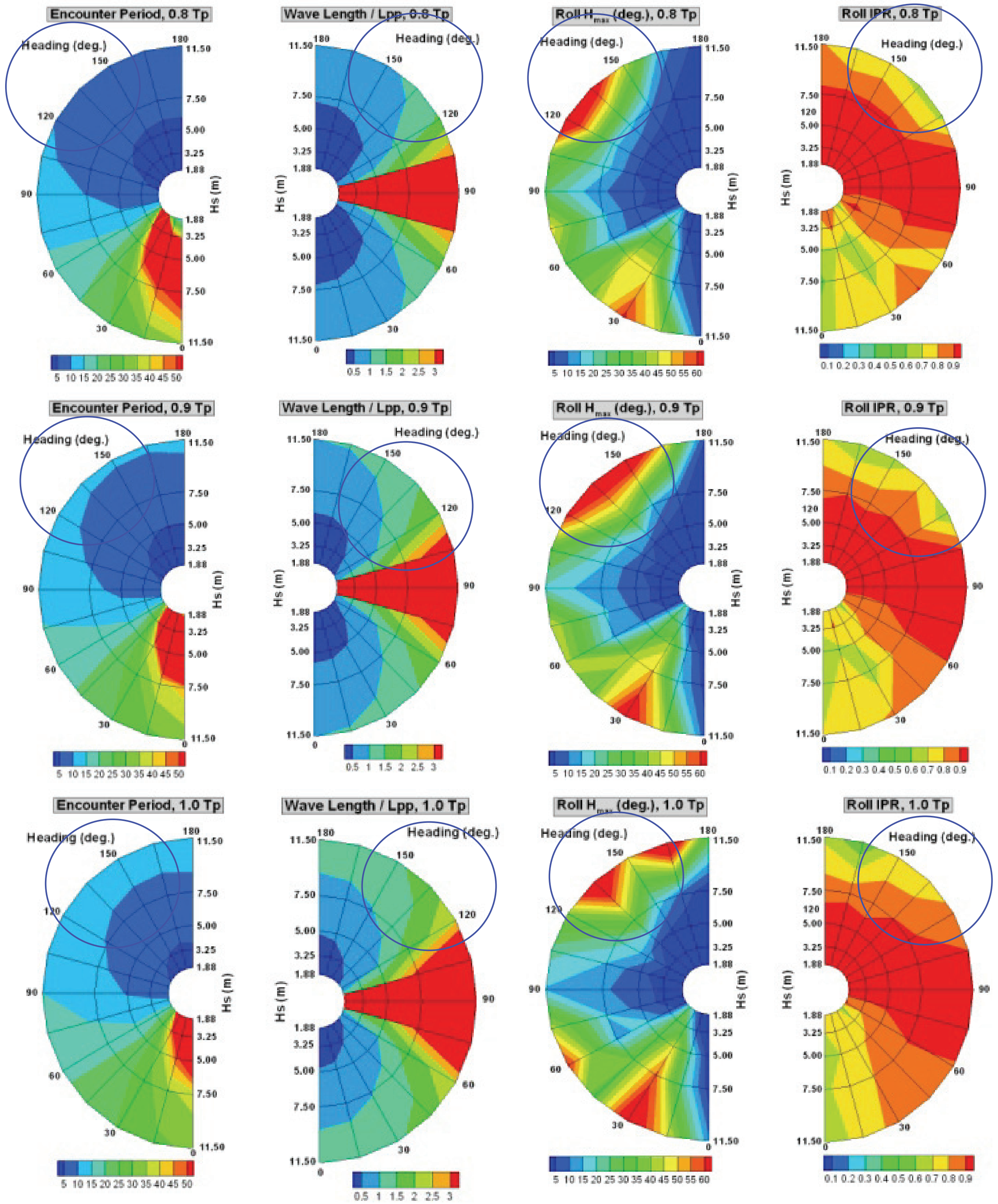


**Fig. 5: Encounter wave period, wave length ratio, Max. roll & IPR contours of a 6,250 TEU container carrier for Tp=0.8 ~1.2 Tp**

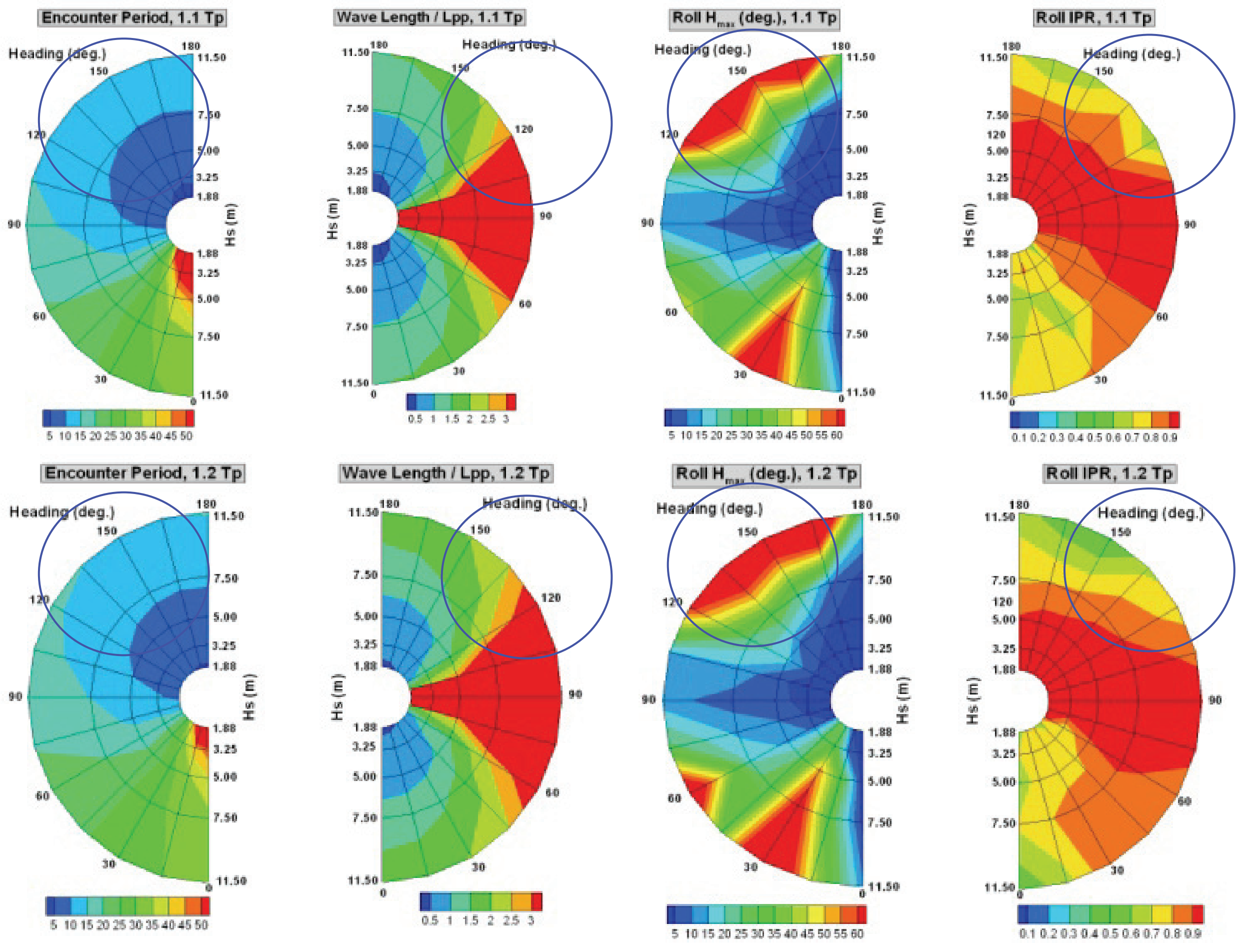


**Fig. 5 (Cont.): Encounter wave period, wave length ratio, Max. roll & IPR contours of a 6,250 TEU container carrier for Tp=0.8 ~1.2 Tp**

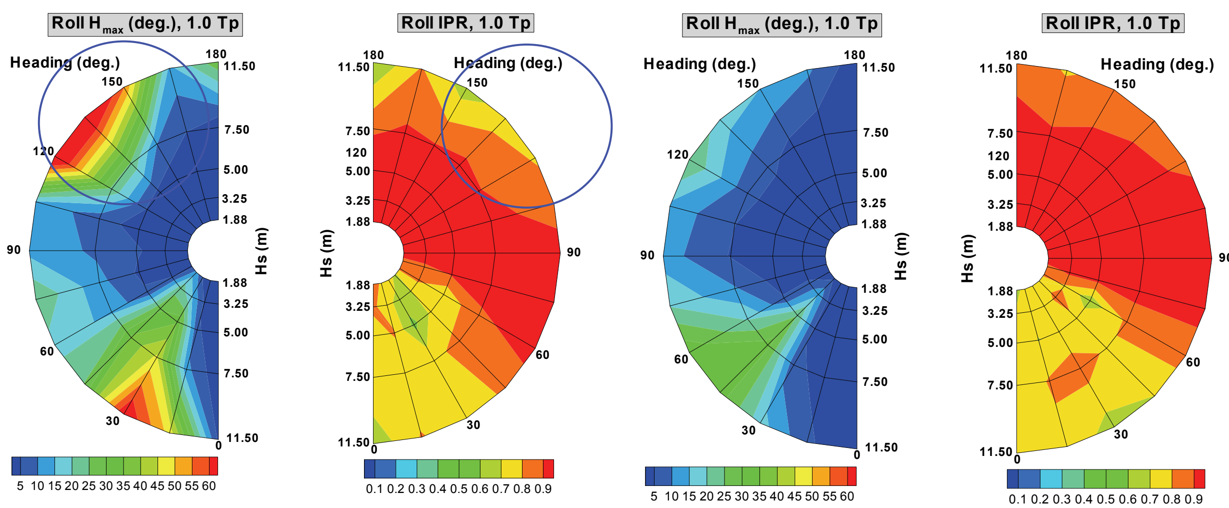


**Fig. 6: Max. roll & IPR contours of a 10,000 TEU and 13,000 TEU container carriers for $T_p$=*1.0* $T_p$**