The Effect of Pod-induced Heeling on the Stability of Large and High-speed Ships

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ABSTRACT

This paper presents a numerical and experimental investigation on the effect of pod propulsor induced heeling on the stability of large and high-speed ships. A six degrees of freedom numerical model to predict the coupled manoeuvring and seakeeping behaviour of a ship driven by pods has been developed and validated using the extensive captive and free-running model test data for a large and high-speed pod-driven Ropax and Cargo ship. The correlation between manoeuvring induced "spike" loads, heeling motion and turning has been investigated using the IMO turning motion tests for different speed ranges. The effect of static heeling on turning manoeuvre and dynamic heeling effects in combination with directional control have been investigated for these vessels. The implication of the effect of dynamic heeling on the stability of pod-driven large high-speed ships is highlighted with a view to improve the design of these vessels for their safe operations.

Keywords: *Azimuthing podded propulsion, steering-induced heeling, maneuvering induced spike loads*

1. INTRODUCTION

The azimuthing podded propulsion system has significant advantages over other conventional propulsion and steering systems during low speed manoeuvre and turning motions; providing large steering forces. However, the large pod induced steering angles could also seriously jeopardise stability and safety of pod-driven ships especially when considered in combination with the generally weak directional stability of pod-driven ships; as a result of prammed aft-shape to accommodate pod-strut unit (Van Terwisga et. al, 2001). Recent studies carried out under two large Europe wide research projects, on the design and operation of pod-driven ships, have also focused on this issue as part of the design for safe operation of pod-driven ships (OPTIPOD, 2002, FASTPOD, 2005). The studies indicated significantly high side forces, so-called "spike" loads, on the pod units of high-speed ships in the case of the turning manoeuvre; which is required by IMO in the ship design process. This is especially a pressing issue now as a growing number of pod-driven high-speed Ropax and Cruise ships are being designed and entering into operation. While, the current IMO manoeuvring criteria (2002) does not reflect significant heel-induced effect on turning and directional stability, the IMO's Committee on revised intact stability code (IMO, 2004) and the 24th ITTC Specialists Committees on Stability in Waves and Azimuthing Podded Propulsion (ITTC, 2005a, b), have issued recommendations to include them as an essential measure of performance-based stability assessment as well as manoeuvring.

Based on the above background, this paper presents dedicated numerical tools to predict pod-induced forces and motions including the effect of waves when they exist. The numerical model has been validated using the extensive captive and free-running model test data for a large high-speed pod-driven Ropax and Cargo ship. The correlation between the "spike" loads, heeling motion and turning has been investigated using the IMO turning motion tests for different speed ranges. The effect of static heeling on the turning manoeuvre and dynamic heeling effects in combination with directional control have been investigated for pod-driven high-speed ships. Finally, the outcome of the effect of dynamic heeling on the stability of pod-driven large high-speed ships is highlighted and the possible solutions for regulatory design and operational issues are discussed.

2. POD-INDUCED HEELING

2.1 Effect of heeling during manoeuvring

The effect of heel, although overlooked in the manoeuvring criteria by IMO (2002), does have significant effect on manoeuvring; especially concerning directional stability and course-keeping. Furthermore, in combination with stability characteristics and inherent yaw-roll coupling, it could produce adverse effects for manoeuvring in waves as reported in (Ayaz et. al, 2005). IMO IS (2002) recommends using the following approximate formula for passenger ships, while the angle of heel on account of turning should not exceed 10°:

$$M_R = 0.196 \frac{V_0^{\,2}}{L} \Delta (KG - \frac{d}{2}) \qquad (1)$$

where M_R is heeling moment, V_o is service speed, L length of ship at waterline, Δ is displacement, d is mean draught and KG is height of centre of gravity above baseline.

A slightly modified form of the formulation is also recommended for high-speed multi-hull vessels in IMO HSC (2000) for the heeling moment and also for turning lever of the hull.

Over the years many researchers have investigated the effect of heel on the manoeuvring motions for conventional vessels; especially at high-speed e.g. Son & Nomoto (1981), Oltmann (1993) and Trägårdh (2003). They have emphasized the importance of inclusion of this mode of motion into the standard 3-DOF (surge, sway and yaw) preferred at conventional analysis. It is proven that expected factors such loading condition (GM), and stern shape as well as length-to-beam ratio and slenderness of the vessel do play a significant role in identifying the maximum heeling during manoeuvring. Trägårdh (2003) has carried out a regression analysis based on 20°/20° zig-zag manoeuvre model test results for 24 ships which included RoRo, LNG, cruise ships and container vessels. For most extreme cases, a maximum roll angle of 26° was recorded for a 60° overshoot angle. The study also reported a strange behaviour where in pull-out tests the yaw rate and roll angle is decreased, as expected, when the rudder was put amidships for pull-out however then increased as the speed picked up. The study concluded that the significant 'increases' and 'drops', respectively, in yaw-rate and speed during turnings would cause such behaviour along with the ship's geometrical characteristics and loading conditions.

Therefore, it is not surprising that current efforts towards performance-based stability analysis is required such analysis as prerequisite to the detailed stability analyses in waves or for limit-state conditions (ITTC, 2005a).

2.2 Effect of heeling during manoeuvring with pod-driven ships

A comprehensive up to date review of the impact of off-design conditions on loads and stability of pod-driven ships has been given by the 24th ITTC Specialist Committee on Azimuthing Podded Propulsion (2005b).

Within the context of steering related heel/roll behaviour, Toxopeus and Loeff (2002) investigated merits and drawbacks of pod-driven ships in operation. Toxopeus and Loeff (2002) identified that high turning rate can cause large gyration forces and thus large roll motions which adversely affect turning rate and the course stability. They also carried out analysis from the database of manoeuvring tests carried out for a number of pod-driven ships. The results showed maximum roll angles up to 28° with steady turning heel angles up to 17 degrees. The authors indicated, although IMO does not provide recommendations regarding roll angles, from practical experiences, angles above 13° are thought to be very large. The comparison analysis with conventionally-driven ships showed higher roll angles for pod-driven ships. Apart from the aforementioned differences, the authors also pointed out that the effect of steering rate of application; which differs between pods and rudders. The authors derived a broadly constant factor to present the trend of this phenomenon:

$$k = \frac{\sin(\phi) g G\overline{M} r_{tur}}{U^2} \qquad (2)$$

where k an almost constant factor, GM is the metacentric height, ϕ is the heel angle, r_{tur} is the turning diameter and U is the ship speed.

While Lepeix (2001), Hamalainen and Heered (2001) and Van Terwisga et al (2001) have emphasised on some safe limits on practical heel angles, more realistic observation of the heeling phenomenon in a pod driven ship has been given by Kurimo and Bystöm (2003) from full-scale trials. They also verified that the source of maximum heel angle is related to the magnitude of the maximum turning rate. The observed maximum heel angle was 13% smaller than that predicted from the model tests. The difference has been attributed to the possible differences in initial speed and initial metacentric heights in both runs. A simplified prediction has been proposed using assumptions that maximum heel angle is proportional to the square of the initial speed and inversely proportional to the metacentric height; as given in (1) and (2).

However, a comparative analysis conducted by Ayaz et al. (2005) for the pod-driven and conventional Ropax type ships, designed within the OPTIPOD project, has shown that successful hydrodynamic aft-hull optimisation could reduce the possible adverse affect of pod-induced heeling. In this analysis the two Ropax ships; a pod-driven and a conventional rudder-propeller steered, which have almost identical ship geometries and aft-body type (with a slightly lower GM value for the pod-driven ship), were investigated for the heeling effect during turning motion and results are shown in Fig. 1.

As shown in Figure 1, a pull-out test, where the ship's rudder is ordered to return to amidships or neutral position after completing a turning circle, was performed. The other major contributed factor for this outcome can be the greater speed loss for the pod-driven vessel as reported by the analysis of Trägårdh (2002) in calm water and waves.

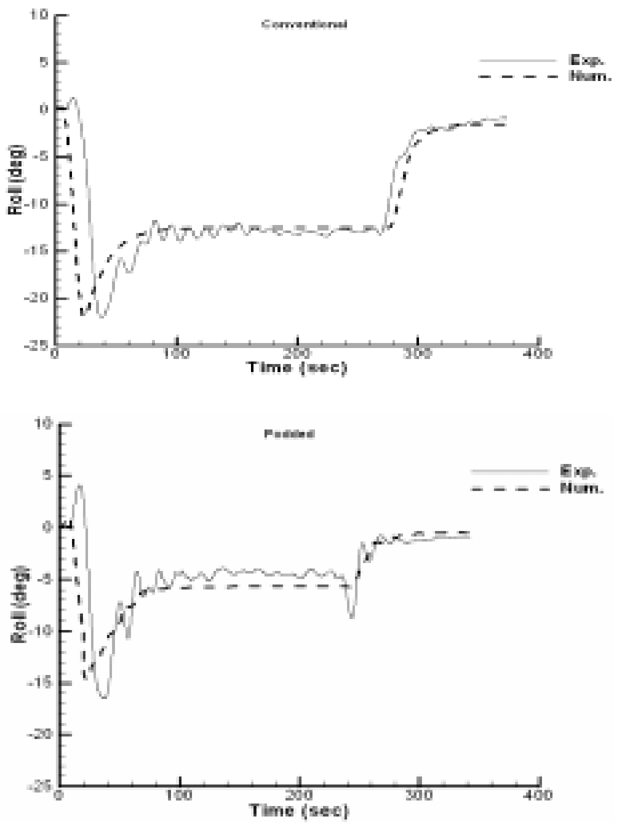

Figure 1 Rolling during pull-out manoeuvre at 28 knots for 172.2 m. conventional (top) and pod-driven (bottom) Ropax, (Ayaz et al., 2005).

In addition to the above, Woodward et al., (2005) were reported on the large magnitude of ”spike” loads and associated “snap” rolling behaviour observed with the pod-driven ships which is discussed in Section 4.2 within more details..

3. NUMERICAL MODEL

The current numerical model consists of non-linear, 6-DOF motion equations allowing a straightforward combination between seakeeping and manoeuvring behaviour whilst accounting for extreme motions. The details of the mathematical model for pod-driven ship have been presented by Ayaz et al. (2005) and in an accompanying paper presented to this conference, Ayaz et al. (2006). The final equation of motion for pod-driven ships is given in (3) and (4);

$$
\begin{aligned}
& m(\dot{U}-VR) = -\iint_S p\mathbf{n}_\mathbf{X}\, dS + X_H - S\sin(\delta) \\
& +(1-t_p)T\cos(\delta) \\
& m(\dot{V}+UR) = -\iint_S p\mathbf{n}_\mathbf{Y}\, dS + \rho U \int_{\Gamma_X} \Phi_D \mathbf{n}_\mathbf{Y}\, ds + Y_H \\
& -(1+a_{Hpod})S\cos(\delta) + X'_{pod}\sin(\delta) \\
& m\dot{W} = -\iint_S p\mathbf{n}_\mathbf{Z}\, dS + \rho U \int_{\Gamma_X} \Phi_D \mathbf{n}_\mathbf{Z}\, ds + Z_H
\end{aligned}
\tag{3}
$$

where pod denotes pod-induced forces. The nomenclature for (3) and (4) including other details was presented in Ayaz et al (2006) and therefore will not be repeated here.

$$
\begin{aligned}
& (I_{xx}\cos^2\theta + I_{yy}\sin^2\theta)\dot{P} = -\iint_S p(\mathbf{r}\times\mathbf{n}_\mathbf{YZ})dS \\
& +\rho U \int_{\Gamma_X} \Phi_D(\mathbf{r}\times\mathbf{n}_\mathbf{YZ})ds + K_H + (1+a_H)z_R F_N \cos\delta \\
& I_{yy}\dot{Q} = -\iint_S p(\mathbf{r}\times\mathbf{n}_\mathbf{ZX})dS + \rho U \int_{\Gamma_X} \Phi_D(r\times n_{ZX})ds \\
& \quad + M_H \\
& (I_{xx}\sin^2\theta + I_{zz}\cos^2\theta)\dot{R} = -\iint_S p(\mathbf{r}\times\mathbf{n}_\mathbf{XY})dS \\
& +\rho U \int_{\Gamma_X} \Phi_D(\mathbf{r}\times\mathbf{n}_\mathbf{XY})ds + N_H - (1+a_H)x_R F_N \cos\delta
\end{aligned}
\tag{4}
$$

In these equations, hull (manoeuvring) force terms are written based on MMG method (Inoue et al., 1981) as follows:

$$
\begin{aligned}
& X_H = X_{\dot{u}}\dot{u} - Y_{\dot{v}}vr - \frac{u}{|u|}Y_{\dot{r}}rr + X_{vr}vr - R_T(u) \\
& Y_H = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v + \frac{u}{|u|}Y_r r + Y_{v|v|}v|v| + Y_{r|r|}r|r| \\
& Z_H = Z_{\dot{w}}\dot{w} + Z_w w + Z_{\dot{q}}\dot{q} + Z_q q \\
& K_H = K_{\dot{p}}\ddot{\varphi} + C(\dot{\varphi}) - z_y Y_H \\
& M_H = M_{\dot{q}}\dot{q} + M_q q + M_{\dot{w}}\dot{w} + M_w w \\
& N_H = N_{\dot{r}}\dot{r} + N_{\dot{v}}\dot{v} + N_r r + \frac{u}{|u|}N_v v + N_{r|r|}r|r| + \\
& N_{r|r|v}rrv + N_{v|v|r}vvr
\end{aligned}
\tag{5}
$$

where, X_H, Y_H, Z_H, K_H, N_H, M_H are surge, sway, heave, roll, pitch, yaw hull forces, respectively.R_T (u) is the total resistance force, $C(\dot{\varphi})$ is the damping moment and z_y is the vertical coordinate of the centre of action of lateral force. Other terms represent the acceleration and velocity coefficients. Furthermore, equation (5) does not include coupling between the vertical and horizontal motions. However, hydrodynamic terms which result from combined sinkage and rotation, that occur during heeling, are added to sway force and yaw moment in (5) if experimental values are available. These terms are represented in the first order on the basis of linear sway and yaw velocity coefficients as follows:

$$\begin{aligned} Y_H &= Y_\varphi \varphi + Y_{v|\varphi|} v|\varphi| + Y_{r|\varphi|} r|\varphi| \\ N_H &= N_\varphi \varphi + N_{v|\varphi|} v|\varphi| + N_{r|\varphi|} r|\varphi| \end{aligned} \tag{6}$$

It should be noted that this model is only valid for small heeling angles (up to 2º~3 º). In the prediction of ship motions in seaway, the accurate representation of roll-damping characteristics becomes important. The non-linear damping motion could be described through linearized coefficients obtained from roll decay tests. However, the terms will be constantly changed based on the loading conditions and subsequent stability characteristics; such as non-linearity due to changes in geometry with the free-surface effects. Therefore, in the numerical model, Ikeda's (Himeno, 1981) pseudo-linearized terms which are obtained based on hull characteristics are used to calculate roll damping which could be expressed as follows:

$$K_{\dot\varphi} = (B_O + B_F + B_E + B_L + B_{BK}) \times (1 - e^{-10Fn}) \tag{7}$$

where the damping coefficient B is the superposition of potential, friction, eddy, lift and bilge keel damping terms, denoted by subscripts *O,F, E, L, BK,* respectively.

Here the mean roll-angle is obtained from the slope of the roll curve in the numerical model. The second term in (7) represents a correction for forward speed. Also, vertical coordinate of centre of action of lateral force can be estimated by applying practical calculation method based on the restoring arm lever (GZ), which is calculated for each loading and wave condition, as follows:

$$z_y = \frac{g\,GZ(\phi)}{U r} \tag{8}$$

where U is ship speed and r is yaw rate.

4. NUMERICAL ANALYSIS

For the validation and further numerical analyses, two ships; a Ropax and a Cargo ship (container), which were designed under the FASTPOD project, have been used (FASTPOD, 2005). The principal particulars of the two ships are given Table 1.

The FASTPOD Ropax is propelled by four puller-type pod units all equipped with 5.2 m propellers. Each pod absorbs approximately 27 MW power at the desired service speed; approximately 38 knots. The forward pods are fixed and the aft pods are azimuthing for ship control.

The FASTPOD Cargo (the design version used in this analysis) is propelled with two azimuthing pod units both equipped with 6.5m propellers and two tandem propellers (6.4 m. diameter each) positioned between them. Each pod absorbs approximately 36 MW power at the desired service speed of approximately 35 knots.

For the validation analysis of the numerical model, free-running model test results for the Ropax (Trägårdh et. al, 2004) and the Cargo ship (Bednarek & Kanar, 2005) were used.

The comparison of the numerical model with the model tests on roll decay tests for each ship is shown in Figs. 2-3. The correlation between the predictions and model test results appears to be very good. Heeling moments obtained from the oblique towing tests of the Ropax for different speed are shown in Fig. 4 to be compared with the numerical predictions later in the paper.

Table1. Principal particulars of FASTPOD ship

Parameter	FASTPOD ROPAX	FASTPOD Cargo
L_{pp}	220.00 m	275.00 m
B (Beam)	30.00 m	30.00 m
D (Depth)	9.70 m	21.65 m
T (Draft)	6.80 m	10.30 m (design)
C_b	0.39	0.57
Δ	17600 t	49600 t (design)
LCG	-5.71 m (aft)	-7.20 m (aft)
VCG	14.60	13.60 (design)

4.1 Pod-Induced Heeling

It was mentioned that the effect of steering forces created by pod drives could be an important issue especially in case of large turning motions e.g. emergency manoeuvre or harbour manoeuvre.

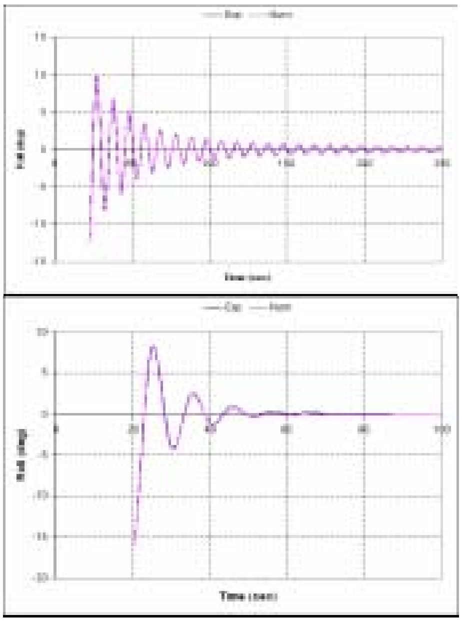

Figure 2 Roll decay tests for Ropax at zero speed (top) and V= 35 knots (bottom).

For the FASTPOD ships, the large size, high speed and high power make the effect of steering on heeling even more significant. During the course of the project, this issue has been highlighted considering manoeuvring loads on ships and their suitability to classification society rules. In the model experiments, KG value of ship has been selected from a scantling analysis. In Figure 5, the model experiment result for heel angle has been compared against the numerical result for the turning circle manoeuvres at two different speeds. Furthermore, the turning manoeuvre motion for the IMO criteria has been carried out using design KG along with the scantling KG value chosen from IMO High Speed Craft rules (2000).

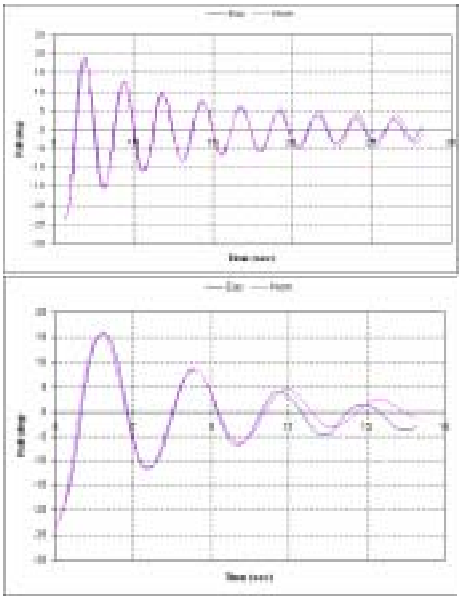

Figure 3 Roll decay tests for Cargo ship at zero speed (top) and V= 21 knots (bottom), in model scale.

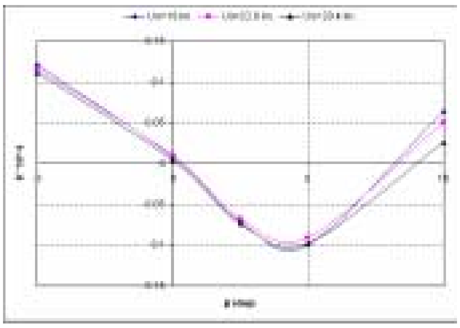

Figure 4 Heeling moments measured from oblique towing tests for three different speeds in non-dimensional form (Vogt, 2005).

Experimental (in full-scale) and design KG values are found as 14.60m and 12m respectively. The value of KG directly affects heeling motion, especially for maximum angle as seen in Fig. 5. For the vessel tested, even in the case of limiting KG, the maximum heel angle of the ship during the turning motion at high-speed still is lower than many lower powered Ropax ships (Ayaz et. al., 2005). The numerical model displays satisfactory agreement with the model experiments at lower speed of 25 knots. While, a good quantitative agreement for maximum and steady heel angles was obtained at 38 knots (Fig. 5), the numerical model displays larger oscillation during the brief period when vessel restoring force applies to the ship to reach a steady heel. This oscillation can be attributed to some weakness in the modelling of the hull and pod induced damping as well as some inaccuracy in the exact position of the vertical centre of effort for the lateral forces given in (4) and (5).

However, for the zig-zag manoeuvre tests, although the model has agreement in terms of maximum amplitude, it is very rigid comparing to larger decaying in amplitude after changing the helm-angle (Fig. 6). The free-surface effects were included in the numerical simulation. This difference could indicate potential vortex-induced effects that occur between pods however which are not fully modelled numerically.

The significant outcome from the zig-zag test was concerning the inherent yaw-heel coupling observed during the tests (Fig. 6). The roll-amplitude increases rather largely with increasing helm angle.

This could be an indication for the effect of the roll-yaw coupling, which is observed during the simulations of ship motions in steep following waves, where similar hydrodynamic mechanism takes places in effect along with wave forces (Ayaz et. al., 2006).

For validation purposes, the maximum heeling moment occurring during the turning circle motion has been compared to the empirical value obtained from the IMO formula; expressed in (1) for the scantling design condition and comparative results are given in Table 2.

Table 2 points out that although the maximum heeling angle did not exceed 10º, approximate formula given by IMO estimates the heeling moment as almost 1/3 of the maximum heeling moment calculated by numerical model and validated with model test.

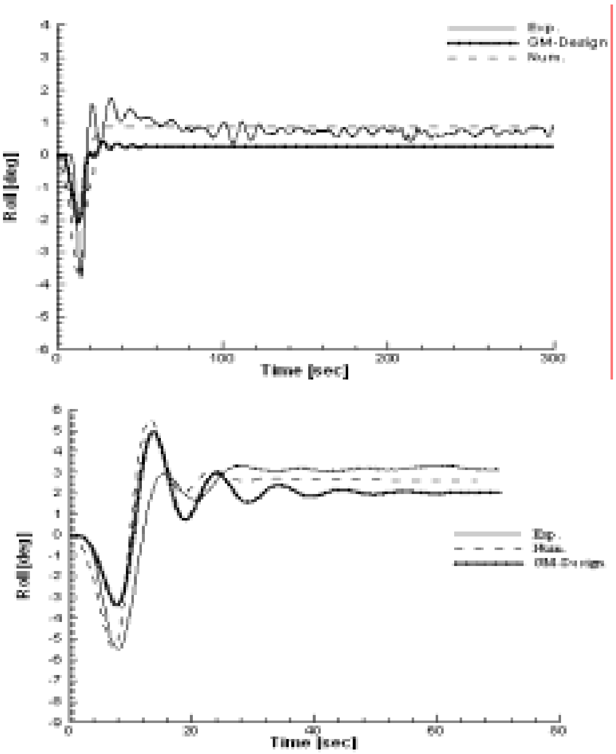

Figure 5 Comparison of roll motion of Ropax during turning circle motion at 25 knots (top) and 38 knots (bottom), for scantling condition (Exp) and design condition (GM-Design), respectively.

Furthermore, as will be presented in §4.2, the extreme steering can exert large manoeuvring induced side loads of spike nature on the entire pod units due to their high acceleration dependency. These loads do not only cause concern for inducing large initial heeling which is safety-critical issue for pod-driven ships but also for structural loads.

Finally, a similar exercise (i.e. turning circle manoeuvre) has been carried out for the Cargo ship in the design condition. Figure 7 illustrates the effects of speed in the design loading condition for this manoeuvre. Due to lower righting arm moment (low GM) the vessel's maximum and steady heeling angle is considerably higher in comparison to the Ropax; even at lower Froude numbers. Also, the maximum heeling moment occurred during the turning circle motion of the Cargo ship, was compared to the empirical value obtained from the IMO formula and presented in Table 3.

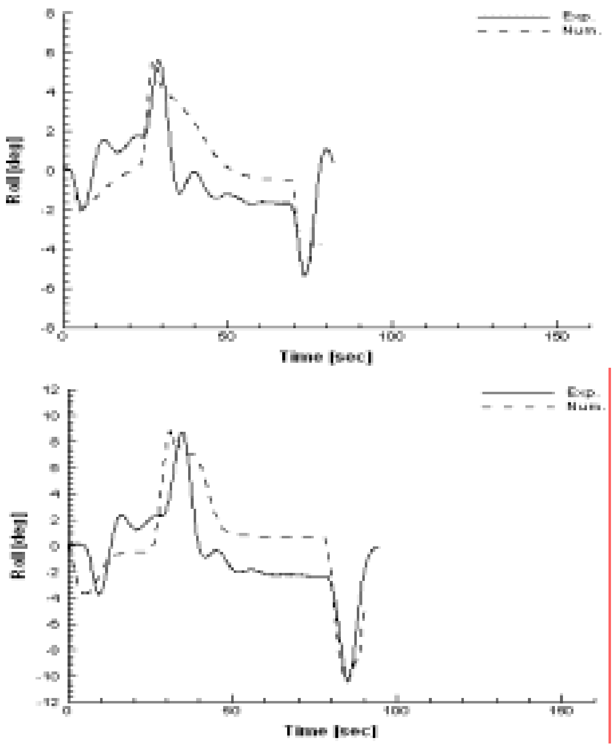

Figure 6 Comparison of roll motion of Ropax during 10º/10 º (top) and 20 º /20 º (bottom) Zig-Zag tests at 38 knots.

The results indicate similar trend as with the Ropax, in which the IMO formula grossly underestimates the heeling moment in comparison to the numerical prediction; shown in Table 2.

Table 2. The comparison of maximum heeling moments obtained by the numerical model and the IMO formula (1) for Ropax.

V (knots)	Numerical (Kn.m)	IMO (Kn.m)
25	79850	29171
38	169321	67397

4.2 Pod-Induced Loads

The improved manoeuvring performance reported for ships fitted with azimuthing pod drives is most closely related to the enhanced slow speed capabilities. Conventional control arrangements can only produce a control force when there is a flow over the rudder; that is, when the ship is moving. Conversely, an

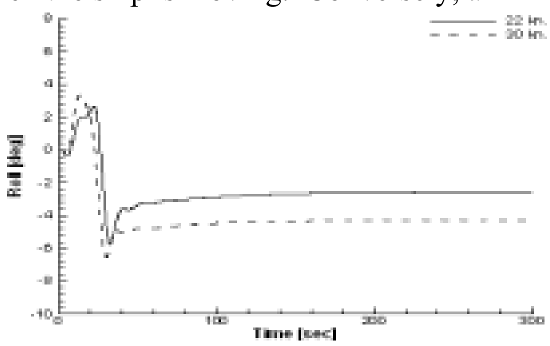

Figure 7 Comparison of roll motion of the Cargo ship during turning circle motion at 22 and 30 knots for design condition.

Table 3. The comparison of maximum heeling moments obtained by the numerical model and the IMO formula (1) for the Cargo ship.

V (knots)	Numerical (Kn.m)	IMO (Kn.m)
22	127888	37996
30	163186	70684

azimuthing pod drive can produce a control force in any direction; even when the ship is at a dead stop. Improved manoeuvring performance at sea-speed is less easy to define as improvements in turning ability are often accompanied by degraded course-keeping ability and vice-versa. Nevertheless, it services to say that most pod-driven applications demonstrate significant improvements in turning ability with equivalent or only slightly less course-keeping ability when compared with equivalent conventionally propelled ships.

This general improvement in control is achieved through the generation of significantly larger forces; coupled less desirably, with greater dynamic load variations.

While the steady state loading is relatively easy to both predict and measure, using scale model tests, the dynamic effect prove more difficult. Clearly, the acceleration related forces induced when slewing a 50t rudder are quite different from those for a 500t pod; especially when this mass has a gyroscopic component. When using predictions for only the steady state condition it is possible to seriously underestimate the total forces acting on the pod. Woodward et al (2005) presents evidence of spike loads associated with dynamic slewing which are shown to be more that double the steady state forces. This phenomenon is further elaborated by Woodward and Atlar (2006) where a relationship between the spike loads and snap rolling is established. Figure 8 shows the roll angle of the FASTPOD Ropax as a 35^{o} helm angle is applied; clearly demonstrating snap rolling behaviour. Woodward and Atlar (2006) argue that the spike loading is highly acceleration dependant and that a more directionally course-stable design should present smaller spike loads. In turn, all things being equal, this should also help to reduce the maximum angle of snap rolling.

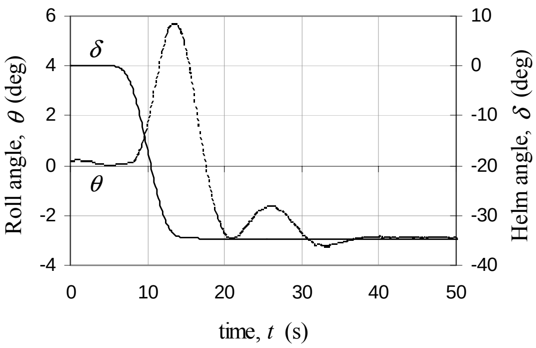

Figure 8 Snap roll motion of Ropax after initiating 35^{o} helm angle.

4.3 Design implications

It is believed that the current approach in safety analysis could be modified in a way to identify potential pitfalls in static heeling and directional control for more detailed analysis in realistic seaways. This is especially vital for the new innovative ship designs fitted with multi-purpose and powerful propulsion systems and operating at high speeds. This could indicate directional instability and steering-induced excessive forces that could be detrimental both static and structural safety. This approach will be in line with current performance-based approach advocated by regulatory bodies.

A good example will be the significant inherent yaw-heel coupling observed during the tests possibly due to pram aft shape to accommodate the pod structure. The roll amplitude increases rather largely with increasing helm angle. This could be precede for potentially dangerous roll-yaw coupling observed during the motions in simulations in steep following waves where similar hydrodynamic mechanism in calm-water manoeuvring tests in effect along with wave forces.

Dynamic manoeuvring induces acceleration dependant spike loads on pod drives that have important implications for snap rolling behaviour. Pod drives can produce a large control force to steer even the most course-stable ship however, poor course-stability can result in much greater, but less advantageous, dynamic forces. To minimise the magnitude of manoeuvring induced snap rolling it is recommended that designers of pod-driven ships care towards greater inherent course-stability.

5. CONCLUSIONS

The effect of pod propulsor induced heeling on the stability of large and high-speed ships has been investigated using an existing 6 DOF non-linear numerical model which was enhanced for the simulation of motion control and stability analysis of pod-driven ships. The key findings and conclusions from this study can be summarised as follows:

- The numerical predictions of heeling motion during manoeuvring compared with the experimental measurements displayed satisfactory correlations in overall. However, the differences observed in some cases could be attributed to the less accurate modelling of hull damping and mainly vortex-induced effects that occur between the pods units.

- Although the steering induced heeling motion by pod drives is significant, it is found that the magnitude of KG more directly affects heeling motion, especially for the maximum amplitude. For the vessels tested in this study, the maximum heel angle of ship during the turning motion at high-speed is still lower than many conventionally driven similar type of ships of which results are available in open literature.
- A simple analysis in this study showed that although the maximum heeling angle did not exceed 10º, approximate formula given by IMO grossly underestimates the heeling moment (almost 1/3 of the maximum heeling moment) calculated by the numerical model and validated with the model tests.
- Dynamic manoeuvring induces acceleration dependant spike loads on pod drives that have important implications for snap rolling behaviour.

Overall, the current numerical model presented herein provides satisfactory results for the analysis of dynamic stability of large and high-speed ships driven by multiple, large pod units and it could be a useful tool for the conducting of the performance-based approach to safe design of such vessels.

6. ACKNOWLEDMENTS

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