Controlling the Roll Responses of Volume Carriers

CARL-JOHAN SÖDER

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Abstract

Modern volume carriers such as container vessels, cruise ships and Pure Car and Truck Carriers (PCTC’s) have become more vulnerable to critical roll responses as built in margins have been traded against increased transport efficiency. The research presented in this doctoral thesis aims at enhancing the predictability and control of these critical roll responses. The thesis presents a holistic framework for predicting and assessing the roll damping, which is a crucial parameter for predicting roll motions, based on a unique combination of full scale trials, model tests, semi-empirical methods and computational fluid dynamics. The framework is intended to be used from the early design stage and gradually improved until delivery of the ship and finally to provide input for decision support in the operation. The thesis also includes a demonstration of a new application for rudder control to be used for mitigation of parametric roll. This is performed by simulating real incidents that have occurred with PCTC’s in service. Simulations with rudder roll control show promising results and reveal that the approach could be very efficient for mitigation of parametric roll. Finally, an approach for monitoring of roll induced stresses, so-called racking stresses in PCTC’s, is presented. The approach involves measurement of the ship motions and scaling of pre-calculated structural responses from global finite element analysis. Based on full scale motion and stress measurements from a PCTC in-service the approach is evaluated and demonstrated to be an efficient alternative to conventional methods.

Keywords: PCTC, parametric roll, roll response, roll damping, rudder control, aerodynamic roll damping, roll mitigation, racking, Ikeda’s method, CFD, model tests, Full-scale tests
Sammanfattning

Moderna volymlastsfartyg som containerfartyg, kryssningsfartyg och biltransportsfartyg (PCTC) är högeffektiva lastbärare. I jakten på ökad systemeffektivitet så har dock de inbyggda marginalerna reducerats vilket bl.a. gör fartygen mer känsliga för vissa typer av kritiska rullningsfenomen. Forskningen som presenteras i denna doktorsavhandling syftar till att förbättra predikterbarheten och kontrollen av dessa kritiska resnonser. I avhandlingen presenteras ett ramverk för utvärdering av fartygs rullningsdämpning baserat på en kombination av semiempiriska metoder, strömningmekaniska beräkningar, modelltester och fullskaletester. Metoden demonstreras i avhandlingen med utförliga modellförsök och fullskaleförsök utförda på PCTC-fartyg i drift. Rullningsdämpningen är en av de fartygsspecifika egenskaper som är helt avgörande för fartygets benägenhet för rullning och är därför i högsta grad viktig att kvantifiera som indata till bl.a. operationell rådgivning. I avhandlingen demonstreras även en ny tillämpning av roderrullningskontroll där korta roderrimpulser används för att begränsa tillväxten av det dynamiska stabilitetsfenomenet parametrisk rullning. Baserat på simuleringar av riktiga händelser visar tillämpningen lovande potential och i alla betraktade fall kan rodret helt släcka ut tillväxten av rullningsrörelser som i annat fall hade blivit kritiskt stora. Slutligen presenteras en ny metod för att övervaka rullningsinducerade så kallade racking-spänningar i fartygsstrukturen baserat på uppmätta rullingssrörelser och skalning av förberäknade struktureresponder. För PCTC-fartyg i allmänhet är racking-inducerade spänningar den strukturerespins som har störst benägenhet att ge upphov till utmattningssprickor och den presenterade metoden visar sig vara ett effektivt alternativ till konventionella övervakningsmetoder där spänningarna mäts på plats.
Preface

The research presented in this thesis was performed at the Center of Naval Architecture at the Department of Aeronautical and Vehicle Engineering at KTH Royal Institute of Technology in Stockholm, Sweden and at the Ship Design department of Wallenius Marine AB in Stockholm, Sweden.

This work has been performed within a joint academic and industrial research program with participants from KTH, Wallenius Marine AB and seaware AB which has been financially supported by Swedish Mercantile Marine Foundation (Stiftelsen Sveriges Sjömanshus) and the Swedish Maritime Administration (Sjöfartsverket). The financial support is gratefully acknowledged.

The research group has been led by Anders Rosén at KTH who also been the main supervisor for this work. Anders, working closely together in this project has been an exciting journey and a privilege. Even though the project has been long and the pace at times irregular you have provided the highest level of enthusiasm, coaching and support throughout. I will keep many good memories from these years where the highlight probably was the epic STAB 2012 conference in Athens which was kind of a spiritual moment. Most rewarding on a personal plane, has been all the creative discussions and sharing of ideas within the research group. Thank you Jakob Kuttingkeuler, Kalle Garme, Mikael Razola, Mikael Palmqvist and Erik Ovegård for the appreciation and support over these years.

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Carl-Johan Söder

Stockholm, March 2017
Dissertation

This Doctoral Thesis consists of an introduction to the area of research and the following appended papers:

**Paper A**


**Paper B**

Söder C-J, Rosén A, Huss M, *Ikeda Revisited, To be Submitted for publication 2017*

**Paper C**


**Paper D**


**Paper E**


**Paper F**

Division of work between authors

Paper A

Söder performed and developed the method for the full-scale roll decay tests while the model tests were carried out by Werner. The methodology for the analysis of experimental data and the implementation of Ikeda’s method was performed by Söder supervised by Rosén and Kuttenkeuler. The paper was written by Söder supervised by Rosén with valuable input from Huss.

Paper B

Söder performed the analysis and CFD calculations. Model tests were carried out by Werner. The paper was written by Söder supervised by Rosén with some input from Huss.

Paper C

Söder developed the method for aerodynamical damping. Kuttenkeuler managed the wind tunnel tests. Ovegård calculated the irregular stability variations and made the analysis related to operational guidance. The work was supervised by Rosén and jointly written by Söder, Ovegård and Rosén.

Paper D

Söder developed the framework, performed the analysis and wrote the paper supervised by Rosén.

Paper E

Söder established the model and performed the simulations and analysis supervised by Rosén and Kuttenkeuler. Ovegård calculated the irregular stability variations. The paper was written by Söder supervised by Rosén with valuable input from Huss.

Paper F

Söder developed the finite element model and performed the stress analysis. Motion measurements were performed by Palmquist. The work was supervised by Rosén and the paper was jointly written by Söder and Rosén with valuable input from Palmquist.
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1 Introduction

The day before Christmas, December 23rd in 2008 the world’s at that time largest and most modern Pure Car and Truck Carrier (PCTC) was steaming in the Mediterranean Sea with reduced speed in following waves. The vessel was fully loaded and fulfilled all the statutory stability requirements with good margin. The conditions onboard were calm and the crew was just about to have dinner when the vessel suddenly started to roll heavily without any apparent pre-warning. A few days later, during a port call, the author to this thesis visited the vessel and downloaded data from the automation systems which contained high-frequency ship motion history. Figure 1 shows the roll sequence and, as seen, the motions went from almost nothing to peak amplitudes of 30° within only a few roll cycles.

![Figure 1: Parametric roll motions onboard a PCTC.](image)

Based on analysis of the motions, loading condition and sea condition it was concluded that this incident was a so-called parametric roll event. In recent years, several similar events have been reported with modern tonnage but this case stands out since it occurred in fairly moderate weather and because all relevant data could be captured and analyzed. The case is described thoroughly in Rosén et al. (2012).

As mentioned by Paulling (2011), parametric roll of ships has been a research topic already since the 1930s, at that time in Germany the aim was primarily to explain capsize events of small ships in rough weather. One of the first high profile incidents with large modern tonnage occurred in 1998 with a container carrier, m/v APL China (France et al., 2003). The vessel experienced heavy rolling during a storm that the cargo lashings did not manage to withstand and lost hundreds of containers over board with remaining cargo severely damaged as illustrated in figure 2.
This event and others such as m/v Aida 2004 (Palmquist & Nygren 2004) drew attention from the classification societies and even the International Maritime Organization (IMO). The American Bureau of Shipping (ABS) issued a thorough guide for the assessment of parametric roll for containerships (ABS, 2004) and the Germanischer Lloyd developed assessment procedures using advanced numerical sea keeping simulation codes (Brunswig & Pereira, 2006). Following a critical submission by the Italian delegation, highlighting the need for a revision of IMO’s Intact Stability requirements in 2001 (Francescutto 2015), IMO’s Subcommittee on Stability and Load Lines and on Fishing Vessels Safety (SLF) was re-established in 2002 (Peters et al. 2011). During SLF’s meeting in 2005 (IMO 2005) it was decided that new performance-based stability criteria should be developed and address parametrical roll and other dynamic stability failure modes under what is called the second generation intact stability criteria.

The research presented in this doctoral thesis has been aiming at enhancing the predictability and control of critical roll responses for modern volume carriers. Assessment of the above mentioned parametric roll incidents showed low roll damping and having a good description of this parameter is crucial for predicting roll motions. The thesis presents a holistic framework for predicting and assessing the roll damping based on a unique combination of full scale trials, model tests, semi-empirical methods and computational fluid dynamics (Paper A to D). The thesis also contains a demonstration of a new application for rudder control to be used for mitigation of parametric roll (Paper E). Furthermore, an approach for monitoring of roll induced stresses, so-called racking stresses is presented (Paper F). Papers A-F are appended to the end of the thesis.

The following sections introduces the problem area and gives an insight to how the design evolution of volume carriers has led to modern ships that are more vulnerable for certain critical roll responses. Parametric roll and other roll responses that require particular attention are described and methodologies for roll response control from a design and operational perspective are discussed.
2 Design Evolution of Volume Carriers

Within the volume carrier family of ships perhaps the most optimized ones are found in the Pure Car and Truck Carrier (PCTC) segment. With focus on maximizing payload and minimizing fuel oil consumption modern PCTC’s have evolved into highly optimized designs, being significantly more efficient than their predecessors. The cargo capacity has been increased to reduce the fuel consumption per transported unit. However, as the length and beam of PCTC’s practically have been constrained by ports and the Panama channel the demand for increased cargo capacity and transport efficiency has evolved into higher and higher vessels as illustrated in figure 3 where the cargo hold of a conventional older PCTC is compared to a modern PCTC. The beam is the same while the newer vessel has got some two additional cargo decks which significantly increases the molded depth. This drives the vertical centre of gravity and naturally makes the stability situation more challenging.

Most volume carriers are designed for high operational speeds which require slender hull forms for minimum fuel oil consumption. At the same time the hulls need to provide sufficient form stability to manage the high centre of gravity. Large form stability is typically achieved by designing hulls with large water plane areas. For slender hulls this requires extensively flared sections which normally are applied in the aft body. As the vertical centre of gravity has been increased for every new generation of vessels the form stability has also been increased to fulfill the static stability requirements. The striking development is visualized in figure 4 comparing the aft bodies of the same designs as in the previous figure. As seen the stern flare is significantly more pronounced for the newer vessel.
Figure 4: The flare in the stern sections has increased for modern Panamax PCTC's to provide sufficient form stability, here a design from the early 1980s and a design from 2005 is seen.

In the drive towards higher cargo capacity the internal arrangements have also been thoroughly optimized for utilizing the full potential of the cargo holds by maximizing the efficient stowing area. For instance, structural obstacles such as pillars and bulkheads in the cargo holds have been minimized. While older designs often incorporated several full or partial transversal bulkheads throughout the cargo holds, transversal structural members of modern designs are kept to the absolute minimum. Figure 5 shows the internal structural arrangement of a typical PCTC. The transversal bulkheads above the main deck are for this design limited to the engine casing, a partial transversal bulkhead amidships and the collision bulkhead.

Figure 5: The structural arrangement of a PCTC built in 1999.

A similar development with higher cargo capacity, highly optimized hull forms and internal structure has also occurred in other segments and essentially makes modern volume carriers highly efficient. However, there are inevitable challenges with these highly optimized designs that certainly require full attention from the designers as well as the operators.
3 Parametric Roll

A consequence of the described evolution is that modern volume carrier designs have become more prone to the dynamic stability phenomenon parametric roll. The driving mechanism behind parametric roll is roll restoring variations induced from waves which may occur in heading, following or quartering waves. These variations occur when the water plane area varies with the position of the wave crests. For vessels with large flare angles these variations becomes particularly large. Variations in $\Delta GM$ can be estimated for different wave crest positions by balancing the hydrostatic forces to obtain pitch and heave equilibrium. This is illustrated in figure 6 for a PCTC in regular waves with the same wave length as the ship. In the figure the water plane area is highlighted demonstrating dramatic differences in especially the aft body between the cases.

![Figure 6: Hydrostatic equilibrium of a vessel in a regular longitudinal wave.](image)

For large amplitude simulations, the momentary righting moment has to be calculated. A quasi-static restoring lever arm for a regular longitudinal wave (following or heading) as function of wave phase and heeling angle is illustrated in figure 7.
Figure 7: The restoring lever arm as function of wave position and heel angle for a regular sinusoidal longitudinal wave with the same length as the ship.

In a simplistic manner, parametric roll can be modeled using a one degree of freedom roll equation according to

\[ \ddot{\phi} + 2 \delta \dot{\phi} + \frac{g}{r} \frac{\partial GM(t)}{\partial \phi} \phi = 0 \]  \hspace{1cm} (1)

where \((\ddot{\phi}, \dot{\phi}, \phi)\) are the roll acceleration, velocity and angle, \(\delta\) is the roll damping, \(g\) is the gravity, \(r\) is the radius of inertia and \(GM(t)\) represent the restoring variations with time. In the most simplified form parametric excitation can be produced by applying a sinusoidal time variation of \(GM(t)\) according to

\[ GM(t) = GM_0 + \Delta GM \cos(\omega_e t) \]  \hspace{1cm} (2)

where \(GM_0\) is the initial metacentric height, \(\omega_e\) is the encounter frequency and \(\Delta GM\) is the amplitude of the \(GM\) variations. In figure 8 equation (1) and (2) are used to simulate parametric roll for different combinations of \(\omega_e\) (in relation to the natural frequency of roll \(\omega_0\)), \(\delta\) and \(\Delta GM\).
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As seen the excitation frequency must be close to twice the natural frequency of roll for parametric roll to occur. The magnitude of the restoring variations in relation to the roll damping is decisive for the roll amplitude in case of resonance. If the damping is sufficiently high parametric roll will never develop, but if the damping is low relative to the stability variation large roll angles can develop rapidly. Predicting parametric roll is thus dependent on an accurate description of the natural frequency of roll, the damping and the stability variations.

For irregular and short crested waves a non-linear time domain sea-keeping code is required to simulate parametric roll. Commercial sea-keeping codes are for instance developed by the major classification societies such as ABS LAMP (Shin et al. 2003), ABS NLOAD3D (Belenky et al. 2006) and DNV-GL SIMBEL (Brunswig & Pereira 2006) and considers ship motions in 6 degrees of freedom. Such codes typically solve the hydrodynamic interaction between the wave and the ship using a 3-D potential flow solution. For parametric roll simulations, it is crucial that the wave forces (Foude-Krylow) and hydrostatic restoring force are calculated based on the instantaneous submerged hull while
the influence of the ship on the pressure field (diffraction and radiation) is convenient to calculate based on the mean submerged hull. In figure 9 irregular $GM$-variations calculated with a code described in Hua and Palmquist (1995) and Ovegård (2009) is used to simulate parametric roll. The case corresponds to a typical resonant condition in following waves and is similar to the condition for the incident shown in figure 1. To again highlight the implications of the roll damping two different settings are used for the simulations. Notably the different damping input results in a significant difference in roll response.

![Figure 9: Parametric roll simulations in irregular seas with different damping.](image)

### 4 Roll Damping Prediction

To be able to predict and control critical roll responses an accurate description of the roll damping is crucial. In the early design stage, simple yet reliable prediction methods for the damping are required to assess the vulnerability in different operational conditions. For onboard guidance a proper consideration of the damping in the actual service condition is crucial to provide relevant decision support.

Traditionally semi-empirical methods or model tests are used for roll damping predictions. Ikeda’s method (1976, 77a, 77b, 78a, 78b, 78c, 78d, 79, 2004) is the most established semi-empirical formulation for roll damping estimation of large vessels and is recommended by ITTC (2011). Ikeda defined five different roll damping components: friction, wave making, eddy making, hull lift and bilge keel which were derived based on a combination of theory and systematic model testing using different hull shapes and 2D sections. However, in Kawahara et al.
(2009) the accuracy of Ikeda’s method was found to be unsatisfying for unconventional vessels with high centre of gravity such as modern volume carriers.

Forced or free roll decay model tests as described in IMO (2006) have been considered the most accurate way to estimate the roll damping for a certain ship. Figure 10 shows two roll decay model test time series for a PCTC. The first series represents zero speed and the second corresponds to a typical service speed in full scale, notably the damping is significantly higher at speed.

Model tests at speed are typically performed in a towing tank with the same Froude number as the full scale vessel so the wave pattern shall be the same in the two scales. However, this implies that the Reynolds number, which describes the viscous forces, are different in the different scales. The model gets a relatively thicker boundary layer than the full scale vessel which gives the model larger viscous damping. On the other hand, the bilge keels are likely negatively affected by that the boundary layer thickness in model scale often can be larger than the actual bilge keel height while that not is the case in full scale. Currently there are however no established scaling procedures for roll damping model tests and evaluated non-dimensional damping is normally assumed to be valid for the full scale vessel. Model tests are also expensive to conduct and for practical reasons limited to one or a few hypothetical design loading conditions.

Computational Fluid Dynamics (CFD) calculations can also be used to study roll damping. Several studies such as Jaouen et al. (2011) have been conducted on different 2D sections showing reasonably good agreement with experimental data. In Gu et al. (2015) free roll decay tests are carried out for a container ship hull without appendices using Unsteady Reynolds Average Navier Stokes (URANS) CFD. The results are principally in line with model tests but quantitatively not satisfying. One challenge with CFD is always to achieve a feasible computational domain with reasonable size. For unsteady flow such as
a free roll decay, where many time step iterations have to be performed every roll cycle, this is even more important. The boundary layer around the hull is small relative to the model but still requires high resolution. This results in that massive number of cells are needed to model the boundary layer and the geometry accurately. Due to the relatively thicker boundary layer model scale requires relatively lower resolution and is therefore more convenient to analyze. Figure 11 exemplifies a 2D slice of an evaluated boundary layer around a PCTC hull due to forward speed in model scale. Adding bilge keels and other appendices further adds extensive complexity to the mesh mixing large and small geometries. In van’t Veer & Fathi (2011) RANS-CFD is used for investigating the roll motion related flow around an FPSO with appendixes and in Araki et al. (2014) the flow with and without bilge keels for a Navy Combat ship was studied demonstrating qualitative agreement with experiments. Within CFD the ongoing research is highly interesting and has shown a rapid development. However, more development is needed before complete roll damping predictions using CFD are established.

![Figure 11: Boundary layer mesh around a volume carrier in model scale.](image)

### 5 Other Roll Responses

In addition to parametric resonance volume carriers can also be subjected to other dynamic roll responses such as excessive accelerations due to synchronous roll, loss of stability and responses on cargo and the ship structure. Synchronous roll as described in IMO (2007) occurs in beam or quartering sea when the wave encountering period is close to the natural period of roll. For large fully loaded volume carriers this is not an issue since the natural period of roll often is well above 20 s while large ocean waves have a period in the magnitude of 8-12 s, in rare cases up to 15 s. Instead synchronous roll typically occurs in partial load cases or in ballast conditions when the natural roll period is much shorter. With a short roll period large amplitude synchronous roll involves particularly large transverse accelerations. In case of synchronous excitation the roll amplitude is dependent on the wave height, the band width of the spectrum and the roll damping of the vessel.
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Pure loss of stability IMO (2016a) is related to parametric roll in that it is caused by changes in the restoring moment during longitudinal wave passages. It may occur in following waves if the vessel is traveling in high speed. As the wave encountering period is long the vessel may suffer quasi-static reductions in restoring lever during the wave passages which if it is large can lead to that a large heel angle is developed. According to the Swedish Accident Investigation Board (2008) this was the cause to the capsizing of the RoRo-vessel Finnbirch in the Baltic Sea where roll angles of $40^\circ$ induced severe cargo shift with fatal consequences.

To avoid shift of cargo at sea, proper securing and lashing of cargo is crucial. Instructions and guidance on this shall be included in the ship’s cargo securing manual which is certified by the administration. Neither lashings nor cargo are however typically designed to withstand the roll angles that may be caused by extreme dynamic stability events. An example of this is given in the Marine Accident Report provided by the Danish Marine Accident Investigation Board (2014) where the very large container carrier Svedenborg Maersk experienced heavy rolling, likely caused by parametric excitation and lost over 500 containers overboard. While roll angles over $40^\circ$ were reported from the incident a theoretical roll angle of only $20^\circ$ had been defined to calculate the dynamic forces on the cargo and lashings based on the expected motions for the voyage.

The most critical structural response for volume carriers with a limited number of transversal members such as cruise ships and PCTC’s is racking. Racking can be described as a global transversal shear deformation of the hull caused by gravity and inertia forces as the vessel is rolling. The response is normally thoroughly assessed in the design stage using finite element modelling according to guidance provided by the classification societies, e.g. DNV (2011). In figure 12 scaled racking deformations of a partial transversal bulkhead in a PCTC are illustrated.

![Scaled racking deformations of a transversal bulkhead in a PCTC.](image)

Figure 12: Scaled racking deformations of a transversal bulkhead in a PCTC.
Except during extreme events, racking-induced stresses are in general well below yield strength levels. However, racking loads induce structural fatigue and if the loads over time are higher than predicted during the design stage, fatigue cracks are typically initiated. For highly optimized designs with low design margins, the racking responses are therefore preferably monitored. This can provide input for fatigue life condition assessment, which can be used for condition-based survey and maintenance.

6 Countermeasures to Parametric Roll and Other Roll Responses

Optimization of volume carriers is a balance between stability, structural integrity, and transport efficiency. Traditionally, volume carriers are optimized for a single contractual design point which normally describes the vessels’ performance in calm weather. A typical design condition may contain very high cargo capacity and even though the vessel fulfills the IMO’s present intact stability regulations, this condition may be too sensitive for safe operation in representative weather conditions. A consequence of this may be that the vessel needs to be routed or loaded with restrictions to get satisfying dynamic stability properties, meaning that the vessel will be less efficient than expected. Therefore, thorough consideration of the behavior of the vessel in relevant service conditions must be targeted in the design process. This shall preferably be addressed in the early design stage before key scantlings are set and will give more efficient and safe designs for the actual operation. The risk for critical events such as parametric roll can either be managed with built-in “passive” design measures, with “active” technical features, with operational measures, or as highlighted by Backalov et al. (2016) and Huss (2016) a combination of these, which probably is the most cost-efficient approach.

The built-in vulnerability for parametric roll can be reduced by reducing the relative restoring variations or by increasing the damping. Lowering the VCG reduces the relative restoring variations. Doing so may however require a reduction in payload, which may not be commercially feasible, or an increase in ballast which generate a penalty in fuel oil consumption. Increasing KM of the hull normally increases the restoring variations in waves but given that VCG is kept unchanged, the relative restoring variations are reduced. KM is typically increased by increasing the water plane area coefficient through large flare angles. When elaborating with KM it must however be considered that an increase typically comes with an increase in wetted surface area which generates a penalty in fuel oil consumption. Normally, an increase in beam gives a substantial increase in form stability but also a corresponding increase in
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restoring variations and wetted surface area. However, if a beam increase is combined with a reduction in water plane area coefficient to keep KM constant the net effect can be a hull form that experience reduced restoring variations without any penalty in resistance. The roll damping can typically be increased by increasing the bilge keel size. However, larger bilge keels means more wetted surface and thus higher fuel consumption. Smaller bilge radius may also increase the roll damping but is also associated with larger wetted surface.

Roll reduction can also be achieved using active dynamic stabilization where fin stabilizers or active tanks are the most common systems. Active tanks are ideally tuned so that the motion of the fluid has the same frequency but are phase shifted to the roll motion of the vessel to counteract the exciting forces. As shown by Sellars and Martin (1992) active systems are generally more efficient than passive systems and are therefore often adopted on vessels that have a high demand for roll reductions such as cruise vessels/ferries or cargo ships with particularly sensitive cargo. Most types of merchant ships however, are rarely equipped with active systems partially due to the relatively large investment costs but also due to drawbacks associated with large free surface effects of the tanks and the relatively high forward speed requirement for fin stabilizers to work well. Alternatively, the rudder can be used to provide active dynamic stabilization to mitigate roll motions. The advantage of rudder stabilization is that no physical modifications are required to the vessel, only changes to the auto pilot algorithm. The basic principle behind this approach is that the inertia in yaw normally is much larger than the inertia in roll which means that short rudder impulses to mitigate roll motions may be possible without causing any significant course deviations. Rudder roll stabilization for reducing roll motions in seaway was described in principle already in the early seventies by Cowley and Lambert (1972) and tested the following decade. Commercial products such as Roll-Nix was developed by SSPA in Sweden and by Hyde Marine Systems in the U.S. incorporating an auto-pilot that managed both roll reduction and course keeping. As described in Schultz et al. (1993) Roll-Nix was successfully tested in full scale on medium size Coast Guard vessels but still none of these systems has been widely adopted by the merchant fleet, which partly is related to reluctance of increased wear and tear of the steering gears. In Wada et al. (2007) promising model experiments with a Post Panamax container vessel are presented where the rudder is able to significantly reduce the roll response due to parametric excitation.

For a ship in operation parametric roll can be avoided if sufficiently large restoring variations in resonance are avoided. Potentially critical routes are possible to detect in the route planning stage using weather forecasts and proper load case specific ship characteristics. As discussed by Backalov et al. (2016) guidance can be provided based on pre-calculations from design stage, real time
calculations on-board or real time calculations ashore. In Belenky et al. (2006) it is discussed how roll responses can be pre-calculations in the design stage for possible combinations of loading conditions, weather conditions, speeds and headings using sophisticated state of the art simulation codes. The information is then presented using polar diagrams where potentially critical conditions in terms of lashing strength and engine condition are highlighted using colour codes based on the criticality. Practically, this is however challenging as each such diagram is dependent on the load case and the sea condition. In Ovegård et al. (2012) a Parametric Roll Failure Index was introduced to quickly evaluate the criticality of any combination of sea state, speed, heading and loading condition suitable to be used for onboard operational guidance. In the commercial decision support system Seaware EnRoute Live this is incorporated where measured ship motions from a motion sensor together with hull form and load case data is used to analyze and evaluate the present wave spectra. The system identifies in real-time which critical combinations of vessels speed and heading that may lead to conditions where parametric excitations of critical magnitude could occur. One alternative approach is signal-based detection algorithms where pitch and roll motions are analyzed to alert when the signals indicate the possibility of parametric resonance. In Galeazzi et al. (2015) the testing of one such algorithm on large time series of data from one PCTC and one container vessel indicated efficient detection of critical conditions. One challenge with such approach is however that the time from warning to development of large amplitude roll motions may be too short to take proper pro-active manual actions for the crew. However, combining such system with active mitigation systems could be an interesting way forward.

The development within IMO with the second generation intact stability criteria addresses parametric roll, excessive accelerations, loss of stability and other critical roll responses incorporating multilevel assessment procedures (Peters et al. 2011). In these procedures (IMO 2016b, c) the first level is a simple vulnerability criterion. If the requirements on the first level are not fulfilled, proceeding to the second level is required which typically requires simplified simulations. For designs that do not pass the first two levels a direct stability assessment for parametric roll failure mode shall be performed and the outcome may be used as basis for operational guidance. The procedure for the vulnerability checks, direct stability assessment and operational guidance are however yet to be further developed, both technically and with regard to the safety levels.
7 Stability Management

The author to this thesis managed the hydro-dynamic design process of the first generation Post Panamax PCTC’s for Wallenius Lines AB. The first vessel will be delivered during 2017. The overall objective with the project was to provide a new design with substantially improved fuel efficiency by exploring the benefits that new “Post Panamax main dimensions” could offer. In this process sufficient built-in robustness for dynamic stability events was set as one important constraint to avoid unanticipated operational limitations. The dynamic stability characteristics was therefore assessed throughout the design stage. In this process, older generations of PCTC’s that have shown a good operational track record were used to defined the maximum allowed vulnerability level and for benchmarking. The new design is wider than predecessors which provides a substantial increase in form stability. This is primarily used to reduce the ballast requirements but the final design could also be given a lower water plane area coefficient and less flare aft. In figure 13 the aft bodies of a modern Panamax PCTC is compared with the new Post Panamax PCTC.

![Figure 13: Comparing wetted surface and flare angles for a Panamax (Left) and Post-Panamax PCTC (Right).](image)

To ensure sufficient damping a new type of high aspect ratio bilge keels were developed and illustrated in figure 14. The bilge keels provide significantly improved damping without any increase in wetted surface area relative to conventional ones.
Figure 14: Illustrating the high aspect ratio bilge keels that are incorporated in a Post-Panamax PCTC design.

With these features the new design incorporates lower relative restoring variations in relation to the roll damping while at the same time providing improved transport efficiency. The design is not invulnerable to dynamical stability events but the risk level is deemed to be operationally manageable. To manage the risk, motions will be monitored in detail and an onboard operational guidance system will be provided together with training of the crew in understanding of the risks and how to use, interpret, and act upon, information provided by the implemented decision support system.
8 Contribution to the Field

As described in the previous section the knowledge, methods and results generated through this Ph.D. project has already been put in practical use in the design and operation of ships for improved safety, efficiency and on-board work environment. In addition, a holistic framework is presented in this thesis (Papers A to D), providing a platform for predicting and assessing the roll damping throughout the early design stage until delivery of the ship and for the operation. The framework is based on a unique combination of semi-empirical methods, CFD, model tests and full scale trials. The thesis also contains a demonstration of a new application for rudder control to be used for mitigation of parametric roll (Paper E). Furthermore, an approach for monitoring of roll induced racking stresses is presented (Paper F).

In (Paper A) a new approach is developed for deriving the roll damping where full scale roll decay tests are performed by inducing roll motions using rudder impulses. The evaluated damping is principally in line with roll damping evaluated from model test however the full scale damping seems to be slightly higher which is further considered in paper D. Full scale trials can be performed in service, without having to take the ship off hire. This means that costs associated with the tests are limited, the test is performed in a relevant actual loading condition (rather than a hypothetical design condition) and uncertainties related to scale effects are eliminated. A sample full scale roll decay test is illustrated in figure 15.

![Figure 15: Time series of rudder angle and roll angle during a full scale roll decay test onboard a Pure Car and Truck Carrier.](image)

In (Paper B) Ikeda’s method for roll damping prediction is revisited and the applicability of the method to modern volume carriers is considered. For volume carriers the hull lift and bilge keel components are the dominating components and the estimation of these components in the original method are benchmarked and scrutinized. It is concluded that the speed dependence of the bilge keels damping is underestimated by the original method. This is partially explained by that Ikeda seems to have underestimated the lift force of the bilge keels in his
analytical expressions. Correcting for this and taking account of the lift force generated pressure on the hull surface gives overall better agreement with model tests. It is also concluded that the hull lift damping component is significantly overestimated with Ikeda’s method. Non-viscid CFD is used to propose a new generic expression for estimating the lift coefficients for volume carriers which greatly improve the accuracy in comparison to model test results. With these improvements Ikeda’s method is revitalized and the applicability is extended to unconventional volume carriers. Figure 16 shows a mesh from one of the non-viscid CFD calculations that was used in the analysis.

Figure 16: Mesh on the hull surface used for non-viscid CFD calculations.

In [Paper C] the importance of an additional roll damping component, aerodynamic damping, is highlighted and an approach for estimating aerodynamic roll damping is formulated. Roll velocity induces a transversal velocity field, linearly increasing from the centre of roll that contributes to the apparent wind. This leads to variations in heeling moment over the roll cycle which can be interpreted as aerodynamic roll damping. The formulated approach utilizes wind tunnel tests and a concept of effective levers to relate roll induced apparent wind to a damping moment. Evaluation of the approach on a typical PCTC demonstrates that the aerodynamic damping in certain conditions can be of similar magnitude as the hydrodynamic damping when the weather is rough and the speed is reduced. In figure 17 operational guidance polars with regard to parametric roll with and without aerodynamical damping considered is exemplified.
In (Paper D) the methods and findings generated in paper A-C are synthesized into a holistic multi-tier roll damping prediction framework. The approach provides a platform for best possible roll damping prediction given the different stages in the design process and in operation. Starting from the earliest design stage the semi-empirical model complemented with an aerodynamic component gives the foundation for a complete model that is applicable for all possible loading conditions and operational conditions. As the hull lines evolves through the design process the model can be updated with input from CFD calculations providing the hull specific lift coefficient and a more precise lift damping component. In the next stage of the design process updated input is provided from model tests. The bare hull damping and the bilge keel damping is treated separately and model tests with and without bilge keels are required to establish these components. Finally, prior to the delivery of the ship the model is tuned using full scale trials.

In (Paper E) a new application for prevention of parametric roll using the rudder is demonstrated to be efficient and particularly suitable for volume carriers. With very high centre of gravity and consequently a large lever to the rudder, the rudder-roll coupling for PCTC’s is generally very distinct which provides good conditions for the application. Moreover, as parametric roll is a very rare event, occurring typically a few times (if ever) over a vessel’s life time, additional wear and tear of the steering gear, which may have caused problems for previous regular rudder roll stabilizing applications, is not an issue. As no modifications to the vessel other than adjustments to the autopilot would be required, the approach is highly cost efficient. Figure 18 shows a simulated sequence where the rudder is successfully employed to mitigate the amplification of parametric roll.
Figure 18: Time series of simulation where the rudder is used to mitigate parametric roll for a PCTC.

In (Paper F) a new approach for racking stress monitoring involving measurement of the ship motions and scaling of pre-calculated structural responses with the measured motions is presented. Calculated stress sequences show good agreement with stress sequences derived from strain gauge measurements, indicating that the method has potential as an alternative to conventional strain gauge based monitoring. Motion based stress monitoring has several potential areas of application such as providing data for decision support for live assistance and short term route planning, structural condition reports, and for supplying feedback to the design process.
Controlling the Roll Responses of Volume Carriers

9 References


Controlling the Roll Responses of Volume Carriers


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