Operational stability beyond rule compliance

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ABSTRACT

This paper summarises operational experience and stability management activities within a shipping company in order to maintain safe and efficient shipping with car carriers. It is recognised that this type of ships has developed to become more sensitive to stability variations in waves and that the existing requirements in the Intact Stability Code and other IMO regulations and guidelines so far give very limited operational guidance. Stability management activities discussed include design measures, decision support systems on board, training and monitoring. It is believed that all these areas should be addressed in the future for ships that are found vulnerable under the second generation intact stability criteria presently under development within IMO.

Keywords: *Stability in waves, Parametric rolling, Car carriers, Second generation intact stability criteria*

1. INTRODUCTION

Although stability criteria in the Intact Stability Code have been applied by most national administrations for a long time, they became internationally mandatory as late as 2010 through amendments to the SOLAS and Load Line Conventions. The general criteria provide *GZ* requirements that aim to cope with various events causing large heeling moments to an intact ship. Together with other design requirements on freeboard, water and weather tightness and damage stability, a reasonable level of stability robustness is in general achieved for ships of any kind. Still, the main contribution to safety can probably be found in proactive operational measures to avoid the critical events to occur; e.g. lashing to avoid cargo shift, route planning to avoid extreme wind and waves and navigational procedures and systems to avoid collisions. Many of these measures are reflected by other requirements in other chapters of the conventions.

For ships designed to carry large volumes and high centre of gravity, such as car carriers, container vessels or cruise ships, stability is one of the major design constraints. The vulnerability to stability variations in waves, which is not explicitly covered by today's rules, becomes much more critical for these ships. The ongoing development of additional intact stability requirements with regard to phenomena such as parametric excitation and loss of stability in waves is certainly well motivated and will also open up for additional proactive actions, including both design and operational measures.

For Wallenius Shipping with a large number of car carriers operating around the world and a continuous program with new vessel designs, stability management has been identified as a key area of interest with regard to safety, quality and efficiency objectives. This presentation gives some examples of how these three objectives have been targeted by activities in design, decision support systems, training and monitoring. It intends to open up for a discussion on what is needed to further improve safe and efficient operation in the future.

2. EVOLUTION OF CAR CARRIERS

The evolution of dedicated ships for transportation of cars and trucks can be traced back to the 1950s. Following the reconstruction after the war, the demand for new cars increased on both sides of the North Atlantic. In 1956, the Swedish ship owner Olof Wallenius who had been engaged mainly with tankers and bulkers but also with two small car carriers for the Great Lakes, received a long-term contract with Volkswagen for transport of cars to the US. At that time cars had mostly been carried in general cargo ships but were now started to be carried on larger scale in combination or alternation with other cargo on bulk carriers on demountable decks or in reefers. During the following years different concepts for handling cars were developed and tested including side ramps, bow ports and elevators but the vast majority of cars were still lifted on/off in traditional cargo holds.

The RoRo concept that initially emerged for short sea transportation during the early 1960s was adopted for ocean transport in the highly innovative first and second generation combined Ro-Ro/Container vessels for Atlantic Container Line that started on Wallenius' initiative. This concept led further to the first two dedicated Pure Car Carriers (PCC) delivered in 1975-1976 with a length of 200 m, a breadth of 28.2 m and a capacity of 4900 cars. They were followed by the two first Pure Car and Truck Carriers (PCTC) in 1977 with length 190 m, Panamax breadth 32.2 m and a capacity of 5500 cars. At that time Wallenius had become a main tonnage provider for the rapidly expanding Japanese export of cars around the world (Wallenius-Kleberg, 1984)

The 200/32 m PCC or PCTC have been standard concepts for world wide car transport since then, mainly driven by the restrictions in Japanese ports and by the Panama Canal. It has been joined by the larger LCTC with a length of about 230 m and lately by 200 m vessels with a breadth beyond the present Panama restrictions, both types with a typical capacity of about 8000 cars. The world fleet consisted in the mid 2015 of about 470 car carriers with a capacity of 5000 cars or more with additionally about 60 ships in order (Fearnsearch, 2015).

Although the main dimensions of typical PCTCs have been maintained for more than three decades, the development towards more efficient ships has continued within those restrictions. Table 1 compares the capacity of three generations of PCTC. The increase in car deck capacity of about 20% is dramatic and has also resulted in significantly higher centre of gravity for the cargo, compensated for by increased form stability and increased ballasting.

Table 1: Comparison of capacity of three generation PCTC, all with length over all 200 m, breadth 32.3 m and design draught 9.5 m.

Date of delivery	Capacity car units	Deck area [m^2]	VCG of load on car decks [m]	KM at design draught [m]
1985	5300	47300	19.4	14.8
1995	5850	52400	20.4	15.7
2006	6700	56400	21.9	16.4

PCTCs may seem just as floating garages by sight but indeed their underwater hull have very sophisticated forms to obtain the lowest possible fuel consumption under variable service conditions and to obtain the the highest possible initial stability to carry large volumes of cargo with high centre of gravity. To raise the metacentre with 1.6 m as shown in Table 1, within the main dimension constraints without increasing resistance is indeed a significant achievement for increased transport efficiency.

From 1983, the intact stability criteria required by the Swedish Administration have been the same as the general criteria in the Intact Stability Code, i.e. they have remained unchanged through the development of the standard PCTC. Due to the large superstructure, the criteria are not decisive in general, only at light draft may the weather criterion require rather high *GM*, but that will anyway be at hand for the ballast conditions. For normal service conditions including margins for manoeuvres, wind and waves, a *GM* below 0.8 m has in general not been considered feasible as an operational seagoing condition. This is significantly above the *GM* limits given by the Code, which typically could be around 0.3 m. When the first probabilistic damage stability requirements for dry cargo ships became effective from 1992, this led to some changes in the watertight subdivision, but the *GM*-limit could still be maintained at about the same level as had been used in practice as minimum before. Even the significantly stricter damage stability requirements from 2009 could be handled by additional horizontal subdivision with a *GM* minimum at loaded condition marginally raised to about 0.9 m.

3. OPERATIONAL EXPERIENCE

The development of stability optimised hull forms has naturally also led to more stability sensitive vessels. Wallenius had an early awareness of the potential problems with stability variations in waves for this type of ships. Early in the 1990s the company supported a research project at KTH (Huss and Olander, 1994) which eventually resulted in the Seaware EnRoute Live on-board decision support system for seakeeping that also included a motion sensor with live motion recording in six degrees of freedom. This system enabled one of the first high frequency full motion recordings ever of parametric roll in head sea with the PCTC "Aida" in 2003. Although this case was not the first and not the most severe the company had experienced at that time, the motion records made it possible to analyse and understand the phenomenon in much more detail. A report of the incident was presented to IMO in a Swedish submission to the IMO SLF sub-committee's work with review of the intact stability code (IMO 2004). After the incident, rough criteria for parametric roll were included in the live on-board guidance on all Wallenius ships in accordance with the early guidance from IMO in MSC.1/Circ.128 (IMO 2007).

Following the introduction of a new generation PCTC and LCTC in the mid 2000s with significantly more stability optimised hulls than previous generations, parametric rolling and pure loss of stability came even more in focus. In 2008, one of the new LCTC experienced heavy parametric rolling with a maximum amplitude over 30° in moderate following seas with a significant wave height of just slightly more than 4 m. Eventually, the vessel got out of resonance by changing course and speed, see Figure 1.

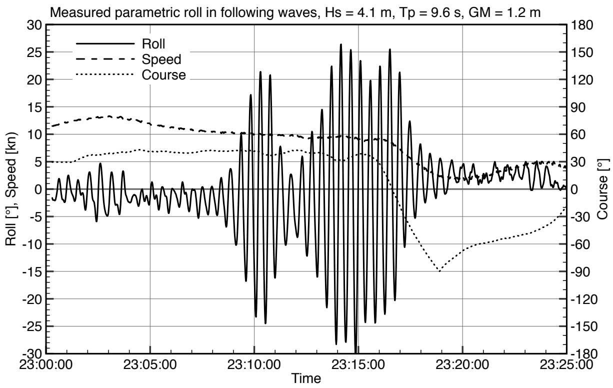

Figure 1: Measured parametric roll in following waves with a LCTC 2008.

At that time, the live warning system was not active, but would anyhow most likely not have identified the situation as critical due to the rather low wave height. This case together with two other measured parametric roll excitation in head and quartering seas with the same vessel generation have been publically reported (Rosén et al., 2012). A few more cases with parametric roll or other stability related incidents have been captured by our monitoring systems and analysed in detail and together they have indicated the need for, as well as made it possible to, develop a more thorough stability management within the shipping company.

4. DESIGN MEASURES

The first step towards achieving better control was to map the characteristics of the existing fleet and identify the trends and changes inherent in the development of more efficient vessels. In lack of suitable standard methods at that time, we developed in-house benchmarking procedures that would capture the influence from differences in hull form, damping and load conditions and provide a qualitative measure of the sensibility. We also started a regular research cooperation with KTH and Seaware in order to further develop knowledge, methods and tools in this area.

Firstly, the vessels quasi-static stability in regular waves of different length and height was analysed and compared. Figure 2 shows an example comparing the three PCTC generations listed in Table 1.

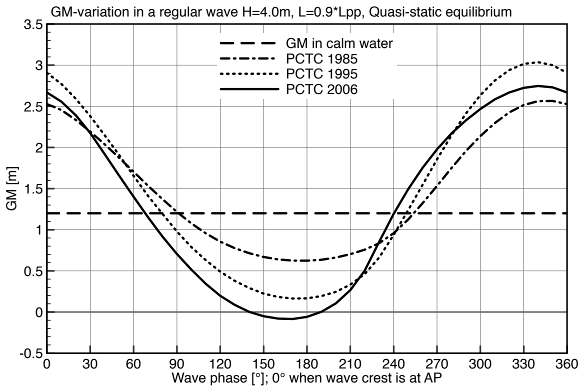

Figure 2: Comparison of three generation PCTC quasi static GM variation in regular waves. Wave height 4m, wave length 90% of Lpp.

Secondly, the roll damping at speed was estimated based on a combination of semi-empirical calculations, model tests and full scale verification (Söder et al., 2012).

Thirdly, given each vessels estimated stability variation and damping, parametric excitation in following irregular seas was simulated using a simple one degree of freedom equation with irregular *GM* variation obtained from linear superposition of response in regular waves. The change of average *GM* was roughly accounted for by adjusting the calm water *GM* with an addition taken from the average variation in regular waves with the same wave height as the significant wave height used in the simulations. These simulations were performed for typical critical conditions experienced under real service, like the one in Figure 1.

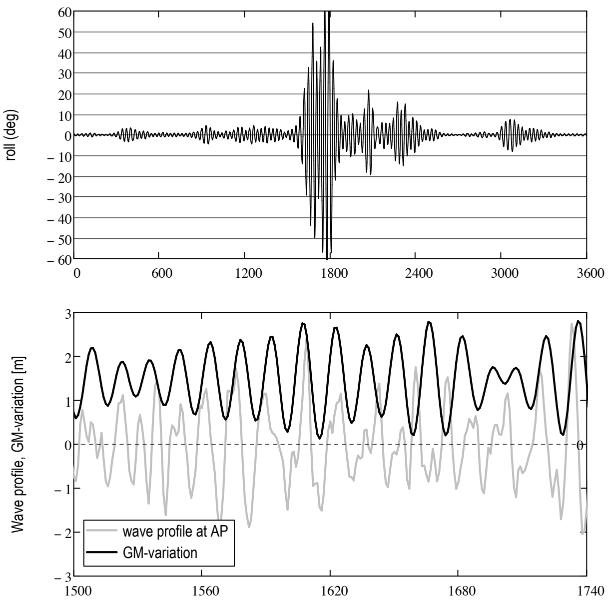

Figure 3: Example of results from a simplified 1-dof simulation of parametric rolling in following irregular sea. The upper graph shows a 1h roll sequence with typical parametric rolling. The lower graph shows a small sequence of four minutes with wave profile and *GM* variation during the development of large amplitude rolling.

All simulations were performed for different wave mean periods at constant significant wave height. The same sequence of waves (generated from 300 components with fixed steps in periods) was used for simulations with different ship characteristics so that the roll sequences could be compared directly with each other. The results were combined in an *ad hoc* "severity index" that incorporated both the relative frequency of roll angles above ±10° and the maximum amplitudes in accordance with Equation (1).

$$pr_{comb} = \sqrt{pr_{max} pr_{>10°}}$$
where
$$pr_{max} = min\left(\frac{\phi_{max} - \phi_{min}}{2 \cdot 60°}, 1\right) \quad (1)$$
$$pr_{>10°} = 1 - F_{\phi}(10°) + F_{\phi}(-10°)$$
F_{ϕ} is the cumulative distribution of roll

For the example sequence in Figure 3, $pr_{comb} = 0.29$ with $pr_{max} = 1.0$, $pr_{>10°} = 0.09$.

This "severity index" distribution over periods provided a very clear qualitative differentiation between the vessel generations sensibility to parametric rolling. See one example in Figure 4 where the sequence in Figure 3 is illustrated by the dot.

As a result of this mapping it was also decided to retrofit the most sensitive existing ships with larger bilge keels in order to increase their damping and robustness with regard to stability in waves.

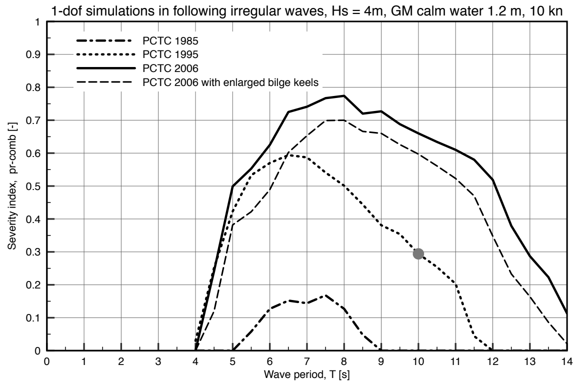

Figure 4: Qualitative comparison of different PCTC generations with regard to parametric roll. Results from 1-dof simulations in following waves with Hs 4m and varying wave periods. The effect of enlarged bilge keels on the most sensitive ship type is also included. The dot represents the simulated sequence in Figure 3 and the condition is similar to the real case shown in Figure 1.

Another aspect of highly stability optimised hull forms is that the *KM* is strongly varying with the trim. Due to very wide aft sections and more vertical forward sections around the water line, the waterplane area and initial stability will increase significantly with aft trim. At the same time also the resistance will increase significantly. Adding ballast in order to increase *GM* for a given cargo condition will also increase the resistance and fuel consumption. For the most optimised ships, typically 0.1 m increase of *GM* will result in about 0.5% increase in fuel consumption for the very best combination of trim and ballast and may result in significantly higher consumption rates for less optimal combinations. In order to be able to optimise stability and efficiency together all vessel types have been model tested in a wide range of combinations of draught, trim and speed. The results have then been incorporated with the loading computer as one of the decision support systems described in the following section.

All these studies of stability characteristics of the existing fleet have also resulted in an enhanced understanding of important design parameters and enabled more thorough owner's requirements on stability and efficiency for new projects which go far beyond statutory minimum requirements.

5. OPERATIONAL DECISION SUPPORT

The Master has the unique authority and responsibility to keep the ship seaworthy in all conditions. This includes the choice of route as well as the load condition and stability. Taken into account the highly optimised ships and their complex individual characteristics and differences, we find it important to supply the Master on board with decision support to enable this authority and responsibility. With the increased knowledge obtained from simulations, monitoring and analysis, we have also realised that the support systems must reflect the individual ship rather than being generic if they are to be fully effective. This has led to a close cooperation with the system suppliers so that we can maintain control over the ship models used in their systems.

Standard support systems on board related to stability include today the following:

- Loading computer with intact and damage stability assessment including statutory limits but also with possibility to modify e.g. hold permeability to better simulate reality in the actual loading condition.
- Ballast optimisation in order to obtain target stability for a given cargo and tank configuration with lowest possible fuel consumption for a given speed.
- Route planning and route optimisation with ship and loading condition specific models for performance in wind and waves and with continuous updated weather forecasts. The objective is to find the most cost efficient route in terms of both track and speed for a given target time of arrival, while at the same time avoiding any critical condition with regard stability and ship motions in waves.
- Live warnings for critical conditions and advice on heavy weather manoeuvring to avoid critical combinations of speed and course based on real time motion measurements and analysis of the prevailing wave spectrum.

In the development of all these systems, Wallenius Shipping has been active both in drafting the detailed system specification and in developing and/or testing new methods and models. One example is the implementation of simplified models to identify risk boundaries for avoiding parametric rolling and pure loss of stability based on linearised *GM* variation (Dunwoody, 1989; Bulian, 2010), which have been adapted and fine-tuned with operational experience and measurements from real incidents within our fleet (Ovegård et al., 2012). These models are since 2011 incorporated in the onboard system for both route planning and live warning so that the specific conditions can be accounted for as precise as possible. This includes the actual sea state and load condition as well as the general stability and damping characteristics of the individual vessel.

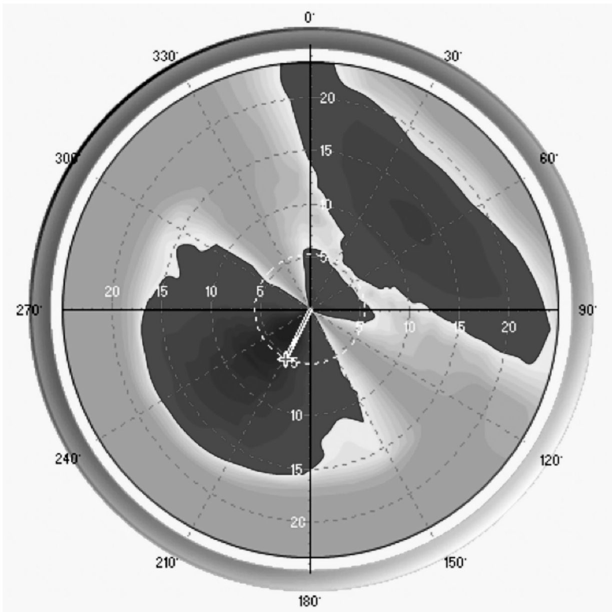

Figure 5: Example of heavy weather manoeuvring advise with regard to stability in waves in the on-board decision support system Seaware EnRoute Live.

In addition to decision support, we are also looking into the possibility to use more active supporting systems that would mitigate critical situations directly without operators' actions. Although it is still not implemented on our ships in service, it is well within reach to mitigate parametric roll using rudder control (Söder et al., 2013). This would be in line with what we see in cars today with active brake assistance systems. One of the crucial components in such systems will be the early detection of critical events that could put rudder control systems into an alert mode ready for active roll mitigation. Promising results from tests with signal based detection have recently been reported (Galeazzi et al., 2015).

6. TRAINING

Like any management strategy, stability management needs to address physical conditions (hardware), systems (software) and people. Operational stability is in the end in the hands of the crew on the ships, and their knowledge, skills and routines are decisive for the outcome. In parallel with the mapping of ship characteristics and the development of operational support, we have been running three-days stability training courses with all senior officers. The courses have been divided on the following three subjects including also hands-on training or demonstration of support systems:

- General Intact stability (Rules; Documentation; Loading computer assumptions and features; Heeling from wind and manoeuvres; Ballast optimization; Ways of assessing the stability during operation; Potential effect of cargo shift; Service experience/statistics)
- Damage stability (Subdivision and damage stability basics; Rules (pre and post SOLAS 2009); Documentation; Emergency awareness on board; Procedures for damage stability assessment on board; Shore based emergency response services; Review of public information from flooding accidents)
- Heavy weather stability (Stability variation in waves; Critical phenomena; Assessment methods and limitations; Comparison between vessel generations; Review of incidents with parametric excitation and loss of stability; Route speed and course optimization; Support system usage; Communication with ship management and ship operation)

The course discussions have mainly been targeting a common understanding that the answer to what is optimum stability is not a specific *GM* but rather an active on board stability management adjusted to the circumstances of each vessel, condition and voyage. From the office we try to support this on board management with technical systems, monitoring, analysis and recommendations.

My experience from these courses is that they have opened up for further discussion and exchange of knowledge/experience between vessels and office, they have widened the view from prescriptive to functional and they have also closed down some myths that still prevailed both at shore and at sea within the organisation.

7. MONITORING

Within just a decade, vessel monitoring has developed from the traditional noon reports sent ashore to high frequency measurements from various systems on board feeding a number of automatic and on-demand analyses and reports for different stakeholders. Among those measurements we have today access to 6-dof rigid body motions recorded with 10 Hz resolution by a dedicated motion sensor on almost all ships. In addition, we have roll, pitch and heave together with speed, position, heading, rudder motions, wind, etcetera, recorded from the navigational systems as well as detailed data from the engine control system with 1 Hz resolution. Because of limitations in the satellite communication, these high frequency measurements are today stored on board and only aggregated statistical properties (in general mean, standard deviation, minimum, maximum and period per 10 min interval) are sent ashore and combined with weather and other route data. However, the high frequency data is still stored on board and can be retrieved on line from the ships when needed. Within short we foresee that also the full high-frequency records will be pushed ashore on a daily basis.

This means that we nowadays have the technical basis for following the dynamic behaviour of each individual ship for each individual voyage and loading condition, literary every second, always. Based on these motion measurements we can also calculate the time series of wave and wind induced (rigid-body) accelerations on any car at any position during the transport. Both for further research and for transport quality this opens up completely new perspectives and we are just in the beginning of exploring the opportunities for getting knowledge and value out of this information. Here are just a few examples included as illustration of the data.

Figure 6 shows an example of results from a study of aggregated roll statistics between June 2014 and September 2015 from 14 vessels. The data set includes in total 593000 records of 10 min data from seagoing conditions.

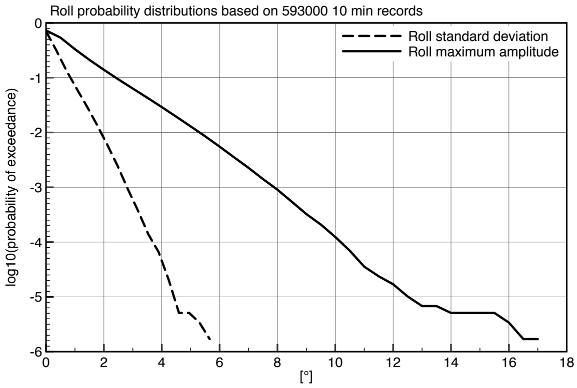

Figure 6: Long term distribution of roll standard deviation and maximum amplitudes within 10 min records from service data between June 2014 and September 2015.

If we consider the roll amplitudes in irregular seas being Rayleigh distributed (narrow banded linear response assumption), the frequency distribution of extreme amplitudes within each 10 min record set will follow:

$$f_{extr}(\phi, N) = = \frac{\phi N}{\sigma_\phi{}^2}\left(1 - e^{-\frac{\phi^2}{2\sigma_\phi{}^2}}\right)^{N-1} e^{-\frac{\phi^2}{2\sigma_\phi{}^2}} \quad (2)$$

where σ_ϕ is the standard deviation and N is the number of amplitudes within the set.

Figure 7 shows a comparison between theoretical extreme value distribution assuming linear roll response (2) and the real distribution of maximum amplitudes to any direction measured for the same period. There is a small bias in the measured distribution compared to the theoretical that well could be the effect of non-linear damping, but in general the fit is surprisingly good.

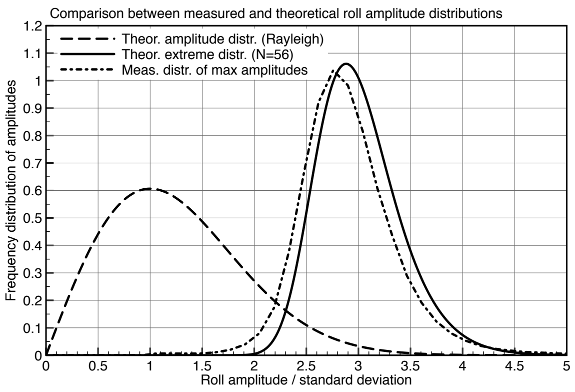

Figure 7: Distribution of roll amplitude extremes within 10 min records. N=56 corresponds to the average number of amplitudes to any direction within all records.

Within this study, limited to 14 vessels and 16 months, the statistics shows in general very moderate rolling. Only 211 10 min records were found where the maximum roll amplitude to any direction had exceeded 10° and 109 of these showed differences between maximum and minimum roll amplitudes that exceeded 18°. Most of these higher roll records could be summarised under 14 different cases/conditions of which half were identified as typically synchronous roll in stern quartering waves and the other half were likely parametrically excited roll from stability variations in waves. Of these were two in head to bow seas and five in following seas. Most of the conditions have been reported to have a *GM* of 2.0 m or more, so they do not in general represent low stability cases.

The two most severe records with amplitudes of 17° were from the same condition in heavy weather with following waves with a significant height of about 7 m. An extract from the records is shown in Figure 8 which include both some aggregated 10 min data and the high frequency roll records. The live warning system on board did show alert during this passage. However, there were no manoeuvring options considered feasible to fully avoid critical conditions at that time so the Master decided to keep high awareness and make necessary manoeuvres to get out of resonance whenever rolling started to develop. The amplitudes could also be kept well below critical levels.

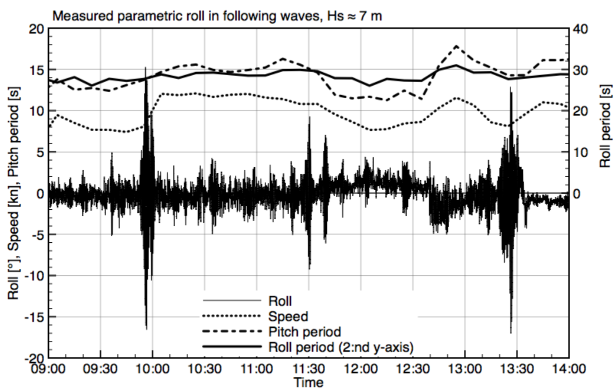

Figure 8: Sequence with the highest roll amplitudes during the studied 16-month period combined with 10 min average data for speed, pitch period and roll period. The periods have been plotted with different scales to better illustrate the excitation of large amplitudes when there is a perfect 2:1 relation between roll periods and pitch periods.

8. FUTURE REGULATORY ACTIVITIES

The IMO work with development of second generation intact stability criteria under the SDC Sub-Committee is expected to, as a first step, result in a MSC Circular to encourage Member States to apply the new interim criteria. The idea is to gain experience before the new requirements are completed and made mandatory as an amendment to the IS Code (IMO 2016). We welcome this development and think it will enhance safety and support a more proactive approach. However, there is of course also a risk that ships found vulnerable under these criteria will be considered as less safe *per se*. In our opinion and based on our experience, this need not be the case, they may just have to be operated with more active management, support and care. As in every other area, the balance between efficiency and safety is not a fixed point in time but is relying on available knowledge and technology.

This presentation aims to show that we have started on the journey towards functional stability management, but it has no intention to say that we have arrived. More research, system development and operational experience is needed to carry us further along this route.

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