On Aerodynamic Roll Damping

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ABSTRACT

In this paper an approach for estimating aerodynamic roll damping is formulated. The approach utilizes wind tunnel tests and the 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. The importance of considering this component in the formulation of operational guidance with respect to parametric roll is highlighted using analysis of a real incident and simplistic simulations.

Keywords: *Roll damping, Parametric roll, Roll decay, Wind damping, Aerodynamic damping, Wind tunnel tests*

1. INTRODUCTION

In November 25 2011, a Panamax Pure Car and Truck Carrier (PCTC), was passing south of a heavy low pressure in the North Atlantic outside of Newfoundland. Wind speeds over 22 m/s were measured onboard and a combined significant wave height of about 5 meter was registered. The vessel was traveling in bow waves and the speed was reduced to about 10 knots to avoid bow slamming. A recorded roll motion sequence from this day is given in Figure 1. The wind came initially in from the same direction as the waves and gave the vessel a static wind list of some 3 degrees to starboard. The roll motion was limited. As the vessel was passing the low pressure the wind rapidly shifted in direction and dropped in speed. As a consequence, the wind list diminished and shortly afterwards the vessel started to roll heavily. During this sequence the course was kept un-changed while the apparent wind direction went from at the bow to straight heading. Minutes later the Master decided to alter the course to port to regain the bow wind effect. After the rolling diminished the vessel was listing to port due to the new apparent wind direction.

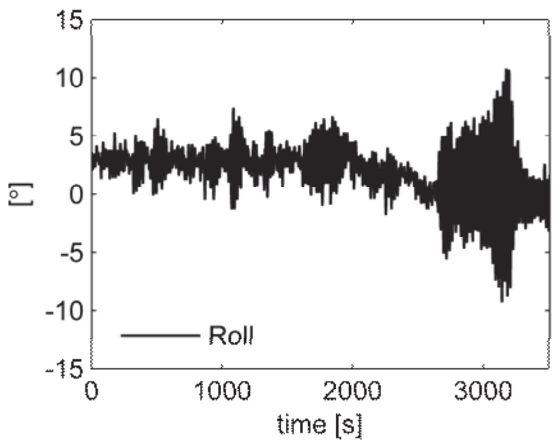

Figure 1: Heavy rolling event in the North Atlantic with a Pure Car and Truck Carrier. Initially small roll angles were experienced onboard but as the wind shifted the wind list diminishes and large roll angles were developed.

When the rolling occurred the vessel was pitching heavily with a period of half the roll period, which indicates that this was a typical case of parametric roll. In case of parametric resonance the roll damping is decisive for the roll amplitude. As long as the damping is sufficiently high the parametric excitation will not result in any amplified roll motions, while if the damping is too low large roll angles can develop rapidly.

Captains of PCTC's generally prefer bow wind in rough weather as the wind is claimed to have a "stabilizing effect" on the roll motions. The here described event gives credibility to this claim and indicates that the changing aerodynamic damping during the turn of first the wind then the ship, had a significant influence on the development of parametric roll.

Today, roll decay model tests are considered the most accurate way to estimate the roll damping for a certain ship (IMO 2006). Due to associated costs, model tests are however normally limited to a few, often hypothetical design load cases. Alternatively, semi-empirical methods such Ikeda (1978) may be used to estimate the damping. In common for both these approaches is that they only consider the hydrodynamic damping. In Söder et al. (2012) it was discussed whether the wind could make any significant contribution to the total damping. Otherwise, very limited work has been done on aerodynamic roll damping.

In this paper an approach for estimating the aerodynamic roll damping is formulated. The approach is applied on m/v Fidelio, a PCTC similar to the one in the event 2011. The significance of aerodynamic damping is assessed relative to the hydrodynamic damping and the importance of considering this component in operational guidance is discussed.

2. AERODYNAMIC DAMPING

An approach for estimating the aerodynamic roll damping is here developed based on similar principles as used to estimate the hydrodynamic lift induced damping in Ikeda (1978).

As illustrated in figure 2 the air flow past the vessel, the apparent wind, V_a and ψ, is determined by the ship speed V_s, the true wind speed V_t and the true wind direction γ. Aerodynamic drag D_A is generated in the flow direction and if ψ differs from zero, an aerodynamic lift force L_A is induced perpendicular to the flow. The sum of the projected transversal components of D_A and L_A decides the transversal force Y. The centre of effort of this force is typically some distance z_Y above the centre of gravity. A heeling moment is hereby generated that is fairly constant if the ship and wind speeds are steady.

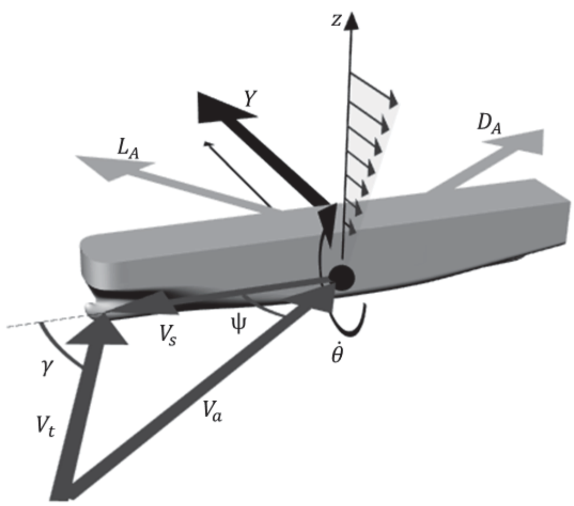

Figure 2: Illustration of velocity and force components that are decisive for the generation of aerodynamic roll damping.

If the vessel is rolling the roll velocity $\dot{\theta}$ induces a transversal velocity field, linearly increasing from the centre of roll, that also contributes to the apparent wind. This results in variations in heeling moment over the roll cycle which can be interpreted as aerodynamic roll damping,

$$B_A\dot{\theta} = \left(Y_{\dot{\theta}}(V_{a\,\dot{\theta}}, \psi_{\dot{\theta}}) - Y(V_a, \psi)\right)z_Y. \quad (1)$$

where $Y_{\dot{\theta}}$ is the transversal force including the apparent wind effect from the roll induced velocity field

$$V_{a\,\dot{\theta}} = \sqrt{(V_S + V_t\cos\gamma)^2 + (V_t\sin\gamma + \dot{\theta}\,z_v)^2} \quad (2)$$

$$\psi_{\dot{\theta}} = tan^{-1}\left(\frac{V_t\sin\gamma + \dot{\theta}\,z_v}{V_S + V_t\cos\gamma}\right) \quad (3)$$

The lever z_Y is here estimated as half the distance from the centre of roll to the bridge deck while z_v is estimated as $z_v = 4/3\,z_Y$ based on the concept of effective levers similarly as in Ikeda (1978). These estimations are obviously rough and should be assessed in future work.

3. EVALUATION

The methodology is evaluated on m/v Fidelio which is a modern Panamax PCTC, built in 2011 with cargo capacity of 8000 cars. A picture of the vessel is seen in figure 3 with main particulars according to table 1.

Figure 3: M/v Fidelio, a Pure Car and Truck Carrier

Table 1: Main particulars of m/v Fidelio in the design load condition

Length	[m]	220
Beam	[m]	32.3
Draft	[m]	9.5
GM	[m]	1.1
Displacement	[m^3]	41000
Air draft	[m]	40

The hydrodynamic roll damping was estimated using towing tank model tests in Söder et al. (2012). The tests were performed at SSPA in Sweden with a 1:30 scaled model and the results are shown in figure 4 for non-dimensional linear equivalent damping at 5° roll angle.

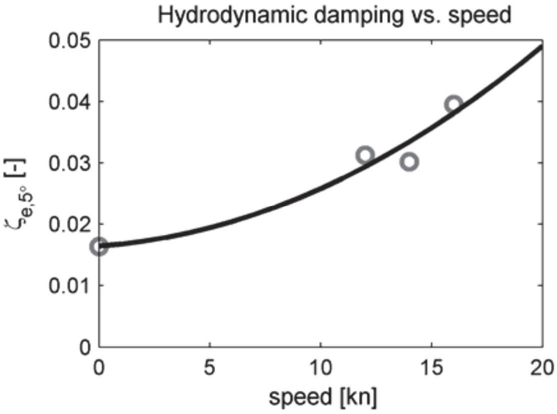

Figure 4: Non-dimensional linear equivalent hydrodynamic roll damping at 5° roll angle vs. speed.

The aerodynamic forces are determined using static wind tunnel tests with a 1:100 scaled model pictured in figure 5.

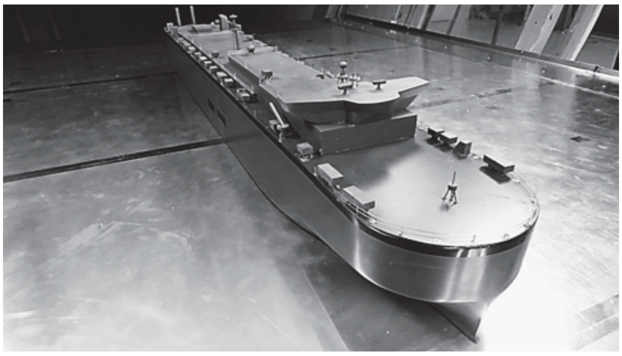

Figure 5: Wind tunnel model of PCTC Fidelio

The tests were performed at STARCS in Sweden. A closed circuit low speed tunnel was used with a test section measuring Ø 3.6m x 7 m. The measured transversal lift coefficient C_Y as function of ψ is given in figure 6, relating to the transversal force Y as

$$C_Y(\psi) = \frac{Y}{\frac{1}{2}\rho_A V_a^2 A_S} \quad (4)$$

where ρ is the air density and A_S is the reference area which here is set to the projected side area of the vessel. The tests were performed in Reynolds numbers in the order of $5 \cdot 10^6$. A sensitivity study showed a slight increase of lift with Reynolds number which indicates that the force coefficients in full scale, with a Reynolds number up to 100 times higher could be somewhat higher.

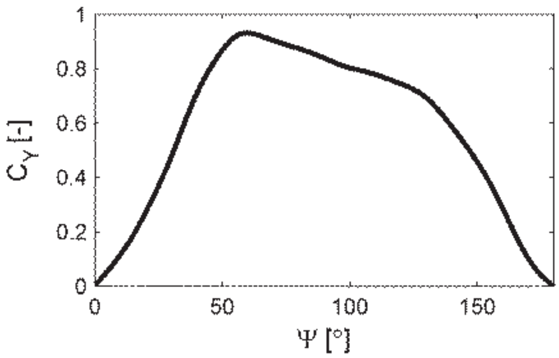

Figure 6: Non-dimensional transversal force coefficient as function of apparent wind angle for PCTC Fidelio.

Figure 7 shows the resulting aerodynamic roll damping for the design load condition at vessel speeds from 0-20kn, true wind directions 0-360° and a true wind speed of 20m/s.

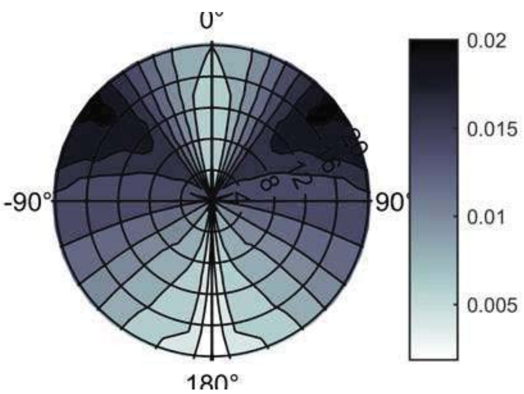

Figure 7: Predicted aerodynamic roll damping at 20m/s true wind speed as function of true wind direction and speed of the vessel.

The aerodynamic damping is practically linear with the roll velocity. At zero ship speed the damping reaches its maximum in bow wind, at a true wind direction of around 35°. At 20kn ship speed the maximum damping is found around 50° true wind direction. That is because the apparent wind direction is decisive and for the given condition a true wind direction of 50° corresponds to an apparent wind direction close to 35°.

The damping increases fairly linearly with the apparent wind speed as a consequence of that the wind pressure increase with the square of the apparent wind speed while the angle of attack $\psi_{\dot{\theta}}$ decreases with the apparent wind speed (equation 3). As a consequence, when the true wind is strong the ship speed dependence is modest.

In figure 8 the ratio between aerodynamic and hydrodynamic damping is shown for different ship speeds and headings for the design load case and a true wind speed of 20m/s.

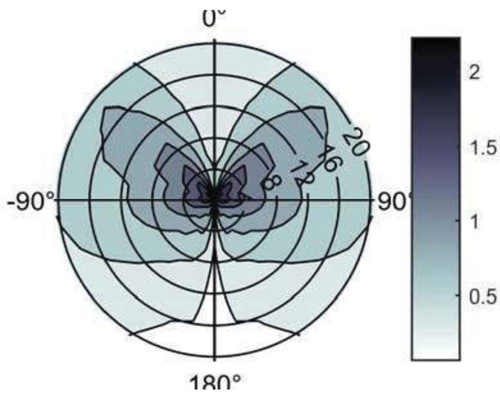

Figure 8: The ratio between aerodynamic damping and hydrodynamic damping for different ship speeds and headings at a true wind speed of 20m/s.

Notably, at bow winds and reduced ship speed the aerodynamic damping is of similar magnitude as the hydrodynamic damping. This implies that the typical roll amplitudes in those conditions will be reduced by half, which supports the Captains preference for bow wind in rough weather to gain a "stabilizing effect".

In figure 9 time series of roll, speed, heading, true wind angle (TWA) and true wind speed (TWS) from the event in 2011 are plotted. The lowest diagram is the aerodynamic damping estimated based on the presented approach. As seen the decreased wind speed and shift in direction causes a sudden drop in aerodynamic damping and after that the vessel starts to roll heavily. There appears to be a strong correlation between the reduction of roll damping and initiation of large roll motions.

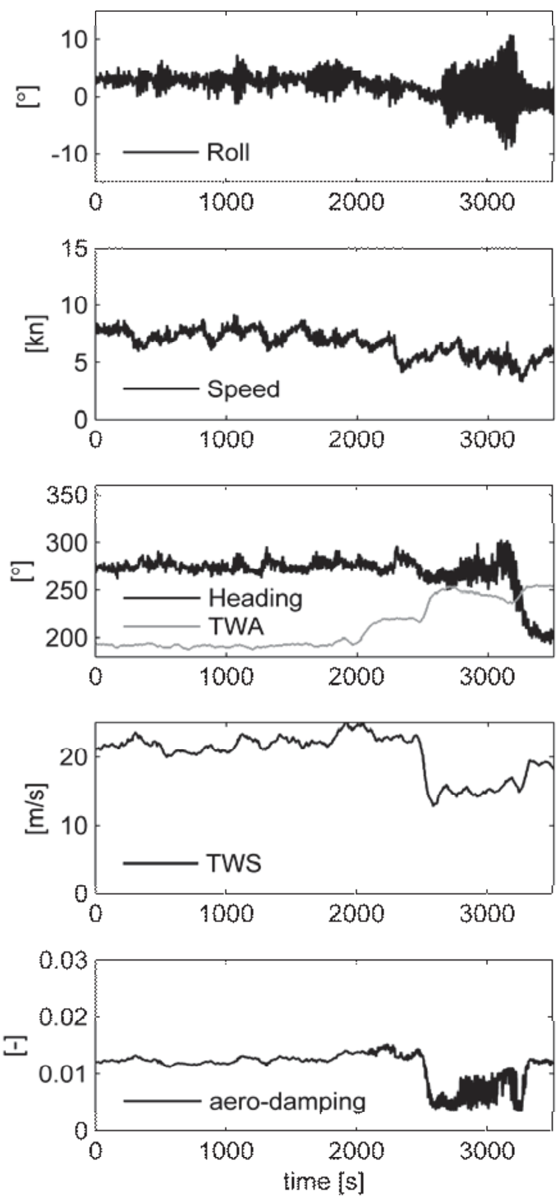

Figure 9: Time series of Fidelio's roll motions, speed, heading, true wind angle (TWA), true wind speed (TWS) and estimated aerodynamic damping from the event in 2011.

4. OPERATIONAL GUIDANCE

The effect of considering or not considering the aerodynamic roll damping in the formulation of operational guidance with respect to parametric rolling, will here be studied in a simplistic manner using the Parametric Roll Failure Index (PRFI) introduced in Ovegård et al (2012). According to Dunwoody (1989a) the GM-variation in waves produces an effect analogous to a roll damping reduction. Based on this the PRFI was in Ovegård et al (2012) formulated as

$$PRFI = E[\zeta^*]/\zeta \qquad (6)$$

where ζ is the linear roll damping expressed as a fraction of the critical damping, while $E[\zeta^*]$ is the expected value of the GM-variation related roll damping reduction. $E[\zeta^*]$ is calculated according to Dunwoody (1989b) based on the GM-variation spectrum, which in turn is calculated from the wave spectrum and the GM-variation transfer function. Theoretically parametric roll will occur in conditions where there is a 2:1 relation between the GM-variation and roll natural frequencies and where the GM-variation related roll damping reduction is larger than the actual roll damping, i.e. where PRFI>1. In Ovegård et al (2012) it was however concluded that PRFI=4 is a more appropriate limit to be used in operational guidance.

Two cases are here studied. The first is a hypothetical case with Fidelio in design load condition, with a ship speed of between 0 and 12 knots, a true wind speed of 20 m/s, and a sea state with a significant wave height of 5m and a mean period of 8s represented by a Jonswap wave spectrum with the shape factor set to 3.3. The two diagrams in Figure 10 could be advisory plots presented to the ship crew in these conditions, with wind and waves coming from 0°. The grey zones indicate ship speeds and headings where PRFI ≥ 4, which hence should be considered unsafe with respect to parametric rolling. In the upper diagram the aerodynamic roll damping is included while only the hydrodynamic damping is taken into account in the lower diagram. As seen the aerodynamic damping has a large influence in these conditions and the crew is advised very differently depending on if the aerodynamic effects are considered or not.

The second case represents the incident in 2011 described in the introduction. The ship speed is here between 6 and 10 knots and the true wind speed is 19 m/s. The sea state is based on analysis of weather data from the ECMWF Wave Atmospheric Model with a significant wind wave height of 5.14 m, a mean wind wave period of 9.81s, a significant swell height of 3.76 m and a mean swell period of 12.0 s. The wind waves are modeled as a Jonswap spectrum and the swell as an Ochi3 spectrum, both with shape parameters of 3.3 (Michel 1999). Figure 11 shows the corresponding advisory plots, with and without aerodynamic roll damping. As seen the difference between the unsafe zones is not as large as in the previous hypothetical case. Nevertheless, the circle that marks the approximate speed and heading during the incident is just at the boundary of the unsafe zone in the case with aerodynamic damping representing the conditions before the wind shift, while it is well inside the unsafe zone in the case without aerodynamic damping representing the conditions after the wind shift when the vessel started rolling.

5. CONCLUSIONS

Captains of PCTC's generally prefer bow wind in rough weather as the wind is claimed to have a "stabilizing effect" on the roll motions. This paper presents a simple approach for estimating the aerodynamic damping of volume carriers. The approach utilizes the concept of effective levers to relate roll induced transversal velocity to relative wind variations which causes angle of attack and wind pressure variations that generates a damping moment.

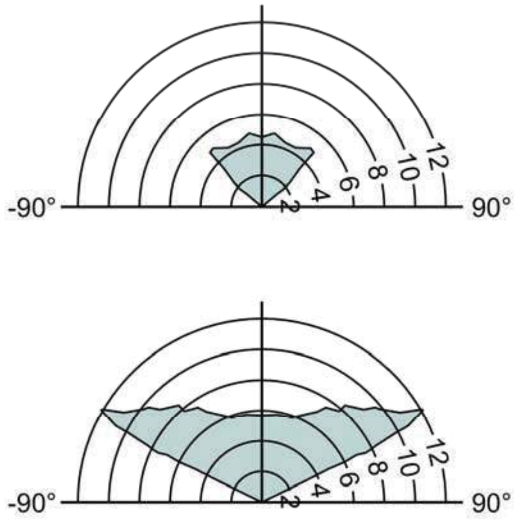

Figure 10: Advisory plots regarding parametric rolling with PRFI ≥ 4 in the grey zones for Fidelio in design load condition, ship speed between 0 and 12 knots, true wind 20m/s, significant wave height 5m, mean period of 8s, wind and waves coming from 0°, with (top) and without (bottom) aerodynamic roll damping.

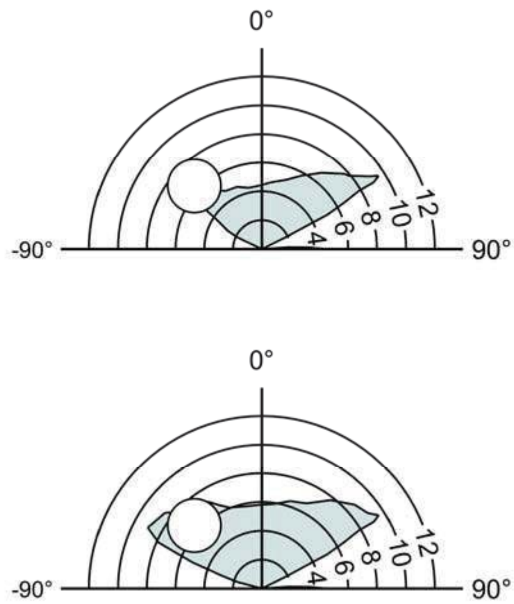

Figure 11: Advisory plots regarding parametric rolling with PRFI ≥ 4 in the grey zones in conditions corresponding to the incident in 2011, with (top) and without (bottom) aerodynamic roll damping representing before and after the wind shift. Head wind is set to 0°.

Evaluation of the approach on a typical PCTC demonstrates that the damping can be considerable in rough weather. For the considered vessel the largest damping is generated at apparent wind angles at the bow. For that heading combined with reduced speed the magnitude of the aerodynamic damping is actually in parity with the hydrodynamic damping. This means that ordinary roll motions will be reduced by half which well supports the captains' preferences for bow wind angles in rough weather.

Critical roll events of PCTC's are normally related to parametric excitation and in case of parametric resonance the roll damping is the limiting factor. For operational guidance systems providing in-situ ship-specific decision support a proper consideration of aerodynamic damping will increase the operability of the vessels. When creating, or validating, a decision support system for roll motions the wind damping is an important component to avoid unnecessary warnings to the crew and unnecessary cost for the owner or operator.

Future work should aim at assessing the effective levers that are used to couple roll velocity to an equivalent (mean) transversal velocity and a subsequent angle of attack and induced lift of the superstructure. These levers have a large influence on the results and were estimated using rough assumptions for this work.

6. ACKNOWLEDMENTS

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