IntroOn the prediction of parametric roll

Author 01 (Presenter), Michiel Gunsing,

MARIN Wageningen

Author 02, Reint Dallinga,

MARIN Wageningen

ABSTRACT

The numerical assessment of parametric rolling by means of time domain simulations is troublesome. This is due to a number of practical and conceptual problems. Therefore, simple transparent methods that give immediate insight in the characteristics of a particular design are still of interest. The present paper describes a method in which the results of linear calculations on the ship motions are used to estimate hydrostatic stability variations. Following Dunwoody (1989a) the stability variations are translated in a reduction of the roll damping and the safe operational limits of the ship. Numerical results are compared with experimental data.

KEYWORDS

Seakeeping, Parametric Rolling, Stability Variations in Waves, Risk Assessment

INTRODUCTION

Over the past years the assessment of the risk on parametric roll for new ships has received considerable attention. Despite these efforts the question how to perform a practical and reliable analysis has not been fully resolved.

In general, tests with a scale model are considered as the most reliable way to obtain data since most of the underlying physical phenomena are included. Think of relevant details like the natural speed variations in irregular waves (France et al. (2001)), the effect of large roll angles on the added resistance, the propulsive characteristics (including propeller ventilation), loss of rudder and stabilizer efficiency and the natural non-linearity's in the wave profile.

However, the design of an experiment with a scale model is not entirely straightforward. First of all there are is a host of practical issues regarding the representation of the wind and waves (spectral shape, directional spread), the target mean speed (governed by the added resistance and prudent seamanship), the modelling of active roll stabilisation, the steering and the modelling of the model propulsion (including the reaction of the main engines on the encountered propeller load variations). Secondly, and perhaps even more demanding, is the question what test duration will give a reliable assessment of the risk of encountering dangerous ship behaviour.

Numerical simulations offer a flexible alternative for tests with a scale model. On one hand in the spectrum of available tools one might consider CFD (Umeda et al(2008)), which incorporates potentially some (but not all) details of the nonlinear ship behaviour in waves if it covers details like appendages, moving rudders, fins and the steering. On the other end of the spectrum of tools are one degree of freedom (1-DOF) time domain models and methods based on statistical approaches (Archer et al. (2009)).

The commonly used time domain, "non-linear" potential flow calculations (see for example France et al. (2001)) are in the midst of this spectrum of tools. They do account for 6-DOF ship behaviour and the weak non-linear effects related to rapid changes in hull geometry around the waterline. However, they neglect the non-linear diffraction and the non-wave making aspects of the roll damping. The latter omission requires correction on basis of empiricism. Furthermore, the added resistance is not covered correctly because of the neglect of the non-linear diffraction, the sustained speed and speed variations are not covered adequately.

Because of the fact that the efforts of going through time domain simulations do not necessarily bring the expected accuracy, there is an interest in simpler transparent methods. The approach adopted in the present paper is a combination of a new method to obtain the variations in stability (δGM) and an existing formulation Dunwoody (1989a) to translate these variations in a decrease in effective roll damping.

The first step in this method uses linear frequency domain potential flow calculations to calculate the motion response and relative wave elevation along the waterline (accounting for reflected and radiated wave components). These results are used to calculate the hydrostatic stability variations, accounting for the hull form variations above and below the calm water line.

In a second step this (non-linear) transfer function of the stability variations is used in a formulation developed by Dunwoody (1989a) to estimate the apparent reduction in roll damping in irregular seas.

In a last step this result, which depends on significant wave height and mean wave period, is compared with the roll damping of the hull (estimated by means of an empirical method or existing model test data) to estimate the wave conditions in which the effective roll damping is negative. It is shown that the results of these computations show a fair agreement the results from tests with a scale model. A number of practical issues will be mentioned and an outlook to future developments will be given.

STABILITY VARIATIONS AS THE CAUSE OF PARAMETRIC ROLL

To illustrate the physics of parametric rolling, a simple 1-DOF model with a time dependant spring term $\widetilde{c(t)}$is analysed.

$$a.\ddot{\phi}\,(t) + b.\dot{\phi}\,(t) + (c + \widetilde{c(t)}).\phi(t) = 0 \quad (1)$$

Where a represents the total of structural and hydrodynamic inertia, b the damping and c the restoring term. To understand why and how stability variations $\tilde{c}(t)$ lead to large roll angles we will assume a harmonic roll oscillation with the associated roll velocity.

$$\phi(t) = \phi_a \sin(\omega_\phi t) \quad (2)$$

$$\dot{\phi}(t) = \phi_a \omega_\phi \cos(\omega_\phi t) \quad (3)$$

We will also assume a harmonic stability variation $\widetilde{gm}$ of the transverse metacentric height GM with a different frequency and phase angle given by Equation (4)

$$\tilde{c}(t) = \widetilde{gm}.\rho g \nabla = \rho g \nabla\, GM_a \sin(\omega_{gm} t + \varepsilon_{gm}) \quad (4)$$

The roll moment exerted on the ship equals the product of the stability moment and the heel angle:

$$M(t) = -\tilde{c}(t) \sin(\phi(t)) \quad (5)$$

The mean of the product of the roll moment and the roll velocity, the work, over a longer period of time (T) is given by:

$$P_{\widetilde{gm}} = \frac{\int_0^T M(t)\dot{\phi}(t)dt}{T} \qquad (6)$$

It can be shown that if $\omega_{gm} \neq 2 \cdot \omega_\phi$ that $P_{\widetilde{gm}} = 0$. Only if $\omega_{gm} = 2 \cdot \omega_\phi$ the work performed by the stability variations affects the energy contained in the roll motion. The phase shift (ε_{gm}) between the change in *GM* and the roll motion determines whether energy is added to or removed from the system. In Fig. 1 the roll angle, roll velocity and moment are shown for $\varepsilon_{gm} = 180\ deg$. In this case the moment due to the stability variations and the roll velocity always have the same sign. The related positive work implies that energy is added to the roll motion. Fig. 2 shows the energy added during in every roll cycle.

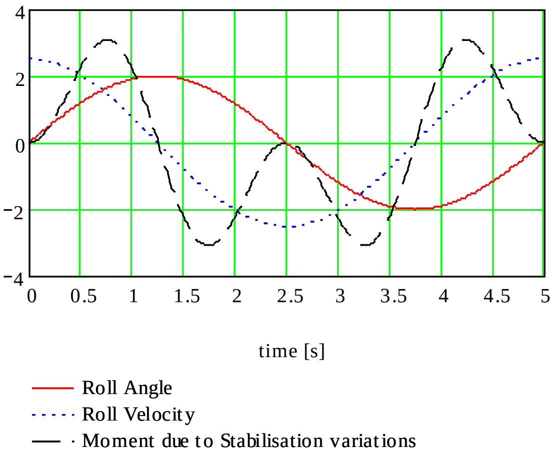

Fig. 1: The roll angle, roll velocity and righting moment during one roll period of roll, when roll and waves are in phase

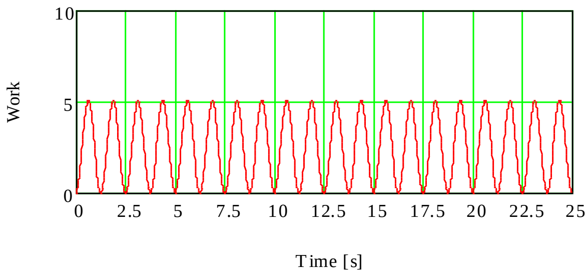

Fig. 2: Energy added during 5 roll cycles (phase shift 180 deg)

Fig. 3 and 4 show the same results, but now for a phase shift of for $\varepsilon_{gm} = 90\ deg$. Fig. 4 shows that on the average no energy is added over one number of roll cycles.

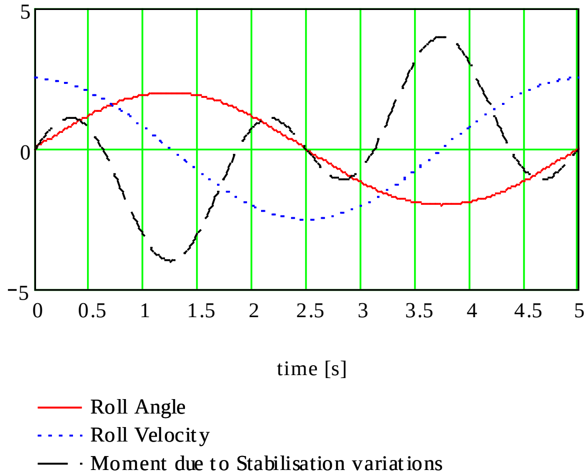

Fig. 3: The roll angle, roll velocity and righting moment during one roll period of roll, when roll and wave show a 90 degree phase shift.

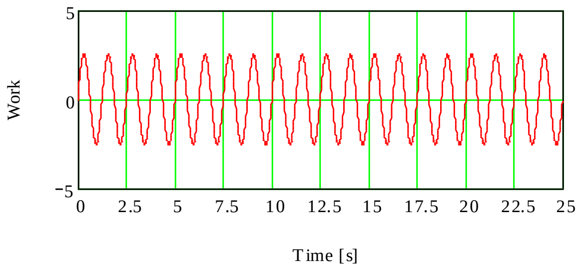

Fig. 4: Energy build up during 5 roll cycle (phase shift 90 deg)

Assuming small roll angles Equation (5) can be linearised in ϕ. In this case the average amount of energy added in roll given by Equation (6) can be rewritten as:

$$P_{\widetilde{gm}} = -\frac{\rho g\ \nabla GM_a \phi_a^2 \omega_\phi}{4} cos(\varepsilon_{gm}) \qquad (7)$$

Where $\rho g \nabla$ is the ship displacement, GM_a the amplitude of the stability variation and ω_ϕ the natural frequency of roll.

Whether or not the above increase in energy materialises in an increased roll angle depends on the average (per roll cycle) amount of energy dissipated by the equivalent linear roll damping b_E, which is given by Equation (8).

$$P_b = \frac{1}{2} b_E \phi_a^2 \omega_\phi^2 \qquad (8)$$

Equating Equations (7) and (8) yields a criterion in terms of roll damping. Parametric roll can start to develop when:

$$b_E < -\frac{\rho g \nabla\, GM_a\, \omega_\phi \cos\varepsilon}{2} \qquad (9)$$

IRREGULAR WAVES

As shown foregoing, the change in metacentric height due to the changing water height along the ship is driving parametric roll. It is also shown that the increase and decrease in roll amplitude can be written as a (negative) contribution to the roll damping.

In irregular waves the random phases of the wave components yield slow variations in the contribution of the stability variations in the total damping. Dunwoody(1989a) gives an expression for the reduction in irregular waves.

Assuming a broad band spectrum for $S_{\widetilde{gm}}$ - the spectral density of stability fluctuations - and taking its value at the encounter frequency that matches twice the roll frequency he arrives at the following expression for the expected value for the reduction of the non-dimensional damping.

$$E[\delta b_E^*] = \frac{\pi\, g^2 S_{\widetilde{gm}}(\omega_e = 2\omega_\phi)}{4\omega_e \omega_\phi^2 k_{xx}^4} \qquad (10)$$

Where ω_e is the encounter frequency. In a dimensional format this result is given by:

$$E[\delta b_E] = \frac{\rho g \nabla . \pi S_{\widetilde{gm}}(\omega_e = 2\omega_\phi)}{4. GM} \qquad (11)$$

Noteworthy is the fact that the expected value for the damping reduction increases with the spectral density of the stability variations. This implies it increases with the wave height squared.

The practical implication of the above result in terms of the risk of encountering parametric roll in a given time frame is an issue that requires further work.

Fig. 5 shows the character of the non-dimensional sum of the roll damping of hull and appendages and the expected value for the reduction due to the stability variations for a range of combinations of significant wave height and peak period. It is clear that a large negative damping is to be expected in the higher sea states in combination with a peak period of 16.5s, which is half the roll period of the subject vessel.

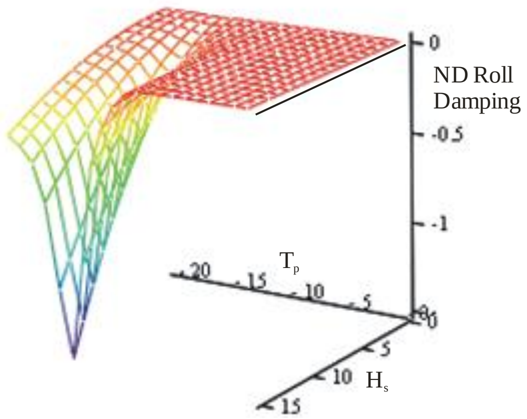

Fig. 5: Typical non-dimensional roll damping ratio as function of significant wave height H_s and wave peak period T_p.

ROLL DAMPING

Obviously the roll damping of a vessel is an important parameter in the assessment of parametric roll. A relevant characteristic is the fact that it decreases with decreasing speed. In the lower speed range it is dominated by the non-linear eddy and bilge keel damping components. At moderate and higher speeds the linear lift damping of the hull becomes a dominant factor (Ikeda et al.(1978), Dallinga et al. (1998)). In other words: the risk on parametric roll decreases with increasing speed. Other means that increase the ships roll damping also decrease the risk on parametric rolling. For example an anti roll tank is a very effective way to increase the damping at low speed. Fin stabilizers are effective as well, but only at some forward speed.

MAGNITUDE OF THE STABILITY VARIATIONS

With the foregoing establishing the risk of parametric roll has reduced to estimating $S_{\widetilde{gm}}$. Assuming linearity this quantity is obtained from a multiplying the square of the transfer function GM_a/ζ_a with the wave spectrum S_ζ.

$$S_{\widetilde{gm}} = \left(\frac{GM_a}{\zeta_a}\right)^2 S_\zeta \tag{12}$$

A correction for forward speed yields the spectral density at the right encounter frequency. Regarding the evaluation of the stability variations experienced by the hull Dunwoody(1989b) uses a method that omits the diffracted and radiated waves. In Umeda et al(2008) a CFD approach was followed to obtain the roll moment, but they also showed that this was heavily overestimated by their method. This is probably due to the grid size. Very fine grids are needed capture all relevant details but this leads to unacceptable time consuming calculations.

In the present paper, the transfer function of the stability variation GM_a/ζ_a is obtained by means of hydrostatic considerations from the relative wave elevations along the ship. The latter calculated by means of a linear three-dimensional frequency domain potential flow code PRECAL. This code calculates the wave induced excitation and the motion induced reaction forces using zero speed Greens functions. The calculated relative wave elevation accounts for the radiated and diffracted waves.

At low to moderate speeds, this method gives a good representation of the wave elevation along the ship, offering a fair and efficient estimate of the stability variations.

The above calculation yields the transfer function of the relative wave elevations (phase and amplitude) at every waterline panel. From the surface elevation the vertical position of the buoyancy point above the baseline (*KB*) is calculated by integrating over the underwater volume (Equation (13)) over the actual hull form. The actual waterline width and hull form are also used to calculate the vertical distance from the buoyancy point to the transverse metacentre (*BM*).

$$KB = \frac{\iiint z\, dV}{\nabla} \tag{13}$$

$$BM_{xx} = \frac{I_{xx}}{\nabla} = \frac{\iint y^2\, dA}{\nabla} \tag{14}$$

The overall values are obtained by integrating over the length of the ship.

The above evaluation is repeated for the full range of phase angles phase between 0 to 2π, each resulting in different waterlines. For the amplitude GM_a the half of the dynamic range between the maximum value GM_{max} and the minimum value GM_{min} was taken.

$$GM_a = {}^1\!/_2\,[GM_{max} + |GM_{min}|] \tag{15}$$

Sample results

A typical result for different wave amplitudes is given in Fig. 6. Since these data are given in a non-dimensional form, the data can be used for a range of ships with a comparable hull shape.

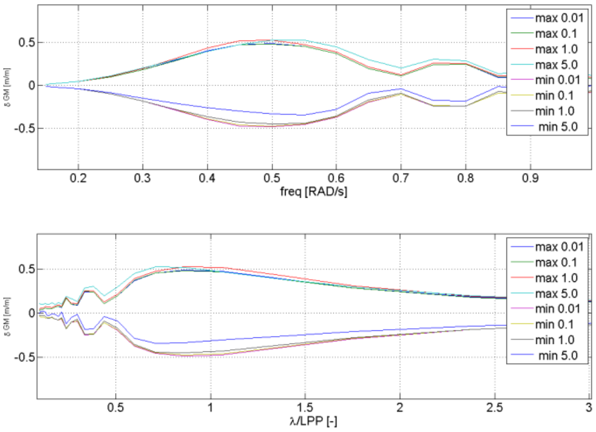

Fig. 6: Typical transfer function for the δGM as function of frequency(top) and as function of wave length over ship length λ/L_{PP}(bottom) for wave amplitudes between 0.01 and 5m.

Fig. 6. shows that the transfer function GM_a/ζ_a reaches its maximum value at a wave length of about 80% of the ship length.

A second observation is that the peak value is relatively insensitive to wave height variations. The remark that the linear contribution to the stability variations is small compared to contribution of the hull shape is therefore not justified. If it would hold, this non-linearity would have been more pronounced in Fig. 6.

Sectional contribution

In the calculation of the stability variations the sectional contribution of KB and BM became available. Fig. 7 shows typical distribution of sectional amplitude of KB and BM over the ship's length. The graph clearly shows that those parts of the ship that have a small draught, have large BM variations and contribute significantly more to the change in GM than those sections that have a large draft.

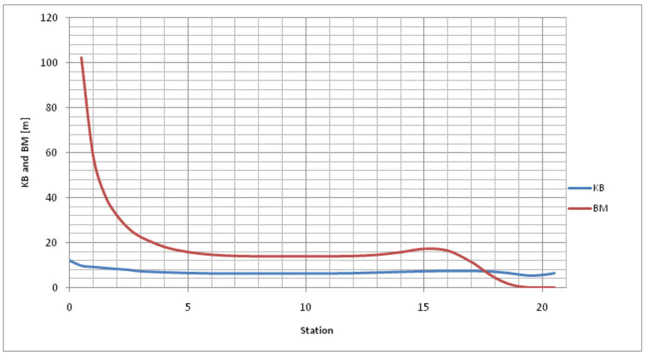

Fig. 7: Amplitude the sectional data on BM and KB

This is in line with theory. If one assumes a half submerged rectangle (draught=T m), the buoyancy point is located half way the baseline and the waterline, at $0.5\,T$. If the relative wave elevation increases the local draft by ΔT, the height of the centre of buoyancy changes by $0.5\Delta T$. Because the waterline width is constant in this example BM changes only due to the change in displacement. The total change in GM for this example is given by Equation (16)

$$\Delta GM = \frac{\Delta T}{2} - \frac{B^2 \Delta T}{12 \cdot T^2} \qquad (16)$$

It is clear from this equation that if T is small, a given ΔT has a large impact on the GM. This is in line with observations that ships with a flat pram type stern have a higher risk on parametric rolling (Levadou et al. (2006))

Note on the method to calculate the relative wave elevation

Because of the use of zero-speed Greens functions in PRECAL, the prediction of the relative wave elevations becomes less accurate at higher speeds. Because the mis-prediction are particularly large in the diverging flow at the bow and the converging flow at the stern, they have a relatively large effect on the derived stability variations. At increasing speed a more accurate description of the dispersion of the waves should be considered (e.g. Bunnik (1999)).

ESTIMATED OPERATIONAL LIMITS

Fig. 8 shows a typical result from a computation. The lines show the calculated results. The markers indicate experimental data. It can be seen that the numerical method predicts a threshold wave height of 2.5 to 3 m significant wave height at a wave peak period of around 16.5 seconds.

The markers in Fig. 8 show test results for a 290m container ship. Green triangles indicate tests that showed (within the adopted test duration) no parametric rolling; blue squares mark the position where large roll angles were found.

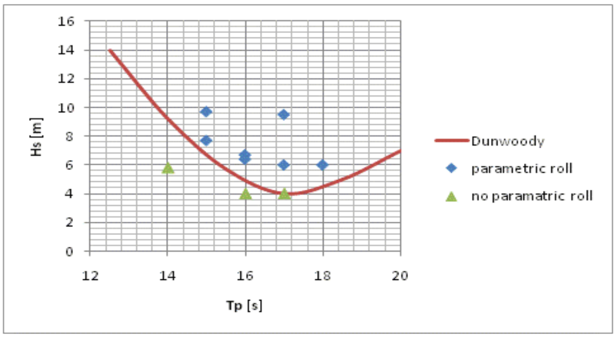

Fig. 8: Comparison of test results to calculated using the broadband approach.

Comparable result has been reproduced in a number of similar projects for different ship types. The calculated trends show a fair agreement with the character of the test results, indicating that the Dunwoody's approach, combined with the present way of evaluating the stability variations, offers a practical estimate of the operational limits.

OUTLOOK/CONCLUSIONS

The method that has been presented in this paper, shows promising results, but the final objective of the developments is to enable an accurate and more transparent prediction of the risk of unacceptable ship behaviour in a particular time frame.

To achieve this there are two intertwined problems to overcome. The first problem is to establish what are the essential physical aspects of the problem. The second problem concerns the statistical aspects.

In the near future we will address the statistical aspects first. The first step will investigate the relation between Dunwoody's estimate of the maximum excitation level with results of simple 1-DOF time domain calculations on the variations in the roll damping. A second step will investigate the related onset of parametric roll (limiting ourselves to the growth up to moderate roll angles), including the effects of non-linear roll damping. Efforts will be made to relate the frequency of critical events to the decrease in roll damping and spectral estimates of this quantity.

Depending on the outcome of the foregoing it may be of interest to improve aspects of full blown numerical simulations. The adequate modelling of the natural speed variations in high waves as well as the effects on non-linear diffraction in the parametric excitation come to mind.

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