Calculation method to include water on deck effects

Nicolas F.A.J, Carette,

MARIN, Netherlands

Frans van Walree,

MARIN, Netherlands

ABSTRACT

Green water is an important issue regarding ships stability as it may dramatically change the loading of the ship compared to its dry deck condition. Until now, computational methods capturing this event are very time consuming as they often try to capture the complete dynamics of the flow over the vessel's structure and deck using CFD. Such methods are not practical when dealing with numerous lengthy time domain simulations for long term stability assessments. MARIN has developed a fast method to be implemented in its 6 DOF time domain program FREDYN . This method has as objectives to be as fast as possible, even real time if achievable, but at the same time take into account correctly the mass of water flooding on the deck during green water events. The method is based on pre-computing the steady forward speed wave pattern and diffracted and radiated waves. The steady wave is computed for a series of sailing conditions using the in-house 3D linear panel code DAWSON. The diffracted and radiated waves are pre-computed using in-house 2D strip theory potential code SHIPMO for a series of frequencies and sailing conditions. A ship generated wave is then computed at each time step during the simulation using the current position and motions of the ship. This improves the computation of a realistic wave elevation consisting of the incident, steady, diffracted and radiated waves along the hull of the ship. This wave profile is then used to feed our flooding module which computes flows in tanks, compartments and through openings. This flooding model is based on a quasi-static Bernoulli formulation and empirical discharge coefficients. It is used to compute the flow over the bulwarks and through the freeing ports to the deck.

KEYWORDS

Time domain, green water, capsize, calculations, FREDYN.

INTRODUCTION

The capsize envelope obtained using time domain calculations appeared to be rather conservative during several risk analysis studies. This appeared to be strongly related to green water events happening too easily, too extremely and too often.

Until now, the Froude-Krylov forces were computed in FREDYN using the instantaneous waterline taking into account the ship motions and undisturbed incoming wave, and by this way these forces are taking care of the green water events. This is most of the time a conservative approach as it neglects diffraction, radiation and the forward speed wave which reduce the critical relative wave heights, this mostly for positions aft of the bow area.

The present new implementation proposes as first step to take into account the vessel and its motions on the water. The objective is to have a better estimation of the waterline to improve the calculation of the hydrostatic forces, including water on the deck.

METHOD

The effect of the ship on the water surface is divided in three components:

- Static forward speed wave
- Diffracted wave
- Radiated wave

Each component is computed separately at the beginning of the time step at several positions along the ship. By summing the three waves we obtain the perturbation wave profile that can be summed with the incoming wave. Points between calculation locations are obtained by spatial linear interpolation. If the point lies outside the waterline contour, for instance in case of bulb, closest approximation is used. By points we mean any location where the water height is needed such as, for instance, a panel on the hull for the Froude-Krylov forces or an opening into a flooded compartment.

Static forward speed wave

The static wave is obtained by linear interpolation between series of wave profiles computed at different speeds, drafts and heel angles. The actual position and speed of the ship is then used to pick up the right databases. Draft and heel values must be extracted from low frequency motions. Wave patterns are computed once before the calculations using a 3D potential solver. From the patterns, only the values along the vessel are extracted to obtain the waterline.

Diffraction wave

The diffracted wave profile is obtained for each section of the ship using databases of linear potential diffraction.

Using MARIN's 2D strip theory code SHIPMO, the diffraction potential is extracted at each section, at the waterline, for a series of wave frequencies, headings and speeds. The potential is saved as a complex number to allow for linear interpolation between the databases without losing the phase information. It is converted to a wave amplitude response operator in m/m. At each time step of the calculation a database of diffraction potentials is made, depending on the actual speed and heading of the ship. Then, for each incoming wave component n and at each section i, the instantaneous diffracted wave profile at each section is computed using (1).

$$\tilde{\zeta}_i = \sum_n \tilde{\zeta}_{in} z_n \sin(\omega_n t - \kappa_n + \varepsilon_n + \tilde{\varepsilon}_{in}) \quad (1)$$

The diffracted waterline is then used further during the time step using spatial linear interpolation to every panel of the ship. The error in this case by the spatial interpolation is rather limited as the triggering factor for water on deck is the waterline itself which is as precise as there were sections in the calculations; the diffracted wave is not needed outside the ship where the spatial interpolation would introduce large errors.

Such pre-calculation followed by some spatial interpolation is used to save computation time as the sum of wave components is done only twice per section, one for port and one for starboard side, instead of doing it for every panel, relative location and flooding opening. Diffracted wave is actually the only wave that could be really computed at any point but the calculation time would be excessive using fine meshes and wave spectra.

Radiation wave

The radiation wave is basically obtained in the same way than the diffraction wave except that there is here the need for retardation functions to go to the time domain.

For each section and wave encounter frequency, the radiation potential is extracted from potential solutions, for instance a SHIPMO calculation. The potential is converted to a wave amplitude response. Then a method similar to what is done with the added mass and damping is applied:

- The real part of the amplitude is divided by ω^2
- The imaginary part is divided by ω

We have thus similarly as for added mass and damping terms the following formula for the radiation wave components:

$$a_i(\omega) = \frac{Re(\phi_{rad_i}(\omega))}{\rho g \omega^2} \qquad (2)$$

$$b_i(\omega) = \frac{Im(\phi_{rad_i}(\omega))}{\rho g \omega} \qquad (3)$$

Converted to time domain functions using (4) and (5), they give “added mass” and “retardation function” of radiation wave amplitude.

$$A_i = a_i(\omega_\infty) + \frac{1}{\omega_\infty}\int_0^\infty B_i(\tau)\sin\omega_\infty\tau\, d\tau \qquad (4)$$

$$B_i(\tau) = \frac{2}{\pi}\int_0^\infty (b_i(\omega) - b_{i_\infty})\cos\omega\tau\, d\omega \qquad (5)$$

The retardation functions are saved for each section and side for the whole calculation. Using correlation with the time history of motions we can thus compute the radiated wave at each section using (6).

$$\breve{\zeta}_\iota(t) = A_i\ddot{x} + B_i(\infty)\dot{x} + \int_0^\infty B_i(\tau)\dot{x}(t-\tau)d\tau \quad (6)$$

As for the diffracted wave, the radiated wave profile is saved for each section at the waterline for both sides during a complete time step and spatially interpolated to any point on the ship.

Calculation

When using only the static wave correction, the calculation can still be done in real time on a PC with a quad core CPU at 2.66 GHz.

The diffraction calculation strongly depends on the number of wave components. On a dual core PC, the calculation time doubles with 80 wave components compared to the calculation without correction. The difference tends to reduce as the interpolation between the databases becomes less and less the bottleneck.

The radiation correction has not been fully tested but non constant time step is the most expensive factor as the retardation functions have to be recomputed for each section every time it changes. Otherwise it costs at every time step two correlations per section.

TANK TESTING

The validation of the present method is based on a series of tests carried out at MARIN using a model of the DDG51 (European version) beginning of 2009. Tests were carried out with a captive and free sailing model. The loading condition was such that stability was low giving a high capsize risk.

Captive tests

The tests with a captive model were done to look at steady forward speed wave and diffracted wave. The tests were done at different speeds and heel angles in regular waves of various frequencies and amplitudes. Relative wave elevation were recorded at several locations along the model.

Table 1: Regular wave captive tests.

Speeds	18, 24	knots
Heel angles	10, 20	deg
Amplitudes	1.25, 1.875	m
Frequencies	0.546, 0.598, 0.661, 0.739	rad/s

Free sailing tests

Free sailing tests were done, in high stern quartering seas to look at green water events. Conditions were such that capsize risk was high during the standard time domain simulations but rather low during the tests. Tests were done at two headings (300 and 330 deg) and three speeds (12, 18 and 24 knots) in irregular waves.

Fig. 2: High roll motion without capsize and very low amount of green water in stern quartering seas.

VALIDATION

Steady wave

The steady wave implementation was validated by comparing the wave profile computed to the average wave elevation during the tests. At the speeds of interest one can observe a large trough at amidships increasing the margin against green water events. This was until now absolutely not taken into account. One can also notice that the heel angle does not have a strong effect on the wave profile in these conditions. The method clearly improves the estimation of the waterline to the original undisturbed wave compared with the experimental measurements.

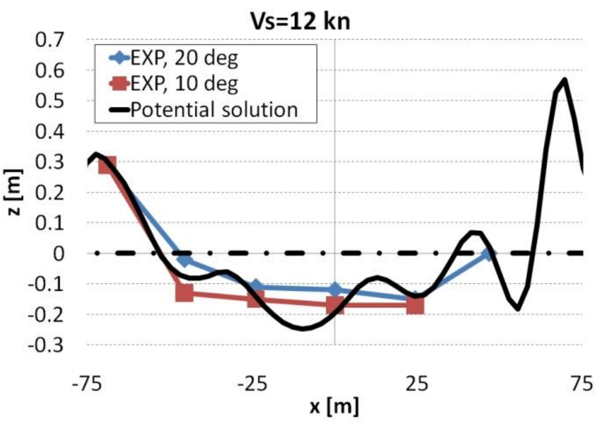

Fig. 3: Computed waterline compared to experimental steady wave profile during captive tests for different heel angles at 12 knots.

Diffracted wave

The maximum wave measurements along the hull have been compared to the maximum amplitude of the potential diffracted wave summed to the incoming and steady waves. The following figures give the profiles of maximum wave elevation along the ship for different conditions during experiments and calculations compared to the deck line and incoming wave for both leeward and windward sides.

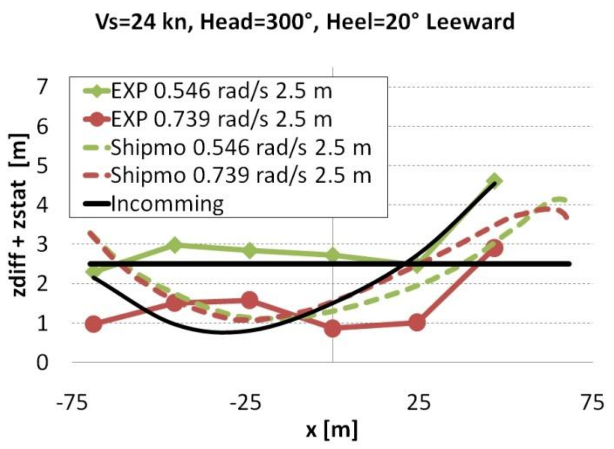

Fig. 4: Maximum wave elevation along captive vessel in regular waves: experimental and computed (leeward).

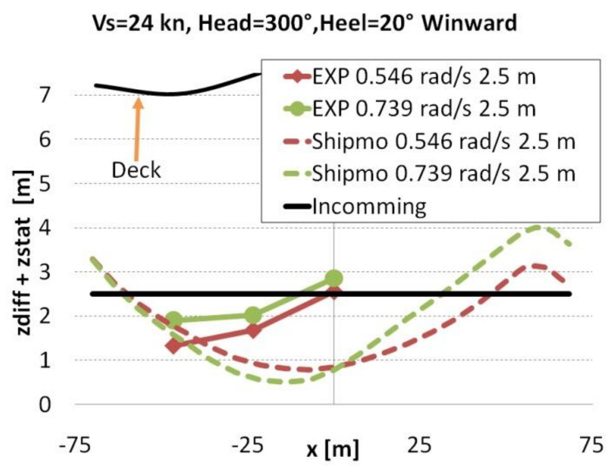

Fig. 5: Maximum wave elevation along captive vessel in regular waves: experimental and computed (windward).

In case of large roll angles, taking diffraction and steady wave into account improves the estimation of the green water events (see Fig. 4). The diffraction most of the time reduces the water elevation along the vessel, and combined with the steady wave very often avoids the water to flood on the deck. However, the effect of the frequency on the diffraction seems often underestimated by strip theory. The diffracted wave is also overestimated at the aft of the ship, but this is a typical drawback from linear theory with forward speed.

Finally, the disturbed wave amplitude on windward seems underestimated for some configurations, this appeared using both strip theory or 3D diffraction (PRECAL), but this is not critical when looking at capsize risk due to green water as most capsize over predictions are on the leeward side.

Radiation wave

The radiation was not used during these calculations as first attempts gave unrealistically high waves. This probably comes from a lack of a forward speed correction. The radiation potential is solved for a series of encounter frequencies but is valid at zero speed, the effect of radiated waves being washed backwards when sailing is not taken into account. Depending of the velocity, the retardation function at one section should become more and more dependent of the ones in front. Another solution would be to compute the potential radiation wave databases at forward speed using an exact solution and have a set of retardation functions for different speeds as it is done for the damping.

RESULTS

A series of free sailing time domain calculations were done with and without steady and diffracted wave correction. For each condition a series of five runs of half an hour was done.

Without correction, almost in all conditions very high capsize risk is observed. Most of the capsize happen very soon and fast. They are always due to excessive amounts of water on deck. For most simulations the deck is almost constantly wet on the leeward side. As the encounter frequencies were quite low, if a wave crest exceeds the freeboard at amidships, it will stay there and induce large and increasing roll angle until capsize occurs. This process appears as a static loss of stability triggered by the first freeboard exceedance event.

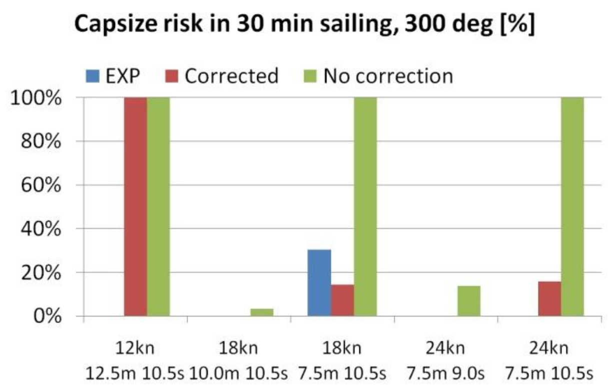

Fig. 6: Capsize risk with and without wave correction for 30 minutes sailing at 300 deg heading compared to experiments.

When the correction is applied, the threshold of the capsize event is definitely increased. One can observe much less capsizes, most of the time those capsizes are now due to broaching. If water on deck occurs, the volume of trapped water is maybe still overestimated due to the absence of a model computing the well known dam break motion of the green water which retards the progression of the water at the beginning of the green water event. This may explain why the correction seems still not sufficient in very large waves. However in those cases, they were also very steep and breaking, which anyhow cannot be captured with linear waves.

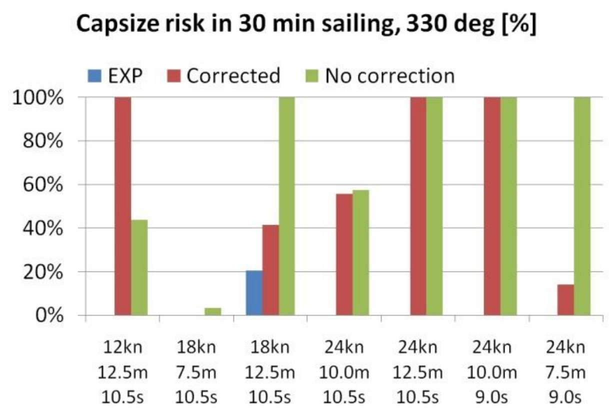

Fig. 7: Capsize risk with and without wave correction for 30 minutes sailing at 330 deg heading compared to experiments.

The reduction of capsize risk is of course accompanied by a reduction of the roll. We can see that this reduction results in a better matching of the experiments most of the time.

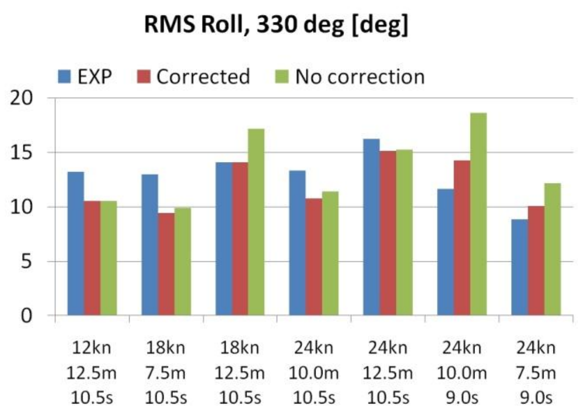

Fig. 8: Standard deviation of roll with and without wave correction compared to experiments.

CONCLUSIONS

The correction of the waterline for forward speed gives, for a very reasonable computation time, a much better threshold for freeboard exceedance. This helps improving capsize risk analysis at high speeds. The effect of the heel angle on the wave profile is limited in a normal rolling range. This should be checked up to very high heel angles to know if the database really needs to depend on the heel angle. A dependence on trim could be easily included but raises the question of how to extract its value from the pitch and wave slope.

The correction for the diffraction slightly improves the asymmetry of the waterline between wind- and leeward sides. This would be even more important for headings closer to beam seas and slightly higher wave frequencies. The correction improves the capsize risk prediction by lowering the waterline in the conditions tested.

As already mentioned, the radiation was not used during these calculations as first attempts gave unrealistically high waves, probably due to a wrong forward speed effect when using strip theory. Two ways are seen, either a correction on the retardation functions or a corrected potential solution.

The case of very high or breaking waves seems still to be an issue. This could maybe be corrected by applying the radiation correction as large amplitude motions generally push the water away from the deck, retarding the flooding. Another correction could also come from a larger database of radiation and steady waves for very large heel angles. Finally, representing the deck by a floodable compartment might introduce some delay in the flooding of this one by using appropriate discharge coefficients and openings representing the flow over the bulwarks. On the other hand, breaking waves cannot be computed using linear wave spectra whatever method is used to correct them.

As this new method relies on steady, diffraction and radiation databases, any improved method to estimates these components would immediately improve the calculation of the instantaneous waterline without need of a reimplementation.

ACKNOLEDGMENTS

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NOTATIONS

z	Incoming wave	[m]
$\tilde{\zeta}$	Diffracted wave	[m]
$\breve{\zeta}$	Radiated wave	[m]
ω	Wave frequency	[s^{-1}]
κ	Wave number	[-]
n	Index for frequency	[-]
i	Index for section	[-]
ε	Incoming wave phase	[-]
$\tilde{\varepsilon}$	Diffraction wave phase	[-]
ϕ_{rad}	Radiation potential	[kg/ms^2]