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Dynamic Stability of Ships in Waves

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ABSTRACT

A method is proposed for evaluating the overall dynamic stability of an intact vessel in a seaway. We use an existing ship motions program to study the motion of a vessel with a certain loading condition, speed and heading, in given wave conditions. A deterministic method is discussed for looking at the stability of a vessel over a wide range of these parameters. This is done with a view to giving operators advice on the safest headings and speeds to adopt in extreme conditions, as well as gauging the overall safety of a particular vessel. It is hoped that eventually such dynamic stability analysis can be used to modify the present IMO stability criteria for ships.

INTRODUCTION

At present, safety regulations with regard to ship capsize are based primarily on static stability concepts. The efficient calculation of GZ curves that is possible nowadays permits quick and accurate determination of a ship's static stability. Although it is well accepted that capsizing of ships is a dynamic phenomenon, static stability considerations are still used almost exclusively to gauge the propensity of a ship to capsize in waves.

This means, for example, that some vessels are at risk of dynamic capsize despite having favourable GZ curves, whereas others are perhaps being over-penalized due to the nature of their GZ curve, despite having good dynamic stability.

Seakeeping is now a well-developed field, and basic techniques for simulating the motion of a ship in both regular and irregular waves are well-known (see e.g. [1,2]). Newton's 2nd Law is used to predict the time rate of change of each of the six degrees of freedom (roll, pitch, yaw, heave, surge, sway), using the nett forces and moments acting on the vessel at each point in time. The hydrodynamic forces and moments are caused by the accelerated motion of the vessel through the water, as well as the action of the wave, and may involve significant cross-coupling. Still, if the time-varying forces and moments on the vessel can be accurately modelled, the computational solution of the resulting ship motions is straightforward.

Such time-domain simulations may be used to predict the "capsize" of a vessel, and thereby used to assess ship safety. The capsize of a vessel is normally defined by a predetermined roll angle, such as the angle at which downflooding occurs, or the angle at which the GZ-curve becomes negative. By definition, capsize involves large roll angles and hence highly nonlinear behaviour. Therefore, basic linear seakeeping theory has given way to more accurate modelling of the hydrodynamic forces for predicting capsize, involving significant cross-coupling and nonlinear terms (see e.g. [3,4,5])

One problem with using dynamic analysis to gauge the stability of a vessel is the large number of parameters involved. Static stability analysis can be condensed into a single GZ-curve for each vessel and loading condition, whereas dynamic stability is also a function of ship speed, heading angle and wave conditions. Despite continuing improvements in the accuracy of ship motions programs, a reliable method for condensing all the relevant data into an overall safety assessment remains an elusive goal.

In this paper we discuss the use of both irregular and regular waves to assess dynamic stability, and propose a method whereby the dynamic stability of ships in waves can be compared through the complete spectrum of relevant parameters. For our results the dynamic stability code FREDYN has been used (courtesy of CRNav and the Australian Defence Force), although the methods are equally applicable to the use of any dynamic stability code.

DYNAMIC ANALYSIS IN IRREGULAR WAVES

Clearly the *ideal* way to approach dynamic stability is to run the ship motion simulation in an irregular seaway, which is as close as possible to the actual seaways the ship is likely to encounter.

In irregular waves, a wave spectrum is chosen to correspond to a likely extreme sea state for a given region, if the operating region of the ship is fixed, or otherwise a representative extreme sea state. Therefore the variables are the type of spectrum used, as well as the governing parameters for that spectrum, such as significant wave height and zero-crossing period.

This method can produce two types of outcome: the average time taken to capsize, or the probability of exceeding a certain roll angle in a specified time.

Time to capsize

For a given speed and heading, simulations are performed up until the ship’s roll angle reaches the predetermined capsize angle. The time to capsize depends strongly on the initial wave conditions; hence many runs must be performed in order to gain a statistically significant “average time to capsize” for that particular seaway, speed and heading.

Probability of exceeding a given roll angle

The other way to numerically model capsize is to perform simulations over a shorter time, say one hour, and then fit a distribution to the probability of exceeding a given roll angle in a specified time. This approach was pioneered by McTaggart ([6], see [7] for a comprehensive overview). The extrapolation to large roll angles is done by assuming a Gumbel distribution of the data, resulting in a “probability of capsize in a specified time” for that particular seaway, speed and heading.

Although irregular wave analysis is considered the optimum method for modelling the motions of a ship in a real seaway, its use in assessing ship stability has some serious complications:

- If using the time to capsize, large simulation times are needed for each run, and many runs (we use 50) are needed to find the average time to capsize. If using the probability of exceeding a given roll angle, the results only loosely follow a Gumbel distribution, and the extrapolation to larger roll angles remains questionable. Even with the extrapolation the computations are very lengthy.
- The question remains what constitutes an acceptable time to capsize, or acceptable probability of capsize for a given situation.
- Validation of the dynamic stability codes with model experiments is very difficult for irregular waves.
- The physics of the capsize phenomenon can be difficult to understand in irregular waves.

Note that at this stage only long-crested irregular waves can be accurately modelled, which are themselves an approximation to the short-crested waves in a true seaway.

DYNAMIC ANALYSIS IN REGULAR WAVES

It has been shown (e.g. [8]) that ship behaviour leading to capsize in irregular waves is similar to that in the dominant regular waves. Therefore, a simplified approach is to conduct stability assessment in regular waves, which are determined by a wave height and length. In order to represent an extreme sea state, a characteristic dominant wave height and length can be chosen, or a wide range of component waves can be considered individually.

This approach is deterministic rather than probabilistic, in that each simulation results in a definitive “capsize” or “no capsize”. If the ship has not capsized in a moderate amount of time in the regular sea, it will never capsize, so only relatively short runs are needed.

Because of the comparative simplicity of a regular sea analysis, another relevant parameter can be brought into the analysis: the vertical centre of gravity height (or KG value – the height of the centre of gravity above the keel line). Running the simulations over a range of possible KG values gives an understanding of how different loading conditions affect the stability of the vessel, and also allows a “limiting KG” value to be determined, above which the ship will capsize in the given seaway [9]. This limiting KG can then be compared to the actual KG of the ship, as a measure of its dynamic stability.

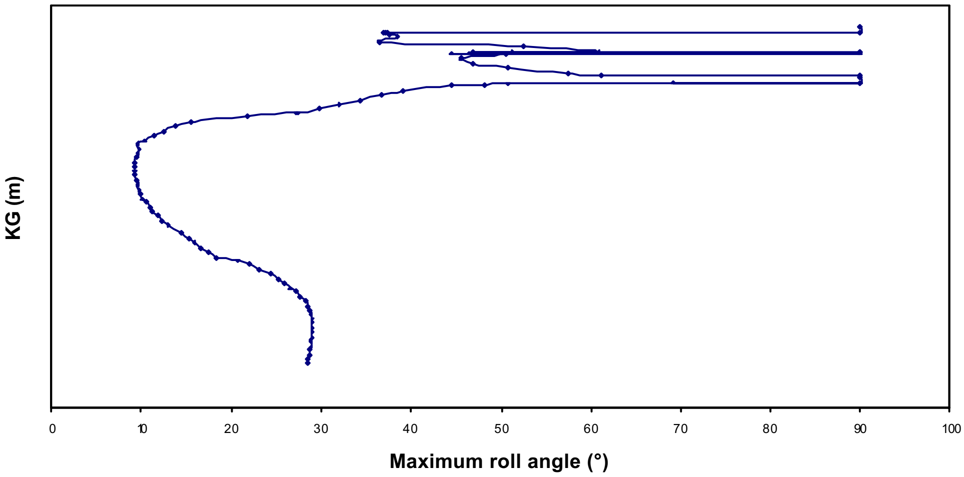

Figure 1: Maximum roll angle in regular waves, with increasing KG

An example of this regular wave analysis is given in figures 1 and 2, which show the maximum roll angle reached in regular waves of height *h*=15.5 metres and length λ=217 metres for a certain ship. In figure 1 a wide range of KG values are plotted, and we see that the dependence on loading is complicated. In this case capsize occurs in bands of KG corresponding to resonance situations. These "capsize bands" were not present over all headings and speeds, but they do provide a complication to the concept of limiting KG values.

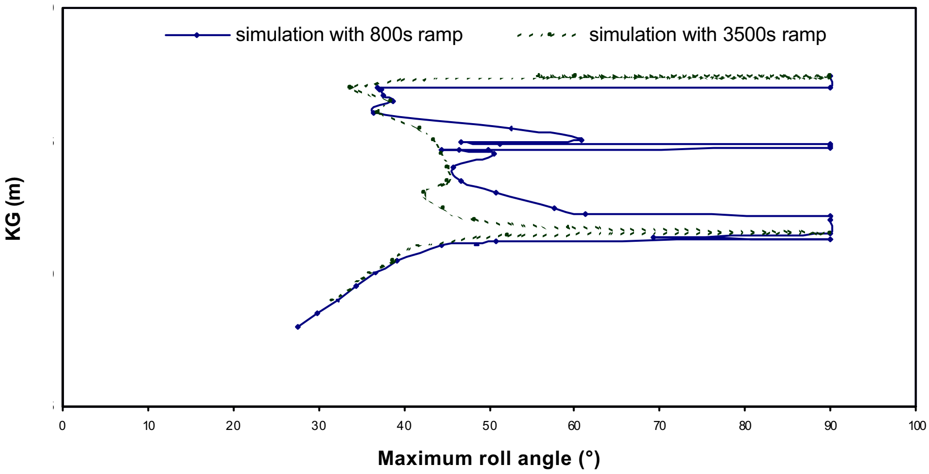

Figure 2: Maximum roll angle with different ramp times.

In figure 2 we see the effect of the ramp time, which is the time from when the program starts in calm water until the target wave height is reached. We notice that a long ramp time is required so that the ship does not capsize artificially on the ramp. Subtleties such as this and the capsize bands tend to be obscured in an irregular wave analysis.

A PROPOSED IRREGULAR / REGULAR ANALYSIS

As we have discussed, both irregular and regular waves have their advantages and disadvantages for assessing dynamic stability. We are currently developing a method that we hope will combine the strengths of each of the methods.

Correlation between irregular and regular waves

The approach is to correlate the capsize risk of a ship in irregular waves with its propensity to capsize in regular waves. To do this we consider a spectrum of regular waves (i.e. the full range of wavelengths) which aims to model the most dangerous components of the irregular spectrum.

The correlation between irregular and regular waves results in a certain wave height for each wavelength, to use in the regular analysis. An example of this is given in figure 3.

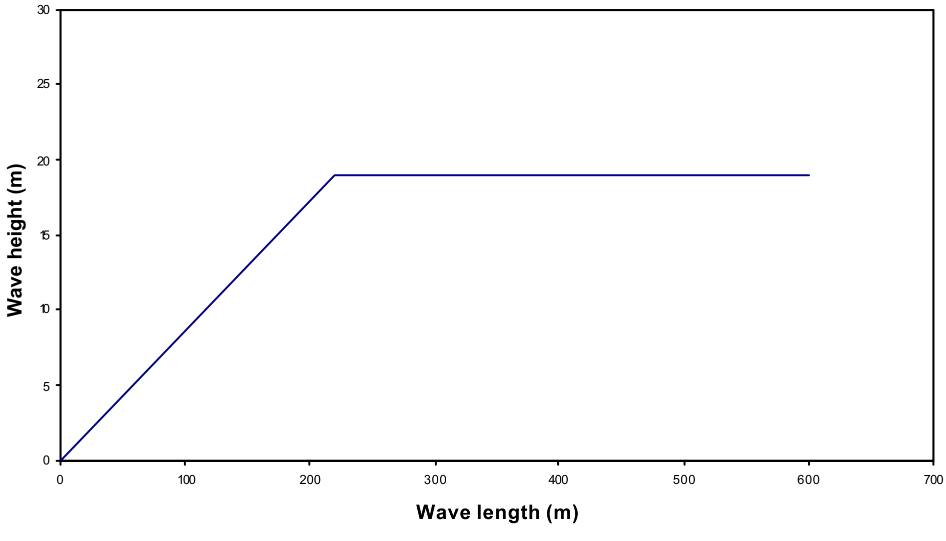

Figure 3: Wave height *h* as a function of wavelength λ for regular wave analysis

The curve of wave height versus length is designed to model the most dangerous elements of an irregular sea, by choosing the larger wave heights that might occur at each wavelength. Even in an irregular sea the wave steepness h/λ generally has an upper limit, and it is this limit that we are modelling in a broad sense. All smaller wave steepness values do not represent the largest wave height for that particular wavelength, and therefore are not as dangerous as the chosen curve, so need not be input.

In order to correlate the results with irregular waves, we choose a constant wave steepness h/λ for the regular waves. We must also cap the wave height at a realistic value; this might be for example $H_{1/100}$, the average height of the highest 1% of waves in the chosen irregular spectrum.

The regular wave simulation can now be run over the entire range of wavelengths and corresponding wave heights to find the maximum roll angle reached by the vessel in each case. Again, we go one step further and consider a large range of loading conditions, in order to determine the limiting KG value both at each wavelength and over the whole spectrum.

We must now correlate the boundary between capsize and no capsize in regular waves (which we measure in terms of the limiting KG value), with an "acceptable risk" or "acceptable time to capsize" in irregular waves. At present we nominally use a 10-hour average time to capsize, which gives us our corresponding limiting KG value in the irregular sea (see figure 4).

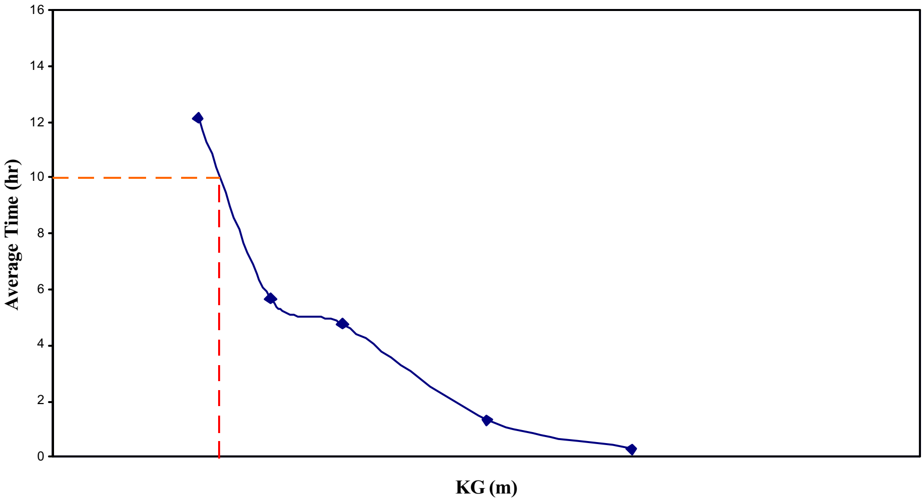

Figure 4: Time to capsize in irregular seas (average of 50 simulations, $H_{1/3} = 11.5$ metres, $T_1 = 11.5$ seconds)

In this way, correlating the limiting KG values in the regular and irregular sea allows the regular wave steepness to be determined, which will ensure that our regular wave results correlate with the irregular wave results.

Preliminary calculations suggest that the wave steepness values obtained are close to those observed in an irregular sea, around 1/14, and that performing the correlations over different cases will yield a sensible average to use.

Regular wave simulations

Having chosen this wave steepness, dynamic stability assessments can be performed with far less computational effort in regular seas, with subtleties such as the effect on capsize of loading, speed and heading readily understood.

Figure 5 shows an example of limiting KG values (marking the boundary between capsize/no capsize of the ship) for a range of wavelength ratios (λ/L, where L is the shiplength) and heading angles (away from astern seas). We see that for this case the longer wavelengths, with larger wave heights, tend to be the most dangerous. It should be noted that this is not true for all headings and speeds; often the most dangerous waves are the smaller ones whose length is close to the length of the ship.

We also notice that the most dangerous heading angle is around 50 degrees (away from astern seas) for most wavelengths at this speed.

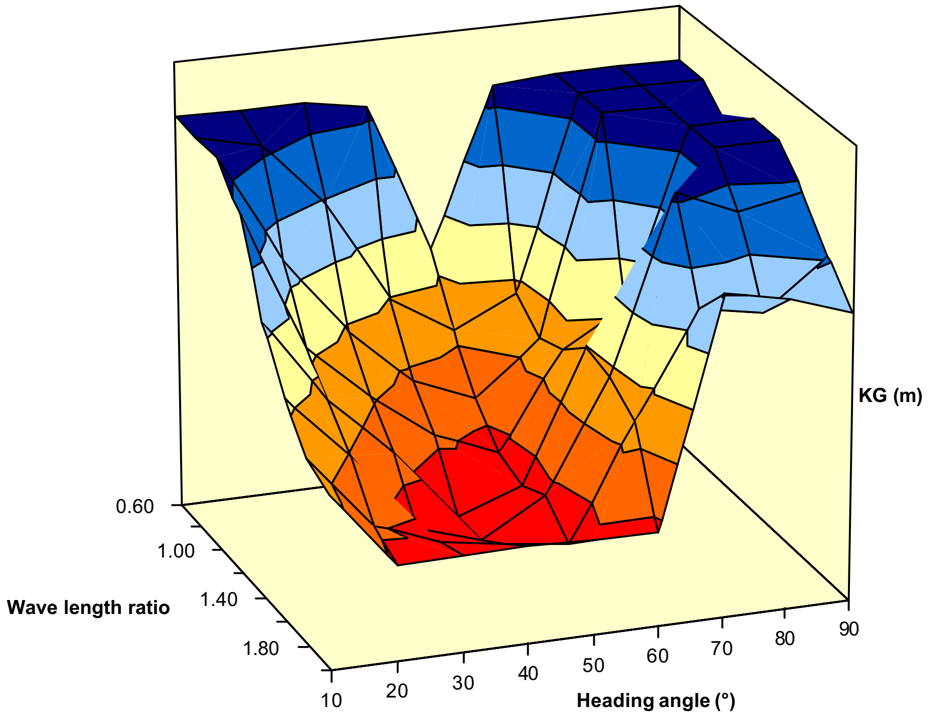

Figure 5: Limiting KG contours as a function of wavelength and heading angle for a given speed

We can now define the overall limiting KG value for each heading and speed by picking off the smallest limiting KG value over all wavelengths. Doing this allows a polar plot to be generated of limiting KG values as a function of speed and heading angle.

Using the results

Areas of small limiting KG on the polar plot are the most dangerous heading/speed combinations, while areas of high limiting KG are the safest. This information can be passed onto ship captains - which headings and speeds are best to adopt or avoid in extreme seas.

These limiting KG values can also be used to gain an overall limiting KG value that is deemed safe for the survival of the ship in these extreme conditions. For example, this might be the smallest limiting KG on the whole polar plot (so that the vessel should be able to survive *all* headings and speeds), or it may not include heading/speed combinations which are known to be dangerous and would be avoided by ship captains.

Finally, the chosen overall limiting KG value can be compared with current IMO criteria to gauge the effect of wave dynamics on the vessel's stability. Comparing this between different vessels shows which are at risk of dynamic capsize despite having favourable GZ curves, or which are being over-penalized due to the nature of their GZ curve, despite having good dynamic stability. This may be used to modify IMO stability requirements in future.

CONCLUSIONS

We have outlined a method for assessing the overall dynamic stability of a ship in waves. The method is based on regular wave simulations, over a range of wavelengths whose heights are chosen to correlate with an irregular sea. The advantages of this method over the full probabilistic method are greatly decreased computing time, a simplified analysis and increased understanding of the essential capsize phenomena.

Acknowledgement

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