TOWARD AN OVERALL DYNAMIC STABILITY ASSESSMENT IN FOLLOWING SEAS

Tim Lilienthal and Tim Gourlay
Australian Maritime College (Australia)

Abstract

Research is being undertaken into methods for assessing the overall dynamic stability of an intact vessel in an extreme sea. Results from a time-domain ship motions program have been computed over a range of wave parameters and vessel types, speeds and headings. Methods will be discussed for collating all this data into a stability assessment method. In addition, use of the data for operator guidance in extreme seas will be discussed.

1. INTRODUCTION

Intact vessel stability is currently assessed almost exclusively using the properties of a ship's righting arm (GZ) curve. This means that a quasi-static technique is used to assess a dynamic phenomenon for stability in extreme seas. The GZ curve criteria gives a simple method to quantify stability, but the method fails to consider the way waves interact with a vessel, which is a major contributing factor in intact vessel capsize. The ultimate aim of a dynamic stability assessment method is to simulate this effect.

Time-domain ship motions programs are increasing in accuracy, with several now able to handle coupled motions in six degrees of freedom. Importantly, large amplitude motions can now be simulated, up to and including capsize. The rapid evolution of these programs means that accurate dynamic capsize analysis is now becoming feasible.

The main obstacle to an overall dynamic stability assessment of ships is the large number of parameters that must be considered. For a given ship, the capsize risk is strongly dependent on wave parameters, vessel speed, and vessel heading relative to the waves. The most dangerous values of these parameters vary significantly from ship to ship. Therefore a capsize risk assessment must include a wide range of the input parameters, and be able to collate the results into an overall stability assessment.

Dynamic stability assessment tends to divide itself into methods based on irregular waves (producing a statistical assessment) or methods based on regular waves (producing a deterministic assessment). In this paper we discuss different methods of assessing ship capsize based on irregular seas, regular seas, and a combined irregular/regular approach.

2. SOFTWARE AND CALCULATION METHOD USED

All of the results presented here have been obtained using the dynamic ship motions program FREDYN, provided courtesy of MARIN and the Cooperative Research Navies group.

The initial conditions used in both irregular and regular wave simulations were the same. The initial heading was set to the desired heading, with the wave height ramped from zero to the desired maximum over four hundred seconds. The vessel initial speed was set to the calm water speed with the appropriate propeller revolutions. This allowed the vessel to establish the correct attitude with respect to the waves as the wave height increases.

This paper discusses the concept of using a time domain motion program to assess a vessel's stability. The research does not concentrate on the workings of the program itself, but rather the use of the results toward an overall stability assessment method, and hence could be applied to any accurate ship motions program.

Although numerical values of capsize parameters have been predicted, these are of course dependent on the accuracy of the program used. Therefore absolute values will change as ship motions programs evolve. The general method suggested, however, will still apply.

3. DYNAMIC STABILITY IN IRREGULAR SEAS

Dynamic capsize assessment is most realistically performed in *irregular* seas, which most closely represent a real extreme sea. In this case the parameters over which capsize risk needs to be assessed include:

- wave spectrum
- vessel speed
- vessel heading relative to waves

In addition, the sensitive dependence of capsize risk on loading may also be analysed.

Irregular sea analysis is naturally stochastic in nature, requiring a large amount of data in order to make statistically significant conclusions. There are two principal methods of irregular sea analysis: roll angle distribution over a specified time; and time to capsize distribution.

3.1 Roll angle distribution

One way of analyzing irregular sea data is to plot a distribution of the probability of exceeding a certain roll angle in a specified time. In order to achieve this, runs of the specified length can be performed for a set of different initial conditions (determined by the seed number of the irregular sea at $t = 0$). The resulting probability of exceedence distribution becomes more reliable the more seed numbers are considered.

Because not many (or perhaps any) capsizes will generally be witnessed in the specified time, large errors occur at large roll angles where data is scarce. In order to overcome this, a distribution may be fitted to the data and the results then extrapolated to large roll angles. This method may then be used to gauge the probability of capsizing in a specified time [1,2].

3.2 Time to capsize

The problem of having too little data on actual capsize, which is inherent in the fixed time method described above, can be overcome by always running the simulations until capsize occurs [3]. A distribution can then be obtained of the time to capsize for each set of parameters, with a simple output being the mean time to capsize. Alternatively, the results could then be used to accurately find the probability of capsize in a specified time.

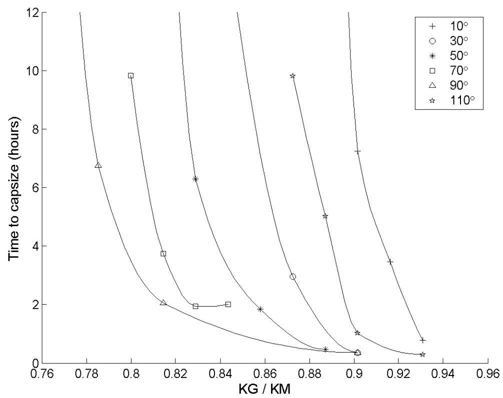

Figure 1: Average time to capsize as a function of KG, for various headings

This method is also highly stochastic in nature; for the same set of parameters, real-time capsize may occur in a matter of minutes with one particular seed number, while taking hours or days with another. Accordingly, many runs must be performed in order to draw statistically significant conclusions.

As an example of this method, Figure 1 shows the average time to capsize, taken over 18 different seed numbers, as a function of KG for an example ship. Results are plotted for different heading angles, all with the same propeller RPM and wave spectrum.

We see the rapid decline in average time to capsize with increasing KG (centre of gravity height) as well as the varying capsize risk over different heading angles. This method can be used to produce two outputs: the average time to capsize for a given loading condition, wave spectrum, vessel speed and heading; or the "limiting KG" value if a minimum acceptable average time to capsize is specified.

4. DYNAMIC STABILITY IN REGULAR SEAS

A simple way of analysing a ship's dynamic stability is to perform simulations in *regular* seas of given wavelength and height. This approach is deterministic rather than probabilistic, resulting in a definitive "capsize" or "no capsize" for each simulation. For a given vessel, the input parameter set consists of

- wave length and height
- vessel speed
- vessel heading relative to waves

Again, the effect of loading may also be analysed through varying the KG of the vessel [4].

This method may also be used to simulate a ship's response in an irregular sea, since it has been shown (see e.g. [5]) that a ship's behaviour leading to capsize in irregular waves is similar to that in the dominant regular waves.

As well as producing a "capsize/no capsize" output from each run, the maximum roll angle can also be output from the "no capsize" runs. This gives a measure of the severity of the motion in each case, and is available for later analysis if the motions criterion is chosen to be a smaller roll angle (e.g. the downflooding angle or limit of machinery operability angle).

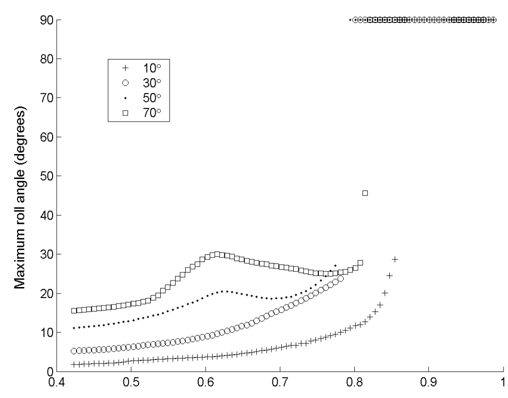

Figure 2: Maximum roll angle as a function of KG, for various heading angles

An example of a regular sea output is shown in figure 2, which shows the maximum roll angle experienced as a function of KG, for an example vessel in waves of a fixed height and length. This is plotted for several different heading angles.

Here again we see the sensitive dependence on loading, with a very small increase in KG causing the maximum roll angles to jump from 30° to 90°.

5. COMPARISON BETWEEN IRREGULAR AND REGULAR SEA METHODS

5.1 Computation time

This is the single biggest drawback to the irregular sea method. Because of the statistical nature of the method, large simulation times are necessary for each set of parameters. This makes an accurate analysis over all speeds and headings very computationally intensive, and a complete method incorporating the effect of loading would seem unfeasible at this stage.

In regular sea analysis the motions quickly reach steady state, so simulation times are short. In addition, only one run is needed for each set of parameters. This allows a large range of wavelengths to be run very quickly, and even the effect of loading can be assessed routinely.

5.2 Simulating real capsize

Clearly an irregular sea analysis most closely represents ship motions in a real seaway.

5.3 Understanding the results

The results from regular sea analysis clearly show the dangerous sets of parameters leading to capsize, since each wavelength component is analysed separately. In addition, the actual mode of capsize is easier to determine in a regular sea. As such, the likely capsize mechanisms for each vessel, and the conditions in which they may be expected to occur, can be calculated simply and methodically using regular sea analysis.

By contrast, the stochastic nature of irregular sea analysis means that the actual capsize mechanism is difficult to judge. The physics of capsize for each vessel tends to be blurred by the large number of contributing wave components. Dangerous capsize situations are more difficult to analyse.

6. A COMBINED REGULAR / IRREGULAR APPROACH

6.1 Overview

Much of this research has been aimed at producing an overall stability assessment that combines the advantages of both regular *and* irregular sea analysis. In other words, the method aims to:

- accurately simulate real capsize
- be simple and fast to run
- give useful information about dangerous capsize situations, for both operator guidance and vessel design

To this end a method has been developed which runs the majority of the simulations in a full range of component regular waves. The corresponding wave heights are chosen to correlate directly with the irregular sea results.

The philosophy is that an irregular sea is a linear superposition of component regular waves, so that in order to survive a realistic irregular sea we may require the vessel to survive each regular sea component wavelength separately.

If this is to be the case, a realistic wave height must be chosen for each wavelength. This wave height should ideally represent the steepest waves of the irregular sea; therefore we may expect that the correct wave steepness will be of the order of 1:10 – 1:14.

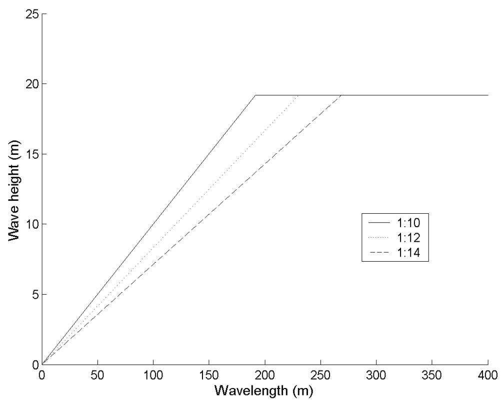

Figure 3: Wave height as a function of wavelength for regular sea analysis, for different wave steepnesses.

A simple method is to choose a *constant* wave steepness over a range of wavelengths. However in order that wave heights do not grow unrealistically large, we must also "cap" this wave height at a realistic value.

An example of such wave parameter sets for regular wave analysis is shown in Figure 3 for three different wave steepnesses. Here the wave components have constant steepness up to a maximum height dictated by the irregular sea that is being simulated (e.g. this could be $H_{1/100}$ from the given irregular sea). The height is then capped at this value.

By running the regular sea simulations over the full range of wavelengths, the most dangerous conditions, and the response of the ship in these conditions, can be found. In addition, particularly dangerous capsize situations can be analysed in detail.

6.2 Effect of loading

The effect of loading can be comprehensively analysed in regular seas by running the simulations over a continuously incremented range of KG values.

By doing this we can determine a "limiting KG" value above which the ship is predicted to capsize for the given speed, heading and wave conditions.

This limiting KG value can be used as a primary output from the regular wave simulations, to judge the maximum allowable KG for surviving a particular sea state over a range of headings and speeds.

Alternatively, simulations with a fixed representative value of KG show the maximum roll angle expected to be encountered, along with any speed/heading combinations where the ship is in particular danger of capsize.

6.3 Correlation between irregular and regular sea results

In order that the regular sea method adequately simulates a real irregular sea, correlations can be performed between regular and irregular sea results. Since dynamic stability analysis is intended to give a relative stability comparison between different vessels, we require the regular and irregular sea outputs to have similar properties.

In order to correlate between the two different methods (one of which is statistical and one deterministic) an appropriate output must be chosen for comparison. The concept of a limiting KG, above which the vessel is at particular risk of capsizing, seems appropriate for this task.

In regular seas the limiting KG represents the boundary between capsize and no capsize. In irregular seas the distinction is not as clear, so we must choose the limiting KG based on either a maximum acceptable capsize risk in a given time, or a minimum acceptable average time to capsize.

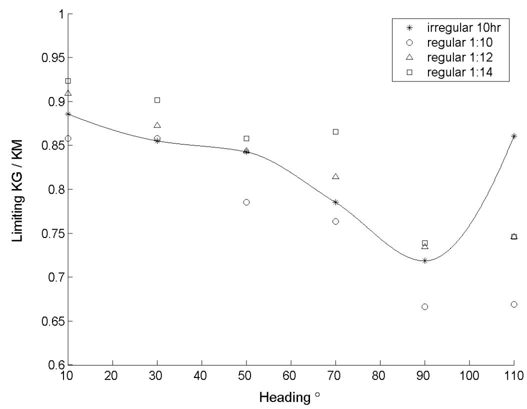

Figure 4: Limiting KG values according to irregular simulations, and regular simulations using three different wave steepnesses

We have chosen to use a minimum acceptable average time to capsize because of its direct relation to the irregular simulations. Because of the very steep nature of the time to capsize curves (see Figure 1) the limiting KG thus found is not highly sensitive to the minimum time chosen. For our comparison we have used an average time to capsize of 10 hours to determine the limiting KG value.

Comparison between the regular and irregular KG values for an example ship is shown in Figure 4, for a range of heading angles at a particular speed.

Results for other speeds show similar comparison. We see that the regular and irregular results correlate fairly well, with both predicting similar magnitudes for the limiting KG values. In addition, the regular results capture the same trend of decreased limiting KG with increased heading angle for this ship.

From this and other speed simulations, the most appropriate steepness for regular wave simulations is 1:10 for this vessel. Since this required wave steepness should be predominantly a function of wave parameters rather than vessel type, it is expected that this wave steepness will correlate fairly well for other vessels too. Further computations are required for other vessels to confirm this.

Computations performed so far have concentrated on headings close to following seas, where significant dynamic stability problems are known to exist. We see that the correlations shown in figure 4 are valid for the range of headings from following to beam seas (0° to 90°). The method loses applicability for headings greater than 90°.

The method based on limiting KG should ideally also correlate the actual modes of capsize between regular and irregular seas. Studies into actual capsize modes reveal that these are very difficult to define in an irregular sea, as capsizes often involve a complicated superposition of modes. In addition, the study of capsize modes must be done carefully on a run-by-run basis, and cannot be simply automated like the limiting KG correlation. For this reason, the prime motive of the correlation is to concentrate on the capsize boundary that is the accumulation of capsizes from the differing modes.

7. USING THE RESULTS

Having decided on a suitable wave steepness to use in regular wave simulations, runs can be quickly performed over the entire range of wavelengths, headings, speeds and loading conditions for each ship. These results will find three main applications:

7.1 Dynamic stability comparison between different vessels

Assessing the *absolute* dynamic stability of vessels using ship motions programs will require extensive validation of both the ship motions program utilized, and the method of collating the results. When this is satisfactory, limiting KG values from dynamic stability assessment may form the basis of a stability standard.

In the shorter term, dynamic stability assessment can readily be used to assess the *relative* dynamic stability of different vessels.

For example, two vessels may have similar GZ curves at their representative loading conditions, but significantly different dynamic stability characteristics (as measured by their limiting KG values over a range of headings and speeds). The vessel with the lower overall limiting KG values is the most susceptible to dynamic capsize and must be loaded accordingly conservatively, as compared to the other vessel.

7.2 Vessel design for capsize resistance

By identifying the danger areas in the regular wave simulations, analysis of the actual capsize modes can be performed in order to better understand the weaknesses of each particular vessel. This will aid in vessel design, by altering the design to better cope with dangerous situations.

7.3 Information for operators

Polar plots of the maximum heading angle expected in a particular extreme seaway may be used by mariners as a guide to which headings and speeds to adopt in extreme seas. These polar plots could be pre-calculated for a ship's representative loading condition(s) and displayed on the ship's bridge for reference.

8. CONCLUSIONS

The state of the art in dynamic stability analysis has been discussed, with particular reference to the advantages and disadvantages of using irregular or regular seas for simulation.

A combined method using both irregular and regular sea results has been suggested, and it is shown how the two methods can be correlated. The combined method is fast to run, represents real capsize results and can be used to better understand capsize mechanisms in extreme seas.

The results of such a dynamic stability assessment can be used for both stability assessment and operator guidance in extreme seas.

9. ACKNOWLEDGEMENT

The authors wish to acknowledge the support of the Australian Defence Force in providing funding for this research through a research contract with AMC.

10. REFERENCES

[1]. McTaggart, K.A. Ship capsize risk in a seaway using time domain simulations and fitted Gumbel distributions. *Proc. 18th International Conference on Offshore Mechanics and Arctic Engineering, St. John's, Newfoundland, July 1999.*

[2]. McTaggart, K.A, & de Kat, J.O. Capsize risk of intact frigates in irregular seas. *Trans. SNAME*, Vol. 108, pp. 147-177, 2000.

[3]. Gourlay, T.P. & Lilienthal, T. Dynamic stability of ships in waves. *Proc. Pacific International Maritime Conference, Sydney, 2002.*

[4]. Renilson, M.R., Hamamoto, M. A Standard Method for Presentation of Capsize Data. *Fourth International Ship Stability Workshop, Newfoundland, Canada, 1998.*

[5]. Takaishi, Y. Consideration on the dangerous situations leading to capsize of ships in waves. *Proc. 2nd International Conference on Stability of Ships and Ocean Vehicles, Tokyo, Japan, October 1982.*