Heavy Weather Guidance and Capsize Risk

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ABSTRACT

Recent advances in simulation of capsize in severe seas have opened the door to the application of risk assessment techniques to capsize survivability assessment, and seaway specific heavy weather guidance for the ship operator. Communication of risk of operation based on seaway severity, ship heading, speed, and loading is essential in providing useful heavy weather guidance to the operator. Members of the Cooperative Research Group, Navies, (CRNAV), and the Naval Stability Standards Working Group (NSSWG) have been developing risk methodologies and techniques to determine both the risk of capsize on an annual basis, as well as for seaway specific conditions. The authors will summarize the methodologies for risk assessment, involving both fitted statistical data and distribution free approaches, and their application to annual capsize risk statistics, and seaway specific operational risks. The development of capsize risk criteria is an essential link in providing heavy weather guidance and tactical shiphandling information for severe seaway operation

NOMENCLATURE

a_X = Gumbel distribution scale parameter
b_X = Gumbel distribution location parameter
C = ship capsize
$F(X)$ = cumulative distribution function for X
Hs = significant wave height
KG = height of the center of gravity above the keel
N_C = number of ship capsizes
N_S = number of simulations
$P(C_D)$ = probability of capsize in duration D
$p(X)$ = disretized probability of X
$Q(X)$ = exceedance probability for X
Tp = peak wave period
V = ship speed
X_i = random variable sample of rank i
β = relative wave heading
λ = wavelength
$\varphi_{max,D}$ = max absolute roll angle in duration D

Head Seas are 000^o relative wave heading and seas on starboard beam are from 090^o.

INTRODUCTION

Design criteria and operator guidance for stability in heavy weather are typically treated as distinct and separate issues. In the past, stability criteria based on righting energy relationships have provided a measure for intact stability. This measure ensured a level of safety, but did not provide specific guidance for capsize avoidance in severe seaway conditions. After nearly 60 years we still don't have that "red light" that comes on indicating that the current combination of speed and heading is no longer safe and that evasive action must be taken to save the ship.

Several references can be found on shiphandling in heavy weather. These typically give general rules of thumb for avoidance of tropical storms, and provide generic guidance to the mariner in the event his ship gets caught in the storm. "Heavy Weather Guide" (Harding, 1965), "Summary of a Course in Shiphandling in Rough Weather" (USCG, 1981), "Knight's Modern Seamanship" (Noel, 1972), "IMO Assembly Resolution 1994, Guidance to the Master for Avoiding Dangerous Situations in Following and Quartering Seas", (IMO, 1994) are a few of the publications available for reference and training of deck officers. Interestingly, there is a progressive trend towards more specific guidance on dangerous zones both in terms of storm avoidance and dangerous headings and speeds.

In recent years the maritime community has started to recognize that capsize sensitivity is related to ship dynamics and subject to several parameters including hull geometry, loading condition, size, heading, speed, and seaway (De Kat, Paulling, 1989). Capsize risk in extreme seas can be expected to vary considerably from ship to ship (IMO 1994). Thus, a ship handler must rely on his wits, experience, and judgement, in maintaining safe speed and heading under the most adverse conditions. Very little information exists today which can provide ship-specific operator guidance to avoid potentially hazardous zones of speed and heading in a severe seaway.

Practical experience in heavy weather shiphandling may be limited to some mariners, especially in the case of naval officers who might not be aboard a particular ship for more than a few years. The advent of weather routing has deliberately (and for good reason) reduced encounters with extreme weather. Thus, practical experience in heavy weather shiphandling may be limited.

The use of innovative features in ship hull designs can provide additional challenges for the ship operator because the dynamic characteristics can substantially differ from conventional ships in severe seaways (De Kat, et. al, 1994). Consequently, the need for ship specific operator guidance becomes even more crucial to ship safety.

Recent work in capsize simulation and probabilistic analysis has opened the door for the development of risk based operator guidance in heavy weather. The use of risk data if properly presented, can provide a powerful tool in communicating potential shiphandling hazards to the operator. Simulations and probabilistic analyses conducted in recent years have shown that some of the traditional storm avoidance guidance should be reevaluated since it can actually put a ship at hazard due to dynamic capsize (Alman et al., 1999).

A good example of this is the situation of hurricane avoidance. Traditionally, the guidance offered to a ship's master is based on determining whether the vessel is in the dangerous semicircle or navigable semicircle and placing the ship's head relative to the wind direction accordingly to depart the area. Shown in Figure 1 is the guidance for departing the dangerous semicircle of a tropical cyclone in the Northern Hemisphere. In this situation the advice would be to bring the wind on the starboard bow (45° relative) and make as much headway as possible in order to evade the storm. Unfortunately, this guidance places the waves on the starboard quarter (i.e.; the waves are coming from 160° relative assuming that the wind is placed at 045° relative). A ship underway at high speed may actually be placed in hazardous following or quartering seas and run the risk of capsizing. Based on present understanding of the physics of ship capsize behavior, placing a ship in following or quartering seas and making as much speed as possible in mountainous seas will likely place the ship in regions where capsizing becomes a distinct possibility.

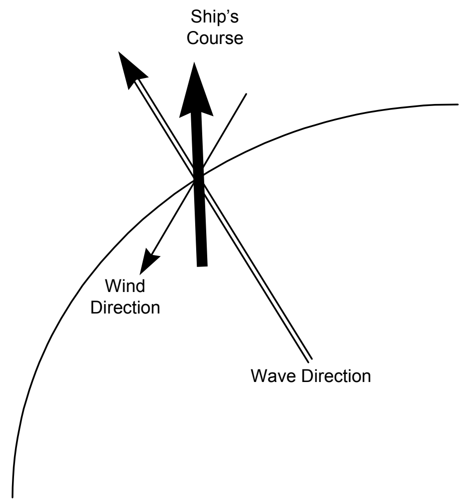

Figure 1. Traditionally recommended ship's course to depart the dangerous semicircle of a tropical cyclone (Northern Hemisphere).

Ships do get caught in storms despite best efforts to avoid them. Guidance given to the operator to avoid capsize must provide two things. The first is a display of the change in risk in a seaway as a function of heading and speed. Such guidance can be provided in capsize risk polar plots, as displayed in Figure 2. The polar plot depicts ship heading relative to the waves with head seas at the top of the plot and following seas at the bottom. Ship speed is depicted by concentric circles starting at the speed of zero knots in the center of the plot, increasing in 5-knot increments.

The second requirement, is for heavy weather maneuvering guidance that describes when it is safe (or unsafe) to execute a maneuver that could entail a risk of capsize. Frequently maneuvers must be undertaken in severe seas to change course and heading for reasons other than stability. Structural damage in head seas may force a ship to come about and run with the waves. Operational planning should also entail operator guidance for when to utilize weather routing for storm avoidance.

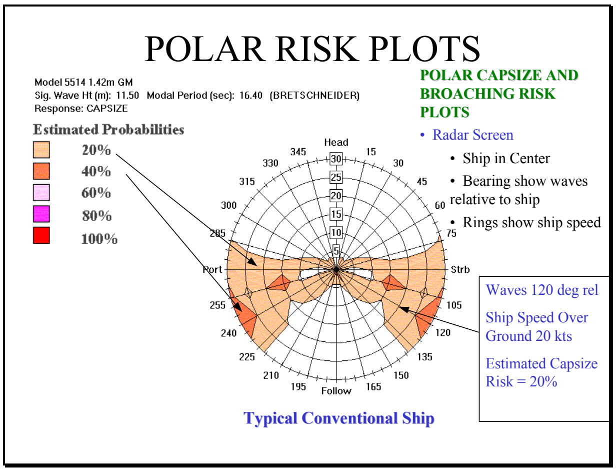

Figure 2. Capsize risk polar plot for a notional destroyer in Sea State 8

The Canadian Navy and the U.S. Navy have jointly pursued development of probabilistic capsize risk assessments for both design and operator guidance. The development of operator guidance for shiphandling in heavy weather can be linked to design criteria, providing continuity in a system safety approach to capsize risk mitigation. Capsize risk based operator guidance and weather routing criteria can provide vital information to the ship handler and operations planner, helping to break the "chain of events" leading to capsize and loss of a ship in heavy weather (Alman et al., 1999). The key to providing vital design and operator capsize risk guidance is in the evaluation of capsize probability using time domain simulations.

ASSESSING CAPSIZE PROBABILITY WITH TIME DOMAIN SIMULATIONS

In recent years, progress in numerical models and computing power has made it possible to evaluate capsize probability in random seaways using time domain simulation. The numerical model FREDYN (De Kat et al., 1994) has been developed by the Cooperative Research Navies Dynamic Stability Project for simulating ship capsize in both regular and random wave conditions.

Extensive validation with experiments (De Kat and Thomas, 1998) has shown that FREDYN gives good predictions of capsize for naval frigates. To enable useful application for ship design and operation, a method has been developed for predicting capsize probability of intact ships in long-crested, random seaways (McTaggart and De Kat, 2000).

Overview of probabilistic approach

The probability of ship capsize during duration D (e.g., one hour) is given by:

$$P(C_D) = \sum\sum\sum\sum p(V)p(\beta)p(Hs,Tp)P(C_D\,|\,V,\beta,Hs,Tp) \tag{1}$$

where $p(X)$ is discretized probability of random variable X, V is ship speed, β is ship heading, Hs is significant wave height, Tp is peak wave period, and $P(C_D|V,\beta,Hs,Tp)$ is capsize probability given V, β, Hs, and Tp. Similarly, the exceedance probability for maximum roll angle can be evaluated as:

$$Q(\phi_{\max D}) = \sum\sum\sum\sum p(V)p(\beta)p(Hs,Tp)Q(\phi_{\max D}\,|\,V,\beta,Hs,Tp) \tag{2}$$

where $Q(\varphi_{max,D}|V,\beta,Hs,Tp)$ is exceedance probability of maximum roll angle given V, β, Hs, and Tp.

Distribution statistics for maximum roll angle in given conditions

The occurrence of capsize for given conditions (i.e., ship speed, heading, significant wave height, and peak wave period), will depend on the realization of the randomly generated seaway. Ideally, the probability of capsize for given conditions could be determined by running a very large number of simulations and using the following equation:

$$P(C_D\,|\,V,\beta,Hs,Tp) = \frac{N_C}{N_S} \tag{3}$$

where N_C is the number of observed capsize in N_S simulations. The cumulative distribution function (CDF) of maximum roll angle for given conditions can be estimated in a similar manner. For brevity, the random variable X is introduced here, which could represent maximum roll angle for given conditions. Madsen et al. (1986) indicate that the estimated CDF values from N_S samples will be:

$$F(X_i) = \frac{i}{N_S + 1} \tag{4}$$

where i is the rank of sample X_i. When predicting roll exceedance probabilities, the main disadvantage of Equation 4 is that it cannot extrapolate beyond observed values. However, Equation 4 is useful because it provides an unbiased estimate and it requires no assumptions regarding the distribution of the variable X, and is thus referred to as a "distribution free" estimate.

Ongoing work (McTaggart, 2000) has indicated that capsize risk in given conditions can be efficiently estimated by modeling maximum roll angle using a Gumbel distribution as follows:

$$F(X) = \exp\left[-\exp\left(\frac{b_X - X}{a_X}\right)\right] \quad (5)$$

where a_X and b_X are scale and location parameters, with b_X being the 36.8'th percentile of X. The Gumbel parameters a_X and b_X can be determined using maximum roll angles obtained from a number of simulations (typically at least ten) in seaways of duration D. Experience predicting ship capsize risk indicates that it is preferable to determine a_X and b_X by minimizing the error in ln[-ln($F(X)$)] from simulated samples. Figure 3 shows an example of a Gumbel distribution fitted to maximum hourly roll angles simulated by FREDYN for a ship in stern quartering seas. The fitted Gumbel distribution provides good agreement with the observed values, particularly in the upper range of roll angles of greatest interest for ship capsize.

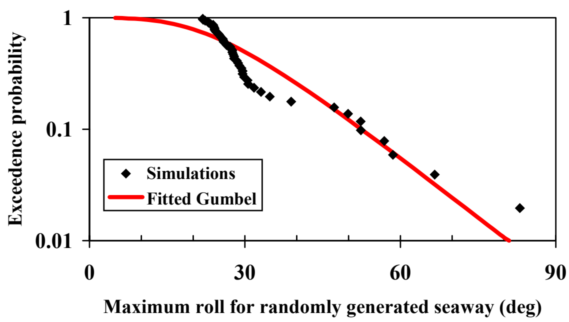

Figure 3. Maximum hourly roll angle, 10 knots, stern quartering seas (150°), *Tp* 12.4 s, *Hs* 9.5 m

In additional to the Gumbel distribution, the type II maximum and generalized extreme value distributions have been tried for modeling maximum roll exceedance probabilities in given conditions. The Gumbel distribution consistently gives more reliable predictions of capsize probability than the other distributions. When deciding between using fitted Gumbel distributions or distribution free estimates for predicting capsize probability, fitted Gumbel distributions have the advantage of permitting extrapolation beyond observed roll angles. Experience computing capsize probability based on fitted Gumbel distributions and distribution free estimates indicates that the two approaches provide very similar results (McTaggart, 1999).

The distribution free approach is especially suited to developing statistics for phenomena such as broaching, which cannot be easily described by a single parameter suited to modelling by a statistical distribution. It is likely that certain ships have roll responses that are not well suited to the Gumbel fit procedure described above; thus, the distribution free approach would be more appropriate for prediction of their capsize risk.

APPLICATION OF PROBABILISTIC METHODS

Probabilistic methods have a variety of applications for design and operation of safe ships. In the design phase, probabilistic methods can determine whether a ship has sufficient intact stability to minimize risk of capsize both in comparison to other ships, and in specific seaway conditions. Probabilistic methods can also be used to determine design feasibility by utilizing capsize probabilities as a measure of suitability. In addition, probabilistic methods can be used to develop relatively simple design guidelines that will ensure adequate intact stability. For example, a suitable range of positive stability (e.g., 90 degrees) for a certain vessel type could be determined by probabilistic methods

For the ship operator, probabilistic methods can indicate which combinations of speed and heading are dangerous for given environmental conditions. Such knowledge can be invaluable when making critical decisions in situations such as search and rescue operations. Capsize and broaching risk polar diagrams show promise as a tool for operational guidance. The resultant probabilities are plotted as isoclines on capsize-broaching polar diagrams, as shown in Figure 2.

Assumptions Regarding Ship Operations

Capsize risk assessments typically make idealized assumptions regarding the operation of a ship. For example, ship speed and heading are often assumed to be independent of seaway. When performing comparative studies between two ships, they are often assumed to have identical speed and heading profiles. These assumptions do not account for shiphandling tactics, machinery limitations, or operational restrictions that may be unique to a class of ships. All of these factors may drastically affect the final statistics. Currently, sufficient data do not exist to permit a more extensive consideration of machinery characteristics and shiphandling tactics in extreme seas. The Naval Stability Standards Working Group NSSWG, is currently considering how data on shiphandling tactics in extreme seas may be gathered and assessed.

Required number and duration of simulations

Of great practical importance is the required duration of simulations for predicting capsize risk for given conditions (i.e., ship speed, heading, significant wave height, and peak wave period). Several different seaway realizations must be simulated for given conditions. Experience has shown that somewhere between 10 and

50 simulations of 30 minute duration should be run to determine hourly capsize statistics. For the distribution free approach, a minimum of 25 realizations is typically used. Using the fitted Gumbel approach, 10 initial simulations can be run to estimate if capsize risk is non-negligible. The number of simulations can be increased (e.g., to 50) if capsize risk appears to be significant.

Computational experience

The use of time domain simulations in the probabilistic assessment of capsize risk is largely constrained by limits on computational speed. For example, the capsize risk polar plot displayed in Figure 2, required 4.5 days of run time to perform 4200 FREDYN simulations on a 933 MHz Pentium III desktop computer. Comprehensive risk assessments using multiple wave height and modal period combinations (see Equation 1) can be performed in approximately one month using between five and seven Pentium III computers. Efforts to continue the development of non-linear CFD codes to improve the precision of predictions are supported by the authors, however, the slowness of the CFD codes (slower than FREDYN by factors in excess of 700) have not yet made them practical in capsize risk assessments.

Climatology

Application of equations (1) and (2) requires the joint probability distribution of significant wave height and peak wave period in the form of a wave climate scattergram. Experience has shown that predicted capsize probability can be highly dependent upon wave climate. Initial capsize predictions based upon the electronic version of BMT Global Statistics for Area 15 gave unrealistically high capsize probabilities for naval frigates. Further investigation revealed that the wave climate scattergram had unrealistically large nominal wave steepnesses, defined by:

$$\widetilde{H/\lambda} = \frac{Hs}{g/(2\pi)Tp^2} \qquad (7)$$

For comparison of different data sources, the following relationship for a Bretschneider spectrum relates peak wave period to zero-crossing wave period:

$$Tp = 1.408\ Tz \qquad (8)$$

Shown in Figure 4 is the maximum significant wave height versus peak wave period from three different sources. The Buckley (1994) data are based on wave buoy observations. For several wave periods, the data from BMT Global Wave Statistics (1986) Area 15 has significant wave heights much higher than those from Buckley do. The hindcast data of Bales (1984) give a limiting wave height envelope that is more consistent with Buckley. Computed capsize probabilities based on the hindcast wave data of Bales appear to give credible capsize probabilities for naval ships.

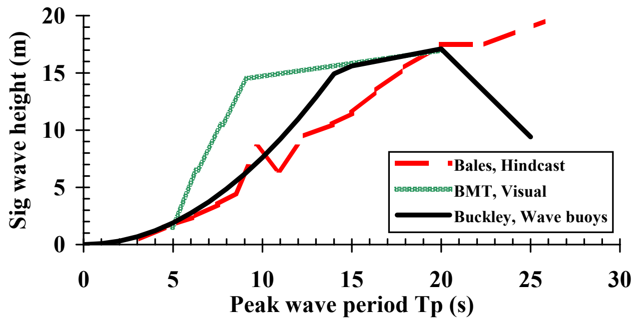

Figure 4. Maximum significant wave height versus peak wave period

McTaggart and De Kat (2000) and the discussion for their paper consider why BMT Global Wave Statistics gives unrealistic nominal wave steepnesses. The problem stems from extrapolation of wave height exceedance probabilities for given wave periods. In the printed version of Global Wave Statistics, the resolution of 0.001 in the wave scattergram data gives reasonable nominal wave steepnesses; however, the electronic version of Global Wave Statistics gives wave scattergrams to a resolution of one millionth, leading to extrapolation problems.

GUIDANCE TO OPERATORS DURING SEVERE CONDITIONS

Efforts to date have focused on understanding the process of capsize behavior and the effects of dynamic stability. Most recently (as presented earlier in the paper) the effort has been to explore the probability of capsize both in a over-the-ship-lifetime global approach and as an assessment of the probability of capsize within given conditions. These approaches will be very useful in the design of a new vessel or class of vessels as a means to compare the relative merits of competing designs in terms of their true heavy weather operability. However, global capsize probability by itself does little to assist the operators of an as-built vessel.

To provide useful guidance to a ship's officer operating in a severe seaway, the polar capsize risk plot (Figure 2) has emerged as a useful tool. A shaded portion of a polar plot is referred to as a capsize region, and indicates combinations of speed and heading where capsize risk is non-negligible. An assessment of capsize behavior within the mapped capsize region offers additional useful information to the ship's officer, and can provide the basis for operator guidance on shiphandling in heavy weather. A first step was described by Alman et al. (1999) for safe operation in the vicinity of tropical cyclones. It was recognized that the traditional guidelines for course and speed to avoid an oncoming hurricane represent the fastest means to get out of the way of the storm. Hurricane avoidance action should be followed as soon as the danger is recognized and before sea conditions worsen. Unfortunately, it is not always possible to successfully avoid a hurricane, and the strategy must be changed from one of avoidance to survival. In such severe conditions, following and quartering seas can become a hazard to the vessel. To mitigate the risk of capsize, either the speed of the vessel should be reduced, the course of the vessel altered, or some combination of speed reduction and course change executed in order to keep the vessel out of its potential capsize regions. This ship-specific information could be computed for the vessel and made available to the master and ship officers in the form of polar plots presented in a heavy-weather stability guidance booklet or by other suitable means such as computer display.

Continuing with the hurricane avoidance scenario, the first choice of a modified course and speed should, if possible, continue to remove the ship from the storm area. However, if sea conditions continue to worsen, again potentially placing the vessel in an expanding capsize region, preparations should be made to weather the storm. Here the maneuvering and powering performance of the ship must be taken into account in developing effective guidance. Care must be taken on board the vessel such that the decision to alter course from hazardous quartering seas and come about in order to weather the seas on the bow is not made after the point at which the vessel becomes unable to complete its turn due to the state of the seas. Dynamic stability analysis using time-domain dynamic stability simulations can determine the limits of a vessel's turning and maneuvering capability.

Effective guidance therefor falls into three categories. These represent a triad for the ship/seaway system. Each is fundamentally important to minimize capsize risk.

1. Ship capsize behavior
2. Ship system capability and configuration
3. Real-time knowledge of seaway conditions

Guidance based on an understanding of ship capsize behavior

Efforts have been undertaken for a few ships and designs to quantify the probability of capsize within the capsize region. These efforts have served to identify the real risk involved for a design over-and-beyond a set of polar plots with just the capsize region indicated. Given a sea condition, one vessel may have a larger capsize region but with very little probability of capsize within the region. Another ship by contrast may have a distinctly small capsize region but is inherently unsafe for operation within the region. Capsize region mapping in this manner results in "isobars" of equivalent capsize probability within the capsize region.

A related approach would involve mapping the interior of the capsize region for the dynamic stability process (or processes from different seed numbers) that results in capsize. In order to develop effective operator guidance, the failure mechanism needs to be known. The mitigation strategy can then be developed to remove the ship from the capsize region, or from near proximity to the capsize region, without initiating a catastrophic dynamic stability response. It is hypothesized that severe ship dynamic response related to stability behavior within a sub-region of the overall capsize region will also be present to a reduced magnitude at headings and speeds just outside the capsize region. Mitigation strategies developed to combat a potential dynamic stability hazard would then be used on the ship in a manner similar to monitoring a ship's GM at sea by observation of its natural roll period. In this case, if the ship's roll constant is known and the ship's natural roll period is observed by using the rudder to induce roll in calm water, then an estimate of GM can be computed. A large increase in natural roll period at sea is thus an indication that GM may have been reduced and corrective action can be initiated.

The same approach can be adapted to dynamic stability guidance while at sea. Suppose through simulation in a given sea condition it is found that a vessel has a propensity to surfride severely, resulting in broaching and capsize at known headings and speeds within the capsize region. Then the mitigation strategy would probably involve a speed reduction rather than a course change because the course change could very possibly lead to further loss of control and broaching. However, if the vessel tends to capsize by loss of transverse stability after wave capture, but possesses good directional control, then a course change might be the safer mitigation strategy.

Naturally, while underway in heavy seas, efforts should be made to stay removed from the ship's known capsize region. But as the true wave steepness is not known with certainty, or the wave direction could change or the ship could be forced off course placing the ship into the capsize region, reliance on specific headings and speeds just outside the capsize region pose an increased level of risk. At these headings and speeds, specific ship motions or response behaviors could serve as indicators of the potential hazard, and the appropriate mitigation strategy would dictate the shiphandling maneuver to employ.

Guidance based on an understanding of ship system capability and configuration

Ship specific guidance also has to take into account the performance capability of the ship. A generally safe heading in severe seas may become threatening if sea conditions worsen, thus necessitating a heavy seas shiphandling maneuver. Using an example of hurricane avoidance guidance, the "safe" heading in quartering seas may become unsafe, forcing the master to attempt to come about into the seas. However, there may not be sufficient power to execute the maneuver, and the longitudinal distribution of a large sail area may make the maneuver physically impossible.

The key issues to address in guidance for heavy seas shiphandling maneuvers are whether the vessel can complete the maneuver; whether the maneuver increases the risk to the vessel; and possibly, whether the new combination of heading and speed is actually less dangerous for the vessel.

Selection of the best heading and speed in terms of avoiding extreme capsize risk can be greatly impacted by secondary affects caused by wind drag on the exposed topside. Wind can play a critical role in determining whether a ship survives a maneuver, especially where a loss of power occurs. Figure 5 shows results from simulations conducted on a frigate type ship executing typhoon avoidance. When power to the ship is lost, capsize probability is very dependent on the wind direction relative to waves. This phenomenon is largely due to the heading that the ship assumes once it is dead in the water. The combination of wind direction relative to sea direction and the longitudinal position of the center of wind pressure can result in either a dead ship riding with the waves or broaching in the trough.

In order to develop appropriate, ship-specific guidance, an understanding of the ship's maneuvering and powering characteristics is needed. Sail area location may be an important factor for some ship configurations. In the case of windage, variance in loading condition may be more important to consider for naval auxiliaries than for naval combatants due to the relatively small changes in draft of the latter. Turning circle maneuvers can be executed using time-domain simulations with different power levels and rudder angles in different sea conditions to determine how the ship responds. Other scenarios can be developed that address hazardous circumstances arising from common ship system failures.

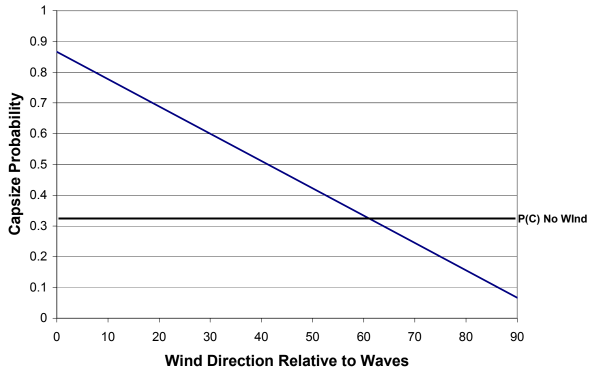

Figure 5. Power loss scenario: P(C) variation with wind direction in hurricane Camille

In order to determine the maneuvering characteristics of a ship in calm water, a set of standard scenarios including zigzags and turning circles has been employed. Maneuvering characteristics in heavy weather are also very ship specific; thus, a set of simulation scenarios for heavy weather can provide critical information concerning capsize risk avoidance which the master should be aware of when planning tactical maneuvers.

Guidance based on real-time measurement of sea conditions

"What is it doing out there?" seems a simple question, but even so requires a quick accurate answer. To date, little work has been done to develop onboard wave measurement systems beyond "Mark I eye ball". The loading condition of a ship can have a significant impact on capsize probability with changes in draft, trim and KG. Likewise, the seaway characteristics can directly impact capsize probability.

It is important that the operator have accurate measurements of significant wave height, modal period and wind speed for the seaway his ship is in. "Eye ball" estimates of wave height and period may not be accurate enough where the ship is sensitive to seaway tuning due to modal wave period and roll natural frequency. McTaggart and De Kat (2000) show that capsize probabilities can change greatly for seaways of the same significant wave height but varying modal periods.

Consequently, usable and accurate operator guidance will depend on availability of reliable environmental data in the immediate vicinity of the ship. Real-time onboard wave sensors are the best way to provide seaway data to the ship.

CONCLUSIONS

Simulation techniques coupled with risk assessment methodologies can provide significant information on capsize risk in severe seaways. Both the Gumbel distribution and distribution free techniques can be employed effectively in developing an awareness of the hazardous areas of ship operation in heavy seas. The fitted Gumbel distribution can be used for estimating roll exceedance probabilities for given conditions. The distribution free approach must be used for assessing phenomena such as broaching that are not easily modelled by statistical distributions. However, for at-sea shiphandling guidance, capsize risk polar diagrams are not enough to provide a complete picture when considering all factors in tactical decision making. A knowledge of the physical capsize mechanisms at play in a particular section of the capsize region will help to develop effective mitigation strategies. A series of scenarios involving ship system failures, wind, and standard maneuvers can be employed to judge the risk of carrying out shiphandling tactical maneuvers to ensure that the maneuver selected will actually lessen the risk to the ship and crew.

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