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CAPSIZE PROBABILITY POLAR PLOTS FOR SHIP OPERATOR GUIDANCE

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Summary

This paper discusses the application of numerical ship motion predictions to ship operator guidance. Prudent ship operators avoid severe sea conditions when possible. Consequently, most ship operators have little experience in severe sea conditions. In the rare event that a ship does get caught in a severe sea, knowledge developed from simulations can supplement existing operator experience. Capsize probability polar plots are a useful tool for presenting which combinations of speed and heading are safe in a given sea state. When creating polar plots, attention has been given to effective display of information.

Nomenclature

C	ship capsize
D	duration
$\overline{GZ}$	righting moment arm
H_s	significant wave height
N_X	number of discretized values of X
$P(C_D)$	probability of capsize during D
$P(C\|X)$	probability of capsize given X
$p_X(X_i)$	probability of occurrence of X_i
T_p	peak wave period
V	nominal ship speed
X	random variable
X_i	discretized value of variable X
α	fraction of time spent at sea
β	ship heading
ϕ	roll angle

1 Introduction

Much progress has been made in recent years in the simulation of ship motions in severe seas. Numerical ship motion predictions are now being used for applications such as evaluation of capsize probability [1] and development of operator guidance [2]. This paper discusses the development and presentation of operator guidance information within the Canadian military context.

Probabilistic methods offer a rational basis for safe design and operation of ships. Probabilistic approaches combined with specified acceptable levels of safety can be used to decide if a proposed design is adequate. For ship operations, probabilistic approaches can aid decisions regarding safe speed and heading under given sea conditions. Search and rescue in heavy seas is an example of a mission that could likely benefit from rational operator guidance.

2 Existing Knowledge for Handling Ships in Heavy Weather

When considering approaches for providing guidance to ship operators, it is essential to review existing shiphandling doctrine.

2.1 Available Information

There is very little written information on the handling of ships in heavy or extreme weather. The Admiralty Manual of Seamanship [3] explains:

> "How best to handle a ship in heavy weather depends so much upon the type, size and capabilities of the particular ship that it would be unwise to lay down precise instructions as to how to act in various circumstances."

The Admiralty Manual of Seamanship devotes 17 pages to the handling of ships in severe conditions; this is perhaps the most concentrated and comprehensive information available. Other references such as Crenshaw's *Naval Shiphandling* [4] and the *Mariner's Handbook* [5] provide information but merely summarize the findings of the Admiralty. Van Dorn's *Oceanography and Seamanship* [6] provides excellent background reading but the seamanship is directed more towards yachts and small boats than to larger ships. It is interesting to note that only oblique references are made to the danger of capsize in any of the references examined.

2.2 General Advice

Each of the references indicates, and the thought process internationally is, that the best way to survive heavy weather is to avoid it. This is borne out by the development of weather routing systems such as Optimum Track Ship Routing (OTSR), a US Navy system that "utilizes short range and extended range forecasting techniques in the route selection and surveillance procedures" (Bowditch [7]). Navigators also use long-range weather forecasting and historical data to develop routes that will both mitigate the weather risk and ensure mission success. Once near the storm, all advice is predicated on minimizing the damage and risk to the ship. For tropical storms, the doctrine is mainly concerned with avoiding the storm centre, depending on the ship's location relative to it.

It is universally accepted that stability is a significant concern and 'secure for sea', both to reduce the free surface effects of taking on water, and to reduce the chances of shifting weight, is the primary concern of all operators.

In heavy weather, decisions regarding speed and heading are influenced by the capability of the ship to withstand the rigours of the seas. Steaming into the sea subjects the ship to extreme forces: the impact of waves against the bow, and water breaking onto the ship, and the hogging, sagging and pounding forces caused by excessive pitch. A small reduction of speed can have a significant effect on the occurrence of slamming and associated loads. Running before the sea lessens the extreme forces but significantly increases the risk of broaching-to. The risk of broaching-to can be minimized by reducing ship speed to about 60 percent of wave speed, but this increases the risk of being pooped. As the ship slows, relative to wave speed, the overtaking waves can wash along the upper decks from astern. This can cause significant damage, and critically, damage that may not be noticed from the bridge.

At present, courses and speeds are chosen based on the general guidance provided in the references and on a subjective 'feel' for how the ship is handling the external forces. In particular, there is little information to guide the mariner who must brave extreme weather to achieve a vital mission. The polar risk diagrams advocated in this paper would provide vital statistical data to the ship captain and navigator, increasing the ability of ship personnel to choose the safest range of courses and speeds to achieve the mission without undue hazard to the ship.

3 Prediction of Intact Ship Capsize Probability

Good seamanship dictates that a ship operator avoid storms when possible; thus, most operators have limited experience handling their ships in severe conditions. Results from time domain simulations, including predictions of ship capsize probability, can supplement operator experience in severe seaways.

McTaggart and de Kat [1] present the following equation for prediction of ship capsize risk in long-crested random seas:

$$\begin{aligned} P(C_D) \;=\; & \sum_{i=1}^{N_V} \sum_{j=1}^{N_\beta} \sum_{k=1}^{N_{H_s}} \sum_{l=1}^{N_{T_p}} \\ & p_V(V_i)\, p_\beta(\beta_j) \\ & \times\, p_{H_s,T_p}(H_{s-k}, T_{p-l}) \\ & \times\, P(C_D|V,\beta,H_s,T_p) \end{aligned} \qquad (1)$$

where $P(C_D)$ is the probability of capsize in a seaway of duration D, V is ship speed, β is the relative wave heading, H_s is significant wave height, T_p is peak wave period, and $p_X(X_i)$ is the probability mass function for the discretized variable X. A capsize is defined as when the ship roll angle exceeds a specified critical value, such as the angle of downflooding or the angle of zero static stability (i.e., $\overline{GZ}(\phi) = 0$). Each independent variable X in the above equation has been discretized into N_X different values. The last term of Equation (1) denotes a conditional probability given a set of operational and seaway conditions. The conditional capsize probability $P(C_D|V,\beta,H_s,T_p)$ can be evaluated by performing several simulations of ship motions for the specified conditions, with seaway realization (i.e., random phases of seaway components) varying among simulations for the specified conditions. Experience indicates that 10-50 simulations of 30-60 minute duration can provide good estimates of conditional hourly capsize probability. For practical application of this approach to a large number of combinations of ship speed, heading, wave height, and peak wave period, the numerical ship motion simulations must be carried out significantly faster than real time. McTaggart and de Kat's example probabilistic analysis for a single ship loading condition simulated over 200 days of real time, and required approximately 15 days using the program FREDYN, which ran approximately 15 times faster than real time.

Once the probability of capsize for duration D has been computed using Equation (1), the associated annual probability of capsize can be computed as follows:

$$P(C_{annual}) \;=\; 1 \;-\; [1 - P(C_D)]^{\alpha \times 1\; year/D} \qquad (2)$$

where α is the fraction of time that the ship spends at sea during a year. If the annual capsize probability is small (e.g., < 0.01), then the above equation can be approximated by:

$$P(C_{annual}) \;\approx\; P(C_D)\, \alpha\, \frac{1\; year}{D} \qquad (3)$$

The traditional method for managing the capsize hazard for Naval ships has been to adopt conservative methods. These include use of prescriptive stability criteria, based on data from past losses; and hurricane avoidance techniques that may not work well under operational conditions. Risk management techniques are becoming more common, being used both in engineering design and in operational planning. Risk is usually defined as product of probability and consequence, and Equations (1) and (2) help to provide data for one part of that product.

Probabilistic data can provide very useful information for decision making. This data can be analysed in a variety of ways, such as the calculation of conditional probabilities (e.g., the probability of capsize given ship speed). Sea conditions that are most relevant to ship capsize can be determined from the following conditional probabilities of significant wave height and peak wave period given capsize:

$$p_{H_s,T_p|C}(H_{s-k}, T_{p-l}|C) \;=$$

$$\frac{1}{P(C_D)} \times p_{H_s,T_p}(H_{s-k}, T_{p-l}) \times \sum_{i=1}^{N_V} \sum_{j=1}^{N_\beta} [p_V(V_i)\, p_\beta(\beta_j) \times P(C_D|V, \beta, H_s, T_p)] \quad (4)$$

The denominator $P(C_D)$ of the above equation is obtained from Equation (1). The combination of H_s and T_p with the highest conditional probability $p_{H_s,T_p|C}(H_{s-k}, T_{p-l}|C)$ is the most likely seaway given ship capsize. Note that the summation of the conditional probabilities $p_{H_s,T_p|C}(H_{s-k}, T_{p-l}|C)$ is equal to one.

4 Acceptable Capsize Probability

When working with computed capsize probabilities, it is useful to consider what would be an acceptable probability of capsize. Examination of risks associated with various activities (Reid [8] gives a suitable overview) indicates that the maximum acceptable annual capsize probability could be approximately 10^{-4}. For a ship at sea 30 percent of the time (2600 hours per year), Equation (3) indicates that this annual capsize probability corresponds to an acceptable hourly capsize probability of 4×10^{-8}.

When a ship is faced with operation in a severe seaway, one must consider what an acceptable capsize probability would be in that seaway. The acceptable hourly capsize probability of 4×10^{-8} suggested above is one possible value. Alternatively, one could argue that the severe seaway is relatively rare, will last only a few hours, will only occur once during the year, and will essentially represent the entire capsize probability for this ship during the year. Accordingly, it could be argued that the acceptable annual capsize probability level of 10^{-4} would also be the level of acceptable hourly capsize probability for the severe seaway.

5 Capsize Probability Polar Plots

Equation (1) does not account for human intervention in preventing capsize. Experienced ship operators can significantly reduce the probability of capsize by appropriate selection of speed and heading. Furthermore, results from numerical ship motion simulations and probabilistic methods have great potential for providing relevant information to ship operators. This will provide a greater degree of capsize risk mitigation than is currently available. Prudent ship operation dictates that severe conditions be avoided when possible. This strategy combined with the relatively low frequency of severe conditions means that ship operators have relatively little experience in severe conditions. Although intended mainly for ship design purposes, operators have found that the results from numerical simulations can supplement their experience in severe conditions. Bridge simulators which incorporate wave-induced motion effects also have great potential for teaching ship-handling in severe conditions.

The usefulness of results from numerical simulations will depend greatly on the presentation format. Operators have responded enthusiastically to capsize risk polar plots (e.g., Alman et al.) which present capsize risk as a function of ship speed and heading. The authors of the present paper, who represent the research, engineering, and operational communities, have engaged in dialogue regarding the presentation format for capsize risk polar plots. Figure 1 gives an example polar plot based on recent computations for a naval frigate. The seaway selected for the polar plot, with $H_s = 13.5$ m and $T_p = 16.4$ s, has high waves and is approaching the physical limit on wave steepness. Analysis using Equation (4) indicates that this seaway is also the most likely combination of H_s and T_p given capsize of this ship during operation in the North Atlantic.

There are several aspects of Figure 1 that warrant comment. The presented capsize probabilities are based on an exposure time of one

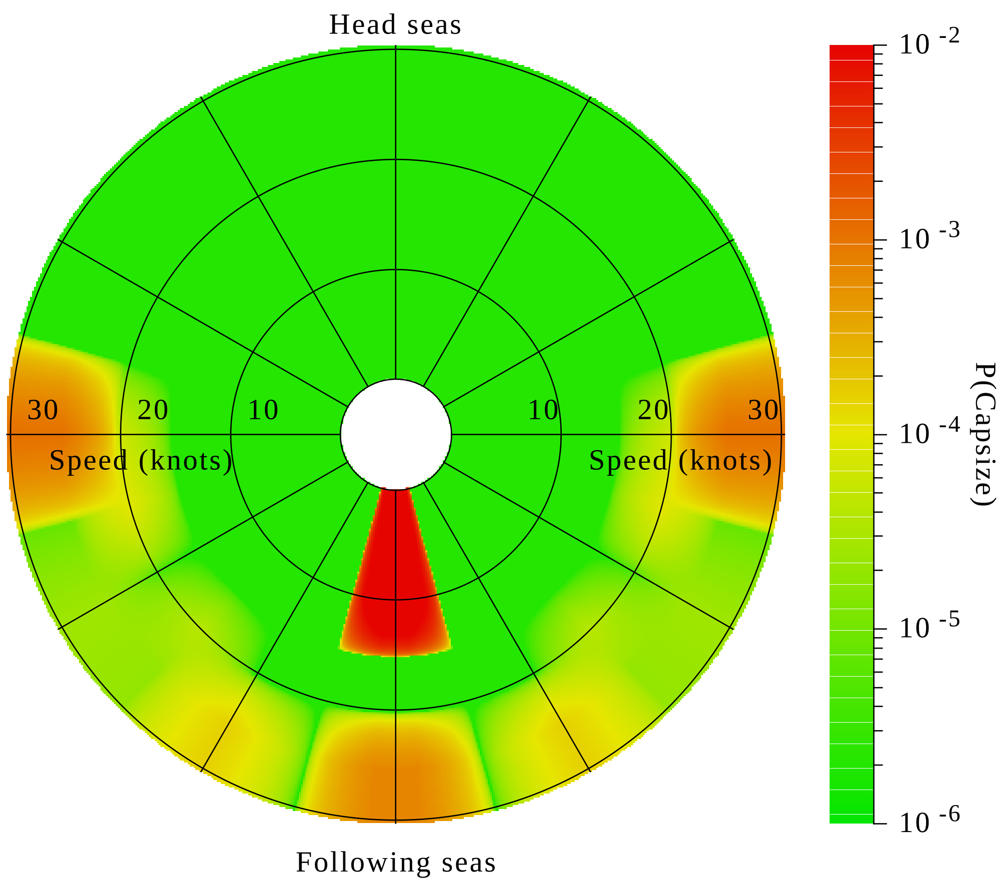

Figure 1: Hourly Capsize Probability Polar Plot for Frigate, Severe Seaway with H_s = 13.5 m, T_p = 16.4 s

hour. This duration was selected because mission durations in severe conditions are often of the order of hours. The convention for sea direction is relative to ship heading, with the top of the polar plot denoting head seas. For the radial axis, a speed of 0 knots is located off-centre so the variation of capsize probability with heading is visible for zero speed. Perhaps the most noteworthy aspect of the polar plot is the colour scale used to represent various levels of capsize risk. The colour scale should be based partly on what is considered to be an acceptable capsize probability. The colour scale for Figure 1 was selected partly based on the assumption that the ship operator will only use capsize probability polar plots when the ship is operating in severe conditions. Such conditions might only occur for several hours during a year, representing most of the annual exposure to capsize risk. The hourly capsize probability of 10^{-2} represented by red is considered unacceptable with the exception of very rare circumstances in which there would be a high penalty for not completing a mission. The hourly capsize probability of 10^{-6} denoted by green represents what could likely be considered as negligible risk, while the value of 10^{-4} denoted by yellow could be considered a maximum acceptable risk level under normal circumstances.

The appearance of the polar plot depends upon the interpolation scheme used for determining capsize probabilities at intermediate speed and heading combinations for which no simulations have been conducted. Figure 1 uses the following equation for interpolation of capsize probabilities:

$$\begin{aligned} P(C|V,\beta) \; &= \; P(C|V_i,\beta_j) \\ &+ \; (V \; - \; V_i) \; \left.\frac{\partial P(C|V,\beta)}{\partial V}\right|_{V_i,\beta_j} \\ &+ \; (\beta \; - \; \beta_j) \; \left.\frac{\partial P(C|V,\beta)}{\partial \beta}\right|_{V_i,\beta_j} \\ &+ \; (V \; - \; V_i) \; (\beta \; - \; \beta_j) \; \left.\frac{\partial^2 P(C|V,\beta)}{\partial V \partial \beta}\right|_{V_i,\beta_j} \\ &\text{for } V_i \leq V \leq V_{i+1} \text{ and } \beta_j \leq \beta \leq \beta_{j+1} \qquad (5) \end{aligned}$$

The derivatives in the above equations are determined using adjacent values of capsize probabilities from simulations, thus ensuring that capsize probabilities on the polar plot are continuous. In some cases, the present interpolation method can give steep colour gradients, such is those at lower ship speeds in the vicinity of following seas in Figure 1. These steep gradients can occur when there are large changes in capsize probabilities between adjacent speed and heading combinations used for simulations. A higher density of simulation values (i.e., more combinations of speed and heading for simulations) would likely smooth out some of these colour gradients. The present results are based on a speed increment of 5 knots and a heading increment of 15 degrees. Another likely reason for steep colour gradients is the coupling of a logarithmic colour scale with a linear interpolation scheme. Colour gradients would likely be less steep if interpolated probabilities were based on logarithms (i.e., if $\log P(C|V,\beta)$ were assumed to vary linearly with speed and heading); however, fundamentals of probability indicate that the interpolation scheme of Equation (5) is more appropriate.

An appreciation of capsize modes (see Reference 1) helps when interpreting polar plots. In Figure 1, the red area at low speed in following seas is likely due to loss of steering capability. At higher speeds in following seas, wave encounter frequency becomes smaller, increasing the potential for loss of static stability while riding on a wave crest.

6 Conclusions

Prudent ship operation dictates that severe sea conditions be avoided when possible; thus, ship operators often have limited experience in severe conditions. For those rare circumstances in which operators encounter severe seas, appropriate selection of speed and heading can greatly reduce the probability of capsize. Results from time domain simulations can provide useful information regarding ship performance in conditions which aren't normally encountered by operators. Capsize probability polar plots are a useful format for presenting this information to ship operators.

References

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