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ONGOING WORK EXAMINING CAPSIZE RISK OF INTACT FRIGATES USING TIME DOMAIN SIMULATION

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Abstract

This paper describes ongoing efforts to develop methods for predicting capsize risk of intact naval frigates. For a given ship condition, the risk of capsize is considered to be a function of ship speed, heading, significant wave height, and zero-crossing wave period. Implementation of the proposed procedure requires a numerical model for prediction of ship motions in severe seas. The program Fredyn, which uses a time domain strip theory approach, provides an appropriate combination of computational speed and accuracy for predicting capsize of slender naval frigates. When predicting capsize risk in irregular seas, the dependence of capsize occurrence on wave process realization must be considered. This dependence can be modelled by using Gumbel fits of maximum absolute roll angles obtained from several different realizations. The proposed risk analysis procedure can be extended to account for capsize avoidance procedures taken by ship operators.

NOMENCLATURE

B	ship breadth
D	seaway duration
H_C	capsize wave height
H_s	significant wave height
$H_{s,annual}$	annual max significant wave height
$\widetilde{H/\lambda}$	nominal wave steepness
L	ship length
N_C	number of capsizes
N_s	number of simulations
N_X	number of discretized values of X
$P(C_{annual})$	annual capsize risk
$P(C_D)$	capsize risk in seaway of duration D
$p_X(X)$	discretized probability of X
$Q_X(X)$	exceedence probability for X
T_p	peak wave period
T_z	zero-crossing wave period
V_s	ship speed
β	ship heading (180° for head seas)
$\phi_{max,D}$	max absolute roll angle in duration D
χ	wave phase seed number

INTRODUCTION

Risk analysis provides the most rational approach for designing safe ships. Kobylinski [1] gives an example of risk analysis applied to ship stability, while Mansour et al. [2] discuss application to structural design. The development of risk analysis approaches is relatively recent, and most ship design continues to be based on rules developed through experience. For stability of warships, the rules developed approximately 40 years ago by Sarchin and Goldberg [3] continue to be used by several navies.

Traditional design rules suffer from two primary problems. The resulting levels of safety for different ships can be highly variable, leading to insufficient safety in some cases and unreasonable restrictions in other cases. The second primary problem with traditional design rules is that they are not applicable to new designs that differ significantly from the ships upon which the rules were originally based. For example, Sarchin and Goldberg's rules were developed for warships with narrow sterns; however, modern warships have wide transom sterns, making them vulnerable to loss of stability during stern emergence, which can occur while riding on a wave crest. Consequently, modern warships may be more vulnerable to capsize than originally intended by Sarchin and Goldberg.

This paper describes ongoing work to develop rational risk analysis procedures for the stability of intact naval frigates. The present research is being conducted in parallel with Canada's ongoing participation in the Cooperative Research Navies Dynamic Stability Project [4, 5].

THEORETICAL APPROACH

Initial work presented in References 6 and 7 assumed that if a ship were to capsize in a given year, it would capsize in the most severe annual storm as characterized by significant wave height. The developed capsize wave height approach was based on the following equation:

$$
\begin{aligned}
P(C_{annual}) \;=\; & \sum_{i=1}^{N_{V_s}} \sum_{j=1}^{N_\beta} \sum_{k=1}^{N_{\widetilde{H/\lambda}}} \sum_{l=1}^{N_\chi} \frac{1}{N_X}\, p_{V_s}\left(V_{s-i}\right) \\
& \times p_\beta\left(\beta_j\right)\, p_{\widetilde{H/\lambda}}\left(\widetilde{H/\lambda}_k\right) \\
& \times \left[Q_{H_s,annual}\left(H_C \mid V_s, \beta, \widetilde{H/\lambda}, \chi\right)\right] \qquad (1)
\end{aligned}
$$

where $P(C_{annual})$ is annual capsize risk, N_X is the number of discretized values of random variable X, $p_X(X)$ is the probability mass function (PMF) for X, V_s is desired ship speed, β is desired ship heading relative to the waves, $\widetilde{H/\lambda}$ is nominal wave steepness, χ is a seed number for generating random waves, $H_{s,annual}$ is annual maximum significant wave height, $Q_{H_s,annual}(H_{s,annual})$ is the exceedence probability of significant wave height for the worst annual storm (typically three hour duration), and $H_C|V_s, \beta, \widetilde{H/\lambda}, \chi$ is the minimum significant wave height which causes capsize given $V_s, \beta, \widetilde{H/\lambda}$, and χ. Equation (1) assumes that if a capsize occurs at significant wave height H_C then capsize will occur all wave heights greater than H_C. The nominal steepness of the worst annual storm is given by:

$$\widetilde{H/\lambda} \;=\; H_s \frac{2\,\pi}{g\,T_p^2} \qquad (2)$$

where T_p is peak wave period and g is gravitational acceleration. Storm data from the Canadian East Coast [8] indicate that a Gumbel distribution provides a good fit for $H_{s,annual}$ and a Weibull distribution provides a good fit for $\widetilde{H/\lambda}$.

A key assumption of Equation (1) is that capsize risk increases with significant wave height and that nominal wave steepness is of secondary importance. Subsequent work has shown that this assumption is too simplistic, and that the joint distribution of wave height and wave period must be considered; thus, it is inappropriate to consider only extreme annual storms based on significant wave height.

Present work is examining risk of capsize for all possible seaways. For a ship in a seaway of duration D (e.g. one hour), the probability of capsize is:

$$
\begin{aligned}
P(C_D) \;=\; & \sum_{i=1}^{N_{V_s}} \sum_{j=1}^{N_\beta} \sum_{k=1}^{N_{H_s}} \sum_{l=1}^{N_{T_z}} p_{V_s}(V_{s-i})\, p_\beta(\beta_j) \\
& \times p_{H_s,T_z}(H_{s-k}, T_{z-l}) \\
& \times P(C_D|V_s, \beta, H_s, T_z) \qquad (3)
\end{aligned}
$$

where T_z is zero-crossing wave period, which is used for compatibility with wave data in Reference 9. Similar expressions have been presented by Kobylinski [1] and Dahle and Myrhaug [10, 11]. An important assumption of the above equation is that desired ship speed and heading are independent of wave conditions. This assumption is conservative because ship operators will alter speed and course to reduce capsize risk.

Once the probability of capsize for duration D has been computed using Equation (3), the associated annual probability of capsize can be computed as follows:

$$P(C_{annual}) \;=\; 1 - \left[1 - P(C_D)\right]^{1\,year/D} \qquad (4)$$

NUMERICAL MODELLING OF SHIP CAPSIZE

A risk analysis approach such at that described above requires an accurate and efficient method for predicting ship capsize in a seaway. The present method uses the time domain program Fredyn, as described in References 4, 5, and 12. Fredyn considers forces from waves, wind, and ship maneuvering. Strip theory gives fast computation times and acceptable accuracy for naval frigates. It is uncertain whether Fredyn can provide acceptable accuracy for low L/B vessels such as small fishing boats. For a typical simulation in waves, the program runs approximately 15 times faster than real time on a 300 MHz Pentium II personal computer.

When the Cooperative Research Navies Dynamic Stability Project commenced in 1990, it was hoped that simplified numerical models could be developed for ship capsize. For example, a simplified numerical model would likely be adequate for predicting ship capsize at zero speed in beam seas. Subsequent research revealed that capsize modes for frigates typically require modelling of all six degrees of freedom. Frigates appear to be vulnerable to capsize in following seas through loss of static stability while riding on a wave crest, parametric excitation, and broaching.

Validation and improvement of the Fredyn program is an ongoing process. For frigate motions in extreme conditions, a lack of useful experimental data for validation prompted a series of model tests described in References 13 and 14. Fredyn appears to give very good agreement with experiments for capsize of a frigate in waves.

SHIP CAPSIZE RISK FOR GIVEN CONDITIONS

The application of Equation (3) for prediction of capsize risk requires a suitable method to determine capsize risk for given conditions $P(C_D|V_s,\beta,H_s,T_z)$. For a Fredyn simulation of a ship in irregular waves, a random phase approach is used to generate a wave realization. The wave realization is dependent upon a seed number χ provided as input for generation of random wave phases. The occurrence of capsize can be highly dependent on the input seed number. Upon initial consideration, it would seem appropriate to determine $P(C_D|V_s,\beta,H_s,T_z)$ using N_s simulations with different seed numbers as follows:

$$P(C_D|V_s,\beta,H_s,T_z) = \frac{N_C}{N_s} \quad (5)$$

where N_C is the number of simulations for which capsize occurs. The main disadvantage of this approach is that a large number of simulations can be required to obtain accurate estimates of $P(C_D|V_s,\beta,H_s,T_z)$. A much more efficient and useful approach is to apply a statistical fit to the maximum roll angles $\phi_{max,D}$ from N_s simulations of duration D. Figures 1 and 2 show fitted Gumbel distributions for a frigate in following seas with significant wave heights of 10 m and 12 m. The results indicate that a Gumbel distribution provides a very good fit to the conditional probability $Q_{\phi_{max,D}|V_s,\beta,H_s,T_z}(\phi_{max,D}|V_s,\beta,H_s,T_z)$. Work in progress suggests that only ten simulations are required to obtain good estimates for the conditional distribution $Q_{\phi_{max,D}|V_s,\beta,H_s,T_z}(\phi_{max,D}|V_s,\beta,H_s,T_z)$. An added benefit of using a fitted distribution for each seaway is that Equation (3) can be revised to give exceedence probabilities for all maximum roll angles in all seaways as follows:

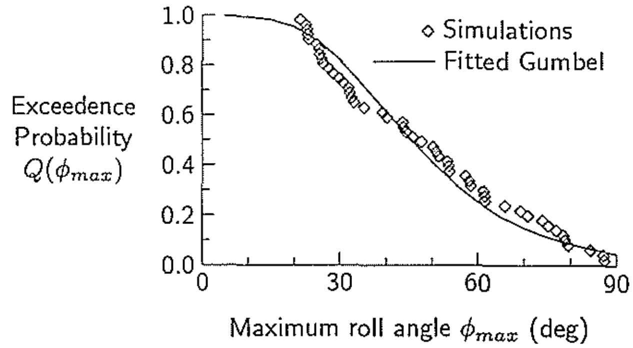

Figure 1: Roll Exceedence Probability for Frigate in One-Hour Seaway, V_s = 10 knots, β = 30 degrees, H_s = 10 m, T_z = 10 s

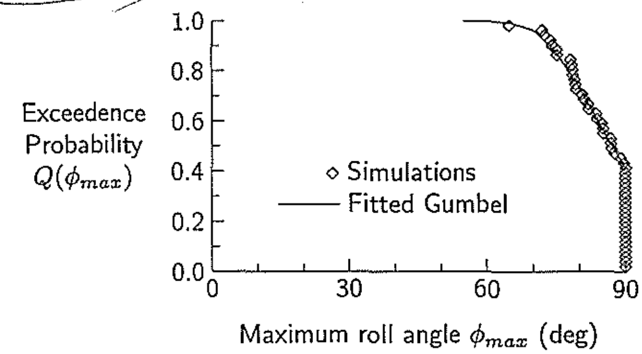

Figure 2: Roll Exceedence Probability for Frigate in One-Hour Seaway, V_s = 10 knots, β = 30 degrees, H_s = 12 m, T_z = 10 s

$$Q_{\phi_{max,D}}(\phi_{max,D}) = \sum_{i=1}^{N_{V_s}} \sum_{j=1}^{N_\beta} \sum_{k=1}^{N_{H_s}} \sum_{l=1}^{N_{T_z}} p_{V_s}(V_{s-i}) \times p_\beta(\beta_j)\, p_{H_s,T_z}(H_{s-k},T_{z-l}) \times Q_{\phi_{max,D}|V_s,\beta,H_s,T_z}(\phi_{max,D}|V_s,\beta,H_s,T_z) \quad (6)$$

INFLUENCE OF CAPSIZE AVOIDANCE BY OPERATOR

The risk analysis approach presented thus far does not consider efforts by the operator to reduce capsize risk. Weather routing and altering of course are two possible methods of reducing capsize risk. Faulkner and Williams [15] suggest that weather routing will not always reduce exposure to severe conditions. For a warship, mission requirements can provide a significant impediment to avoiding severe conditions.

Numerical simulations and experiments have shown that modern naval frigates are most susceptible to capsize when travelling at high speed in high following seas. Figure 3 taken from Reference 7 shows the conditional probability of heading given capsize, and indicates that capsize risk can be greatly reduced by altering course. Fortunately, the quantitative results are consistent with operator practice of altering course to head seas in severe conditions.

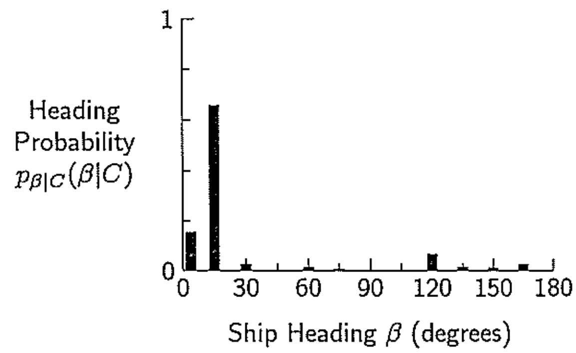

Figure 3: Conditional Probability of Ship Heading Given Capsize

Various researchers are examining ship operational records to determine operator actions in severe conditions. For example, Glen et al. [16] have recently completed a study for the Ship Structures Committee. Using operational profile data, it should be relatively simple to incorporate capsize avoidance behaviour into risk predictions by modifying Equation (3) to obtain:

$$
\begin{aligned}
P(C_D) &= \sum_{i=1}^{N_{V_s}} \sum_{j=1}^{N_\beta} \sum_{k=1}^{N_{H_s}} \sum_{l=1}^{N_{T_z}} p_{V_s|H_s}(V_{s-i}|H_{s-k}) \\
&\quad \times p_{\beta|H_s}(\beta_j|H_{s-k})\, p_{H_s,T_z}(H_{s-k}, T_{z-l}) \\
&\quad \times P(C_D|V_s, \beta, H_s, T_z) \qquad (7)
\end{aligned}
$$

The above equation neglects possible weather routing but considers altering of speed and course in response to significant wave height.

FUTURE PLANS

Work continues with the presented risk analysis procedure so that it can be used for routine engineering computations. Although the procedure has been implemented, there are several areas for refinement.

The properties of the Gumbel distribution suggest that simulation durations can be a fraction of the nominal seaway duration for which the capsize probability $P(C_D)$ is required. For example, it is possible that 10 simulations of 15 minute duration could be adequate to determine the statistical properties of maximum roll for a given seaway of 60 minute duration, thus permitting a significant reduction in computation time.

When applying the proposed risk analysis procedure, an acceptable level of capsize risk must be specified. Selection of an acceptable risk level is complicated by the fact that any risk analysis procedure gives risk predictions which are different from actual risk levels; thus, a risk analysis procedure usually has to be calibrated using past operational experience. The present proposed risk analysis method will likely be calibrated using operational data for naval ships which have had long service lives without any near capsizes.

As mentioned in the previous section, operator avoidance action will greatly reduce the risk of ship capsize. Equation (7) provides a promising approach for considering such avoidance action, and will likely be implemented as required operational profile data become available.

The ongoing validation and improvement of the Fredyn ship motion program will lead to improved capsize risk predictions. It is likely that Fredyn will eventually be superceded by another time domain code with a more sophisticated treatment of nonlinear and three-dimensional effects.

CONCLUSIONS

A rational method has been developed for predicting capsize risk of intact naval frigates. The method requires an accurate and efficient numerical model of ship motions in severe seas. The program Fredyn fulfills this role for naval frigates. For a ship in an irregular seaway, the occurrence of capsize can be highly dependent on the wave process realization. This effect can be effectively modelled by fitting a Gumbel distribution to maximum roll angles from several different seaway realizations. Future improvements to the risk model will include the effects of actions by ship operators to avoid ship capsize.

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