Estimating Probability of Capsize for Operator Guidance

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ABSTRACT

Ships that are routinely called upon to perform demanding missions that often require operation in extreme weather environments will benefit from the development of Heavy Weather Guidance (HWG). This guidance is intended to assist vessel operators in the selection of safe speed and heading in severe weather conditions, thereby reducing the probability of dynamic instabilities and potentially disastrous capsize events. A simplified method of estimating the encounter-dependent capsize probability based on the results of time domain simulations is outlined along with procedures to extend these estimates to fully characterize the time-dependency of the probability. Additionally, an alternative method of calculating capsize probability involving integration of the Joint Probability Density Function (JPDF) of wave height and length over a region of predicted critical waves.

Keywords: dynamic *stability; operator guidance; heavy weather; risk assessment; mission planning; capsize; probability*

1. INTRODUCTION

A single analytical ship motion and dynamic stability simulation results in a single coherent dataset that represents the motion response and extreme motion behavior for one loading condition and one wave description over a range of operating speeds and headings; however, environmental conditions and ship loading are constantly changing and evolving during a realistic operational scenario, the practical utility of any single dataset or simulation is limited at best. For active operator guidance, therefore, it is necessary to produce predictions based on the actual loading condition of the ship, and the current “real-time” sea conditions.

This presents a significant challenge in the design and development of an effective operational guidance strategy, particularly in the case of ships that are often called upon to operate in extreme environments for offshore patrol and search and rescue missions. Several potential solutions have been explored and found to possess significant limitations. Some of the more noteworthy approaches considered have included running time domain simulations onboard operational assets at sea, which gives highly accurate condition-specific results, but is too slow for timely guidance and therefore impractical. A second suggestion involved the development and maintenance of a catalog of previously generated polar plot bitmap images for a series of representative loading and seaway conditions, which could be referenced at sea to obtain approximate guidance on safe speed and heading based on the closest catalog condition. This approach eliminates the need for real-time simulation, but is both cumbersome for the end-user, and of questionable accuracy as the deviation between actual conditions and catalog conditions increases.

The approach presented by the authors combines the individual advantages of each approach discarded above by 1) providing results for actual real-time seaway and loading conditions, and 2) relying on a pre-existing database to increase the analytical speed. Specifically, a prototype Heavy Weather Guidance (HWG) module for the Flooding Casualty Control Software (FCCS) program utilizes an electronic interpolation methodology to generate polar plots of potential capsize conditions based upon input of real-time significant wave height, wave period and ship loading conditions. Numerical simulations are carried out ashore to develop a comprehensive matrix of ship-class-specific, dynamic response polar plots that are stored in an electronic database. The actual at-sea and loading conditions are used to develop a reasonable polar plot for use in real-time operational guidance or mission planning and routing purposes.

2. NUMERICAL SUMULATION AND ANALYSIS

2.1 Dynamic Stability Simulation

During the development of the HWG module and methodology, numerical simulations were carried out utilizing the large amplitude ship motion and maneuvering prediction program FREDYN, developed by the Maritime Research Institute Netherlands (MARIN) in conjunction with the Cooperative Research Navies (CRNAV) consortium, which includes representation from navies of the U.S., U.K., France, Canada, Australia, and the Netherlands, as well as the USCG.

FREDYN automates the solution of the six degree-of-freedom (6-DOF) equations of motion in the time-domain for a steered ship in regular or longcrested irregular waves, with or without wind contributions. The numerical models at the heart of the FREDYN program code have been extensively validated against both captive and free-running model tests for frigate type ships, which are in general reasonably similar in form, stability characteristics, and operational speed regimes as the ships considered in the present work.

2.2 Calculating Capsize Probability

The foundation of any operational guidance strategy ultimately lies in 1) the accurate characterization of the probability of capsize, or any other undesirable dynamic behavior, and 2) the translation of these probabilities into a useful decision aid based on a specified level of acceptable risk.

This requires a statistical extrapolation of a relatively limited set of short-term simulation results into a robust and accurate long-term measure of capsize probability. Although these calculations are transparent to the end-user, they form the basis of the polar plots at the heart of the HWG Module. Several new strategies for the calculation of capsize probability have been explored during the HWG developmental effort, including a simplified estimation technique, and a modification of an alternative method first proposed by de Kat et. al. (1994).

2.3 The Target Estimator Method.

The *Target Estimator Method* provides a simple direct-calculation procedure for the estimation of the *encounter-dependent probability of capsize* based on a set of simulation results, and it's subsequent extrapolation to fully characterize the *time-dependency* of the capsize probability.

As a first step in this process, the capsize probability per encountered wave, *p(c)*, is estimated based on a simulation series where N_C represents the number of capsize occurrences in N_S simulations of constant duration, T. This calculation is shown in eq. 1,

$$p(c) = 1 - \left(\frac{N_s - N_C}{N_S}\right)^{\left(\frac{T_e}{T}\right)} \tag{1}$$

where T_e represents the encounter period for the specific condition being investigated. T_e can be estimated based on the relationship shown in eq. 2, in which T_z represents the average zero-upcrossing period of the seaway, $V_{m/s}$ is the ship speed in meters per second, g is the acceleration of gravity and y is the vessel heading (0 deg = following seas).

$$T_e = \frac{T_Z}{1 - \left[\frac{2\pi V_{m/s}\cos(\gamma)}{gT_Z}\right]} \tag{2}$$

The calculation procedure defined in eq. 1 is readily extended to characterize the time-dependent probability of capsize, $P_T(t)$ utilizing the simple relationship contained in eq. 3, where t represents the expected exposure duration.

$$P_T(t) = 1 - [1 - p(c)]^{\left(\frac{t}{T_e}\right)} \tag{3}$$

The *Average Return Period*, or *Mean Time-to-Capsize*, μ_t, for this process is easily calculated as shown in eq. 4, while the variance of the time-dependent probability, σ^2_t, may be estimated as shown in eq. 5.

$$\mu_t = \frac{T_e}{p(c)} \tag{4}$$

$$\sigma_t^2 = \frac{P_T(1 - P_T)}{N_S} \tag{5}$$

The primary advantages of the *Target Estimator Method* are it's relative ease of use, and it's ability to characterize the time-dependency of the capsize probability based on known ship and seaway-related variables. Many other calculation techniques in use throughout the CRNAV community require fitted statistical distributions to characterize the time-dependent probability, which often rely on arbitrary shape, scale, and/or location parameters which have no real physical relationship to the ship or the seaway.

The *Target Estimator Method* has also been shown to provide generally excellent correlation with simulated capsize data for a 378 ft. High Endurance Cutter utilized as the baseline test case during the present work. This is illustrated in Fig. 1, which provides a comparison of time-dependent capsize probability estimates developed using the *Target Estimator Method* to actual simulated capsize occurrences for the 378 ft. Cutter at 15 knots and a heading of 15 degrees (near following seas) for a variety of severe seaway conditions. In Fig. 1, the plotted data points represent the cumulative fraction of individual FREDYN simulations that have capsized by a given time-step in each seaway, and the plotted lines reflect the use of the *Target Estimator Method* (e.g. a continuous plot of eq. 3, with exposure duration, *t*, treated as an independent variable). Similar levels of agreement have been observed for other speeds, headings, and seaway conditions as well.

2.4 Limitations of the Target Estimator Method.

Although the *Target Estimator Method* is both accurate and simple to use, it's range of practical application is restricted by the amount of simulation time required to produce reliable estimates in the operational range (e.g. speed-heading combinations) and seaway conditions for which capsize probability is relatively low.

For the most extreme sea states, where capsize probability is comparatively high, capsizes are encountered frequently during simulations, and as such a reasonable statistical sample can be obtained quite readily for use in a direct calculation of the incident capsize probability. On the other hand, when simulations take place in more mild environmental conditions, the amount of run-time required to achieve even a single capsize occurrence may be quite substantial. The run-time requirements are then magnified by the need to collect multiple capsize occurrences for a reasonable statistical sample. The complications presented by this issue become evident when typical levels of acceptable risk are considered.

2.5 Risk Assessment.

A proposed level of maximum acceptable annual risk, or annual probability of capsize, is given by McTaggart et. al. (2002) and Dahle and Myrhaug (1995) as approximately 1×10^{-4}. However, the time dependency of capsize risk is not addressed.

The author's contend that an evaluation of the climatology of extreme seas suggest that an exposure duration may be necessary to provide for an adequate level of safety. A possible source of exposure time frame may be determined from inspection of climatological data. A time-history of significant wave height and dominant (modal) period during Hurricane Katrina, measured at National Data Buoy Center (NDBC) station 42040 off the coast of Alabama in August 2005 is illustrated in Fig. 2. Very severe sea conditions, with significant wave heights above 10 meters, persisted for a duration of nearly 12 hours are clearly shown in Fig. 2. Likewise, conditions with significant wave heights greater than 8 meters persisted for more than 20 hours.

These trends are illustrated in more detail in Fig. 3 which shows the total duration of storm conditions as a function of significant wave height for Hurricanes Katrina and Ivan (also measured at NDBC station 42040 in September 2004).

Although a detailed treatment is not given in the present work, based on a review of historical archives available at NDBC, the seaway durations indicated by Figs. 2 and 3 are fairly typical of severe storm and hurricane conditions measured from a stationary reference (e.g. a tethered buoy).

Because an operational asset facing these types of conditions does not remain stationary, the correlation of historical seaway duration to operational exposure can not be performed on a one-to-one basis.

However, there is overwhelming evidence to suggest that operational exposures are likely to be substantially longer than one hour, should a vessel face this type of severe conditions.

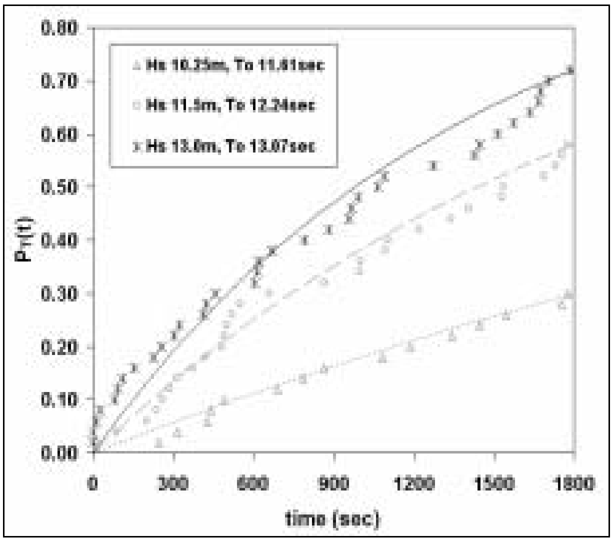

Figure 1. Correlation of Cumulative Time-to-Capsize Estimates made with the *Target Estimator Method* and Simulated Data

Based on the inspection of storm data, the author's would suggest that a cumulative probability of capsize of 1×10^{-2} in a 12 hour exposure period is reasonable to form the basis for short-term operational guidance. This assumes the acceptable level of risk is inversely proportional to exposure time and an annual probability of capsize is on the order of 1×10^{-4}. This is an area that requires further investigation.

2.6 Simulation Requirements.

Considering the fact that a typical time domain simulation series is composed of a unique, user-specified number of individual simulations, each of which is typically 30 minutes in duration, it is easy to develop an estimate of the simulation requirements to characterize a probability of capsize on the order of $1x10^{-2}$ for a 12 hour exposure period using the simple *Target Estimator Method* are substantial.

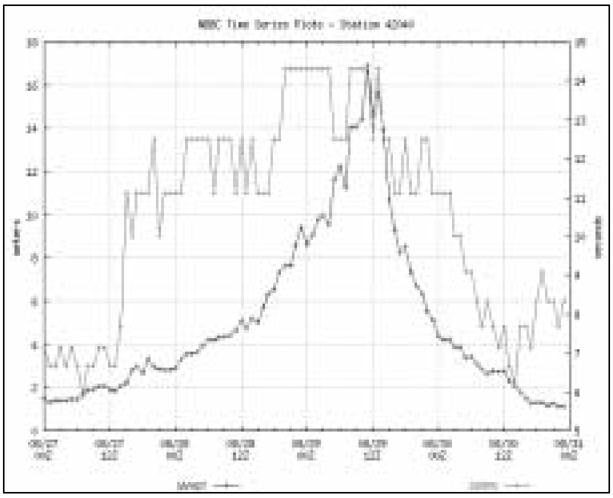

Figure 2. Hurricane Katrina Seaway Data

This fact is illustrated in Fig. 4, which shows the cumulative time-dependent probability levels calculated based on a single realized capsize occurrence for varying numbers of 30-minute simulations, assuming a constant encounter period slightly greater than 11 seconds. Although the assumption of constant encounter period in the development of Fig. 4 is not strictly valid, considering the variations shown in the number of simulations required to achieve a single capsize event, it is utilized to illustrate the basic order of magnitude of the problem only.

Inspection of Fig. 4 clearly demonstrates that more than 1,000 simulations would be required to provide the data necessary to characterize a cumulative capsize risk on the order of $1x10^{-2}$ for any appreciable exposure duration. Furthermore, since all time domain data contained in the present work is based on multiples of discrete, 30 minute simulations, the number of simulations indicated by Fig. 4 is approximately twice the total simulation time required to capture one simulated capsize event, in hours.

For a complete statistical sample, there will need to be even more simulations run (10 to 100 times more). If $1x10^{-2}$ the number of time domain simulations is very large, but feasible given current processing capabilities.

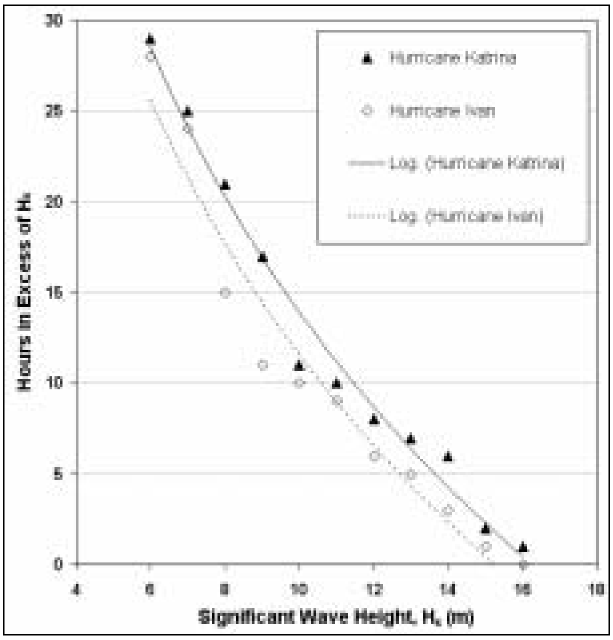

Figure 3. Duration of Extreme Sea Conditions for Recent Major Hurricanes

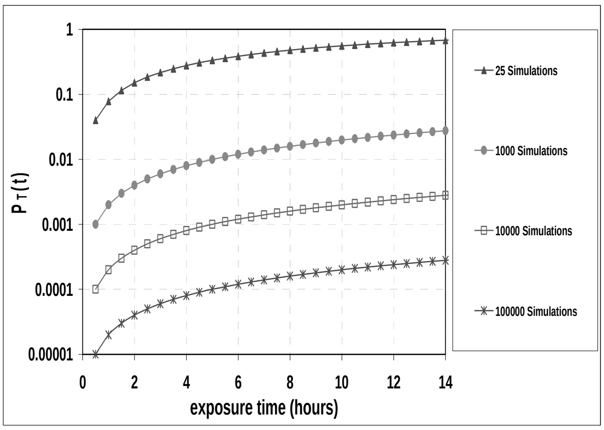

Figure 4. Time dependant probabilities for a single capsize occurrence in a varying number of simulations

2.7 The JPDF Integration Method.

As an alternative to direct-calculation method for the estimation of capsize probability, the authors considered an approach proposed by de Kat et. al. (1994) that offers the potential for less simulation duration requirements. Briefly, this approach involves:

a) running time domain simulations for a series of severe seaway conditions, and characterizing the localized wave height and length producing a capsize event. This is accomplished through an evaluation of the time-dependent spatial wave conditions in the vicinity of the ship immediately prior to a capsize event,
b) cataloging the wave characteristics associated with each simulated capsize event, such that, as many capsizes occurrences are collected, a deterministic region of "critical wave" parameters is defined within the generalized domain of wave height and length,
c) estimating the probability of occurrence of individual waves in a target seaway using a Joint Probability Density Function (JPDF) of wave height and length, and,
d) integrating the JPDF over the "critical wave" region to estimate the probability capsize for the target seaway.

This approach is repeated for each specified set of ship conditions (loading, speed, heading, etc.) in order to provide a comprehensive database of capsize probability calculations that form the basis of real-time operational guidance.

To facilitate these calculations, the JPDF may be approximated using the approach described in Longuet-Higgins (1983), or alternatively, an "exact distribution" may be computed for a Gaussian wave process as advocated by Rychlik et. al. (2004). Although the "exact" method of developing the JPDF is more accurate from a physical standpoint, the Longuet-Higgins approximation remains convenient for computational simplicity, given it's reliance on a straightforward and easy to use mathematical relationship, as shown in eq. 6,

$$p(R,\tau)=\left(\frac{2}{\pi^{1/2}\nu}\right)\left(\frac{R^2}{\tau^2}\right)e^{-R^2\left[1+\frac{(1-1/\tau)^2}{\nu^2}\right]}L(\nu) \qquad (6)$$

in which R and τ are non-dimensional references to wave height and period, such that,

$$R=\frac{H}{2(2m_0)^{1/2}} \qquad (7)$$

$$\tau=\frac{T}{T_1} \qquad (8)$$

where H is the wave height, T is the wave period, and m_0 and T_1 are the variance (i.e. zero[th] spectral moment) and average period of the seaway, respectively.

The JPDF calculation in eq. 6 is also dependent upon a spectral width parameter, ν and a normalization factor $L(\nu)$, in which,

$$\nu=\left(\frac{m_0 m_2}{m_1^2}-1\right)^{1/2} \qquad (9)$$

$$L(\nu)=\frac{2}{1+(1+\nu^2)^{-1/2}} \qquad (10)$$

where m_n is the n^{th} spectral moment of the seaway.

Because a spatial wave analysis is utilized in the definition of "critical wave" characteristics, the "critical" parameters are given in terms of wave height and length. Therefore, to allow for a one-to-one correlation, the calculated JPDF of wave height and period shown in eq. 6 is converted to the space domain according to the basic dispersion relationship, given in eq. 11.

$$L=T^2\,\frac{g}{2\pi} \qquad (11)$$

Although the application of the dispersion relationship is valid for simple harmonic (regular) waves, this relationship is generally not satisfied for an irregular seaway, except as an approximation for an extremely narrowband sea. However, use of this relationship remains relatively common for this type of analysis, mainly for convenience in the transformation of wave characteristics from time records to the space-domain, even if not strictly valid. In this case, the author's feel that the proposed method is sufficient to support a basic "engineering solution" to the estimation of capsize probability, without requiring unrealistically extensive simulation requirements.

2.8 Limitations of the 1994 JPDF Integration Method.

A key component of the de Kat et. al. (1994) JPDF integration methodology involves the contention that the probability that "critical" conditions exists in any given seaway is equal to the encounter-dependent probability of capsize. This is equivalent to a statistical assumption that any single wave occurrence falling within the range of "critical" parameters will result in a capsize event.

Early evaluations supporting the present effort have indicated that estimates made utilizing this assumption result in an overestimation of capsize probability by approximately an order-of-magnitude for a 378 ft. High Endurance Cutter, when compared to corresponding estimates developed with the previously described Target Estimator Method, for sea states in which adequate capsize data is available. Similar findings have also been reported by Leadbetter and Rychlik (2005).This suggests that, at least for this particular ship class, many of the so-called "critical waves" can be encountered without resulting in a capsize.

2.9 Current Innovation: The Capsize Region Transfer Function.

In order to eliminate the order-of-magnitude overestimates in the calculation of capsize probability observed utilizing the original methodology proposed by de Kat et. al. (1994), Stambaugh and Eisele have developed a *Modified JPDF Integration Approach*. The primary innovation in the newly proposed methodology involves the definition of a *Capsize Region Transfer Function* (CRTF), which modifies the calculated JPDF of wave height and length to account for "critical wave" encounters which do not result in capsize. The author's liken this approach to the utilization of Response Amplitude Operators (RAO's) to translate sea spectra into derived responses in frequency domain seakeeping analysis, the only difference being that the CRTF is defined in three-dimensional space over the generalized domain of wave height and length.

For the purposes of mathematical simplicity, the first step in the modified approach involves the discretization of the JPDF of wave height and length into "bins" measuring 1 meter in wave height by 0.2xLBP in wave length, primarily to facilitate calculation in a simplified spreadsheet format, and to allow for subsequent modification by the empirical CRTF.

The CRTF itself is then generated concurrently with the definition of the "critical wave" region. Specifically, as capsizes are collected during a simulation series consisting of N_S simulations for a specific baseline seaway condition, the spatial wave analysis introduced in the original de Kat (1994) methodology is carried out as usual to identify the "critical" parameters associated with each capsize wave. The capsize wave occurrences are then organized in "bins" of wave height, H_j, and wave length, L_k, consistent with those utilized in the characterization of the discretized JPDF, such that as many capsizes are collected, a three dimensional histogram of capsize occurrences, $N_C\ (H_j\ ,L_k)$, is generated.

In addition to the collection of "critical wave" characteristics, the simulation time step at capsize is also recorded for each occurrence during the simulation series as $t_1, t_2, \ldots, t_{Nc}$ where N_C represents the total numbers of observed capsizes. Where a capsize does not occur for any particular simulation within the series, the total simulation duration, T_{sim}, is recorded, such that when eq. 12 is applied, the total simulated exposure duration for the baseline seaway, T_{exp}, is characterized.

$$T_{\exp} = \sum_{i=1}^{N_C} t_i + \left(N_S - N_C\right) T_{sim} \tag{12}$$

Based on this exposure duration, the total number of waves encountered during the simulation series, N_e, follows as shown in eq. 13, where T_e represents the encounter period.

$$N_e = \frac{T_{\exp}}{T_e} \tag{13}$$

The total number of wave encounters in the simulation series are then distributed into similar discrete "bins" in the generalized domain of wave height and period using eq. 14, such that a second three dimensional histogram, $N_W(H_j, L_k)$, is created,

$$\begin{gathered} N_W(H_j, L_k) = JPDF(H_j, L_k) \times N_e \\ for \;\; j = 1..N_{hb} \;\; and \;\; k = 1..N_{lb} \end{gathered} \tag{14}$$

where N_{hb} and N_{lb} represent the discrete number of wave height and wave length "bins", respectively, and $JPDF(H_j, L_k)$ represents the joint distribution of wave height and length for the baseline seaway, calculated in accordance with eq. 6. Note that the parameters H_j and L_k in this relationship represent the individual wave height and wave length "bins", respectively.

The process of time domain simulation, and subsequent characterization of capsize and wave occurrence histograms is repeated for several baseline seaway conditions, until a reasonable set of capsize data has been obtained for the specific speed-heading combination under investigation. Current practice includes 50 individual runs of 30 minute duration, for a total of five to six steep seaway conditions located along the Buckley (1988) "envelope of extremes", where capsizes generally occur more frequently. The three dimensional histograms of capsizes occurrences and total wave encounters developed for each individual baseline seaway are then summed to result in an aggregate characterization of capsizes and wave encounters for all simulations made at a specific speed and heading combination is repeated for several baseline seaway conditions, until a reasonable set of capsize data has been obtained for the specific speed-heading combination under investigation. Current practice includes 50 individual runs of 30 minute duration, for a total of five to six steep seaway conditions located along the Buckley (1988) "envelope of extremes", where capsizes generally occur more frequently. The three dimensional histograms of capsizes occurrences and total wave encounters developed for each individual baseline seaway are then summed to result in an aggregate characterization of capsizes and wave encounters for all simulations made at a specific speed and heading combination.

The composite histograms are utilized to compute the CRTF for a specific speed and heading in accordance with eq. 15.

$$\begin{gathered} CRTF(H_j, L_k) = \frac{N_C(H_j, L_k)}{N_W(H_j, L_k)} \\ for \quad j = 1 \ldots N_{hb} \quad \text{and} \quad k = 1 \ldots N_{lb} \end{gathered} \tag{15}$$

This process is illustrated graphically in Fig. 5. Note that for the sample shown in Fig. 5, the majority of capsizes resulted from wave conditions with heights ranging between 7 and 10 meters, and wave lengths between 0.8 and 1.0 times the ship length. However, the total number of wave encounters in this region is also relatively high, and in fact only a small fraction (~10%) of these encounters actually resulted in a simulated capsize event, therefore the computed CRTF is also relatively low in this area. On the other hand, only a handful of simulated capsize events resulted from waves greater than or equal to 16 meters in height, but the total wave encounters exhibiting these characteristics was also very low, and therefore the CRTF is comparatively high in this region.

Once the CRTF has been developed for a particular speed and heading of interest, based on a relatively small sampling of baseline seaway conditions along the Buckley (1988) "envelope of extremes", no additional simulation is required to characterize the *encounter-dependent* probability of capsize, *p(c),* for any other target seaway. This calculation is carried out strictly through mathematical variation of the JPDF of wave height and wave length for the target seaway, as shown in eq. 16.

$$p(c) = \sum_{j=1}^{N_{lh}} \sum_{k=1}^{N_{lb}} \left[JPDF_{target}(H_j, L_k) \times CRTF(H_j, L_k) \right] \cdot dH \cdot dL \qquad (16)$$

where $JPDF_{target}(H_j,L_k)$ is the discretized joint probability density function of wave height and wave length for the target seaway condition, calculated using eq. 6, and *dH* and *dL* are the discrete "bin" dimensions for wave height and wave length, respectively. The time-dependency of the capsize probability can then be characterized using eq. 3. The procedure for calculating probability of capsize for a target seaway utilizing the CRTF in accordance with eq. 16 is illustrated graphically in Fig. 6.

Comparisons between the CRFT approach and the target estimator approach are presented in Table 1. There is a variability of results with wave height resulting from the statistical effects of the presence of multiple waves and ship dynamic memory effects. However, results are conservative for smaller seaways with low probability of capsize or interest for operator guidance. Recent work with a slope based CRTF shows promise in minimizing the variation with wave height. This should be the subject of additional investigation.

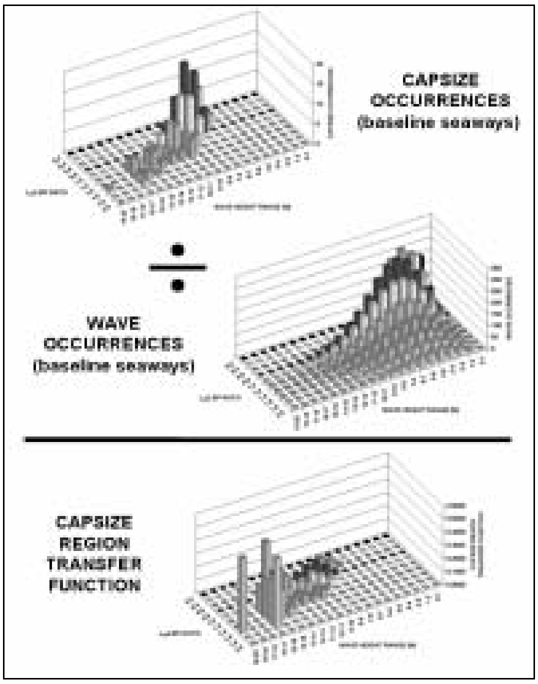

Figure 5. Capsize Region Transfer Function (CRTF) Development

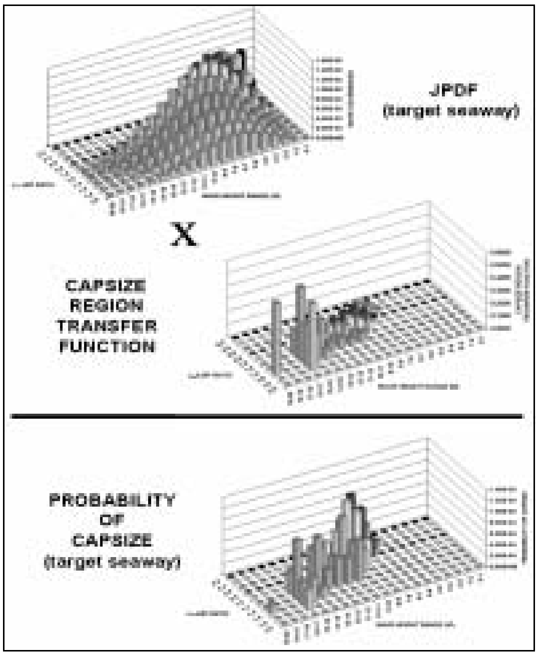

Figure 6. Use of the CRTF to calculate capsize probability

Table 1 Comparison of Probability of Capsize Calculation

	Seaway and Simulation Parameters						Target Estimator Method		Modified JPDF Integration Method	
	H_S [m]	T_m [sec]	T_Z [sec]	T_p [sec]	N_c	N_S	p(c)	$P_T(t)$ for t=1 hr	p(c)	$P_T(t)$ for t=1 hr
45 degrees	7.50	8.98	7.46	14.03	19	50	3.72E-03	6.16E-01	8.97E-03	9.91E-01
	9.00	10.07	8.12	14.28	34	50	6.98E-03	8.88E-01	1.35E-02	9.99E-01
	10.25	11.61	8.62	14.58	45	50	1.84E-02	9.99E-01	1.69E-02	9.99E-01
	11.50	12.34	9.05	14.74	48	50	3.15E-02	1.00E+00	2.01E-02	9.99E-01
	13.00	13.07	9.61	15.18	50	50	4.90E-02	1.00E+00	2.23E-02	9.99E-01
18 degrees	9.00	10.07	8.12	15.71	11	50	2.72E-03	3.50E-01	5.59E-03	6.41E-01
	10.25	11.61	8.61	18.32	15	50	3.62E-03	5.10E-01	7.49E-03	7.54E-01
	11.50	12.34	9.05	18.16	29	50	9.19E-03	8.24E-01	8.73E-03	8.07E-01
	13.00	13.07	9.61	18.18	38	50	1.34E-02	9.22E-01	8.88E-03	8.18E-01
	14.00	13.56	9.96	18.13	39	50	1.60E-02	9.52E-01	8.76E-03	8.09E-01

3. CONCLUSIONS

This paper has summarized an approach for the estimation of probability capsize based on numerical simulation using a time-domain ship motion and maneuvering program for use with an operator Heavy Weather Guidance (HWG) system.

New approaches for the calculation and interpretation of the probability of capsize have been presented, along with a strategy for the use of these probabilities as an operational decision aid based on recommendations for acceptable levels of short-term risk.

Based on the work presented herein, the following conclusions are presented:

a) The time domain capsize prediction technique proposed is suitable for predicting the general capsize and dynamic stability behavior necessary for effective Heavy Weather Guidance.

b) The estimation of capsize probabilities are now possible based on the time domain simulations using estimated capsize probabilities from a discrete number of time domain simulations and developing a capsize transfer function for wave parameters in combination with a JPDF for a given seaway. Although refinements to the approach are necessary, the general approach is certainly worth further investigation.

c) Additional effort is required to evaluate the acceptable level of capsize probability for short term operator guidance applications.

4. ACKNOWLEDGEMENTS

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The opinions expressed herein are those of the authors and do not represent official policy of the U.S. Coast Guard.

5. REFERENCES

Buckley, W.H., September 1988, "Extreme and Climatic Wave Spectra for use in Structural Design of Ships." *Naval Engineers Journal*.

Dahle, E.A., and Myrhaug, D. October 1995. "Risk Analysis Applied to Capsize of Fishing Vessels," *Marine Technology*.

De Kat J.O., Brouwer, R., Mctaggart, K., and Thomas, W.L. 1994 "Intact Ship Survivability in Extreme Waves: Criteria from a Research Navy Perspective," STAB 94, *Fifth International Conference on Stability of Ships and Ocean Vehicle*, Melbourne, Florida.

Leadbetter, M.R., and Rychlik, I. April 2005, "Capsize Prediction Based on Wave Statistics," USCG Task Report.

Longuet-Higgins, M.S. 1983, "On the Joint Distribution of Wave Periods and Amplitudes in a Random Wave Field," *Proceedings of the Royal Society of London*, A 389, pp 241-258.

Mctaggart, K., Carnie, P., Witzke, D., and Maze, R. 2002, "Capsize Probability Polar Plots for Ship Operator Guidance," *Proceedings of the 2002 Stability Workshop*, Webb Institute.

Michel, W.H. Winter 1999, “Sea Spectra Revisited,” *Marine Technology*, Vol. 36, No. 4, pp. 211-227.

Rychlik, I., et., al., 2004, “Wave Analysis for Fatigue and Oceanography: A toolbox of Matlab routines for statistical analysis and simulation of random waves and loads,” Version 2.1.0, Mathematical Statistics Department, Lund University.