# Regular Wave Testing as a Crucial First Step for Dynamic Stability Evaluation

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**ABSTRACT**

The DDG51 pre-contract hull form as represented by Model 5514 was evaluated for capsize events at End of Service Life Load Limit for the Righting Arm Limiting and Intact 100 Knot Wind Limiting KG Conditions. The hull was evaluated using a matrix of various following sea headings and Froude Numbers at various regular wave lengths and steepness. The results provide a good comparison point to computer simulations and a way to verify regimes of concern as relates to dynamic stability. The domains of reduced dynamic stability can be used to determine future areas of study for random or deterministic irregular wave testing. The model test also provides data to compare measured roll decay and maneuvering characteristics against simulation predictions for validation. Experimental techniques and model layout are described. Suggestions for future improvements in regular wave testing are provided. Even though regular wave dynamic stability testing provides a basic evaluation of dynamic stability, the results can be used as a key starting point for additional testing or as a basis for operational guidance.

**KEYWORDS**

Regular Waves, Parametric Evaluation, Dynamic Stability

## INTRODUCTION

Laboratory testing for dynamic stability can assume many forms, with different type of wave environments. A free running or very lightly tethered model, will yield the purest results when testing for 3-D dynamic stability events. Instrumentation should be suitable to capture all motions, control surfaces, and the wave environment. With respect to waves the experiment can utilize steep regular waves, random irregular waves with a spectral shape known to produce steep wave fronts by the nature of the height and period, or deterministic irregular wave sequences. At its simpliest level a free running model operating in dynamic stability type conditions in regular waves can provide great insight to performance in other more realistic seaways. This type of testing will be described.

## EXPERIMENT DESIGN

### *Model Scale and Facility*

Selection of model scale is typically based upon need to get waves with sufficient steepness at wavelengths likely to create a dynamic stability event. The ability to achieve speed, power and instrument the model, and provide sufficient run length should be considered in model scale selection. The ability to meet the data and control needs and still meet ballast conditions is often the most challenging part of preparation. Model 5514 is a ten foot model requiring vigilance with respect to ballasting. But when testing at end of service life (EOSL) the ballast condition is much more obtainable. The model operating in the basin is shown in Figure 1. The MASK provides a long run length suitable to initiate dynamic stability events in regular waves, and still generally have time for the dynamic event to occur prior to reaching the edge of the basin. Plastic net fences are installed along the beach edges of the basin to capture the model in the event that the model operator can not stop the model in time. The schematic of the MASK basin is shown in Figure 2.

### *Test Matrix*

The test matrix can be designed based upon simulations or past experimental experiences with the conditions which cause dynamic stability events. The most likely wave conditions to cause dynamic stability events are λ/L values surrounding 1.0. For this test λ/L values from 0.75 to 1.50 had been choosen for testing, with wave steepnesses ranging from H/λ=1/20 to H/λ=1/10.

**Figure 1. View of Model 5514 During Capsize Testing In MASK Basin.**

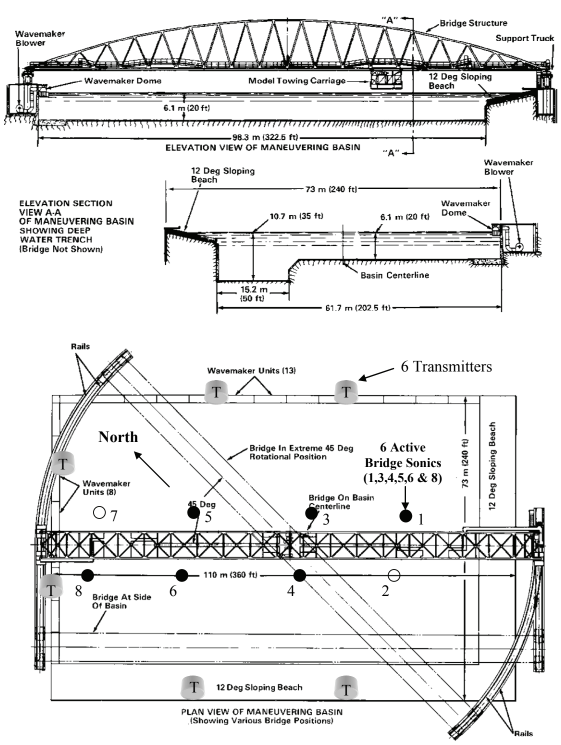


**Figure 2. Sketch of Maneuvering and Seakeeping (MASK) Basin.**

The corresponding target regular wave heights are provided in Table 1. The model was tested at speeds of Fn=0.0, 0.1, 0.2, 0.3, and 0.4. Headings aft of beam to pure following were tested. In this case the conditions tested were based upon simulation results from FREDYN 9.3.

***Instrumentation***

I Instrumentation should be sufficient to capture the motions of interest required to define the event. Accelerations were measured at the center of gravity (CG), bow, and stern. Angular rates, roll, pitch, and heading via a gimbaled flux-gate compass were used to measure angular characteristics. The rudder was measured via a rotary potentiometer, and shaft RPM was measured via optical pulsor and a in-house circuit board with an Analog Devices F to V Converter. The wave environment was recorded with six sonic wave surface probes suspended from the MASK bridge. The bridge was rotated to a 30º angle to provide better basin wave probe coverage. The model position and track were recorded with an ArcSecond Constellation 3DI indoor GPS system. A single ArcSecond receiver was placed on the forward deck of the model and is visible in Figure 1. The approximate spacing and position of the wave sonics and ArcSecond transmitters are shown in Figure 2. The instruments were filtered, sampled, and stored via and on board computer (OBC) and associated filter cards and analog to digital converter (ADC). The OBC and some of the CG instruments are shown in Figure 3.

**Figure 3. Midship OBC, GM Pole, and instruments.**

**Table 1. Desired Wave Conditions as Defined by Test Matrix and Model Geometry.**

**Full Scale Test Conditions**

**Ship Length : 466.00 ft**

| Wave/Hull Length | Wave Length (ft) | Wave Length (m) | Wave Period (sec) | Wave Freq (Hz) |
|---|---|---|---|---|
| 0.75 | 349.50 | 6.71 | 8.26 | 0.1210 |
| 1.00 | 466.00 | 8.95 | 9.54 | 0.1048 |
| 1.25 | 582.50 | 11.18 | 10.67 | 0.0938 |
| 1.50 | 699.00 | 13.42 | 11.68 | 0.0856 |

**Model Scale Conditions - lambda = 46.6**

**Ship Length : 10.00 ft**

| Wave/Hull Length | Wave Length (ft) | Wave Length (m) | Wave Period (sec) | Wave Freq (Hz) |
|---|---|---|---|---|
| 0.75 | 7.50 | 2.29 | 1.210 | 0.826 |
| 1.00 | 10.00 | 3.05 | 1.398 | 0.716 |
| 1.25 | 12.50 | 3.81 | 1.563 | 0.640 |
| 1.50 | 15.00 | 4.57 | 1.712 | 0.584 |

| Wave Heights | | | | |
|---|---|---|---|---|
| | Wave Length / Hull Length | | | |
| Wave H/L | 0.75 | 1.00 | 1.25 | 1.50 |
| 1/20 | 11.4 cm | 15.2 cm | 19.1 cm | 22.9 cm |
| 1/15 | 15.2 cm | 20.3 cm | 25.4 cm | 30.5 cm |
| 1/10 | 22.9 cm | 30.5 cm | 38.1 cm | 45.7 cm |
| | Wave Length / Hull Length | | | |
| Wave H/L | 0.75 | 1.00 | 1.25 | 1.50 |
| 1/20 | 4.50 in | 6.00 in | 7.50 in | 9.00 in |
| 1/15 | 6.00 in | 8.00 in | 10.00 in | 12.00 in |
| 1/10 | 9.00 in | 12.00 in | 15.00 in | 18.00 in |

## EXPERIMENTAL PROCEDURE

### *Pre Experiment Preparation*

Prior to testing the model was outfitted and ballasted. The powering and steering systems were somewhat fixed based upon the ship arrangements. The instrument location was fixed for those channels to be measured at a specific location. The OBC and batteries were then located to provide the approximate CG and gyradius characteristics. The remaining ballast weights were used to fine tune the ballast conditions. Additionally a pole is located at the longitudinal CG (LCG) location with weights which can be slid up and down the pole to adjust the metacentric height (GM). The GM pole was located to have minimal effect on other desired ballast variables. The GM was verified by performing an incline experiment. The results of the ballasting effort are shown in Tables 2 and 3.

### *Model Characterization Runs*

The roll period and roll decay were measured at all speeds to be tested. This measurement procedure was performed by depressing the model on the gunwale while the model is lightly tethered under the MASK carriage, then releasing the model and measuring the roll decay after release. This procedure was repeated for both port and starboard sides, and for varying angles of initial roll. The roll period and amount of roll decay can be used to compare against anticipated roll period and roll decay from simulation. The difference between measured roll period and FREDYN calculated roll period is also used as a way to adjust the coefficients of the autopilot algorithm at the operational speeds.

The speed of the free running model was set by performing a calm water speed calibration. The hall-effect motors were controlled with a voltage command from the OBC. The model was run at set voltage commands parallel to the long bank of the MASK across a measured distance. This is done for 12 to 20 speed increments across the range of operation. Crurve fits were then performed relating measured speed, shaft RPM, and throttle command. The throttle commands at each target speed can then be calculated and used to set the target at each matrix condition of concern. Once the calm water roll periods and speed settings were defined, then other operations of the test matrix could be performed.

**Table 2. Model Mass Properties End of Service Life Load Limit, Intact 100 kt Wind Limiting KG**

| | FULL SCALE DESIRED | | MODEL SCALE ACHIEVED | |
|---|---|---|---|---|
| | Values English | Values Metric | Values English | Values Metric |
| **Displacement** | 9400.00 LTSW | 9549.21 m-ton SW | 202.46 lbs FW | 91.92 kg FW |
| **LCG wrt Station 10** | -5.90 ft | -1.80 m | -1.52 in | -3.86 cm |
| **KG** | 28.06 ft | 8.55 m | 7.12 in | 18.08 cm |
| **Draft** | 21.37 ft | 6.51 m | NA | NA |
| **Trim** | 0.36 ft | 0.11 m | NA | NA |
| **$GM_{w/FS}$** | 3.00 ft | 0.91 m | 0.76 in | 1.93 cm |
| **$k_{pitch}$** | 116.50 ft | 35.51 m | 29.73 | 75.52 cm |
| **$k_{pitch}$/LBP** | 0.250 | 0.250 | 0.248 | 0.248 |
| **$k_{roll}$** | 24.09 ft | 7.34 m | 6.67 | 16.94 cm |
| **$k_{roll}/Beam_{WL}$** | 0.383 | 0.383 | 0.412 | 0.412 |
| **Roll Period $_{Zero\ Speed}$** | 15.41 | 15.41 | 2.421 sec | 2.421 sec |

**Table 3. Model Mass Properties End of Service Life Load Limit, Righting Arm Limiting KG**

| | FULL SCALE | | MODEL SCALE ACHIEVED | |
|---|---|---|---|---|
| | Values English | Values Metric | Values English | Values Metric |
| **Displacement** | 9400.00 LTSW | 9550.85 m-ton SW | 202.46 lbs FW | 91.92 kg FW |
| **LCG wrt Station 10** | -5.90 ft | -1.80 m | -1.52 in | -3.86 cm |
| **KG** | 26.97 ft | 8.22 m | 6.81 in | 17.29 cm |
| **Draft** | 21.37 ft | 6.51 m | NA | NA |
| **Trim** | 0.36 ft | 0.11 m | NA | NA |
| **$GM_{w/FS}$** | 4.09 ft | 1.25 m | 1.04 in | 2.63 cm |
| **$k_{pitch}$** | 116.50 ft | 35.51 m | 29.65 | 75.31 cm |
| **$k_{pitch}$ /LBP** | 0.250 | 0.250 | 0.247 | 0.247 |
| **$k_{roll}$** | 24.09 ft | 7.34 m | 6.29 | 15.97 cm |
| **$k_{roll}$ /$Beam_{WL}$** | 0.383 | 0.383 | 0.388 | 0.388 |
| **Roll Period $_{Zero\ Speed}$** | 13.19 | 13.19 | 1.971 sec | 1.971 sec |

### *Maneuvering Runs*

Though not required for dynamic stability, the calm water maneuvering characteristics as measured by turning circles and zig-zags can be quite useful for comparison against simulation efforts. The effects of the control surfaces, bilge keels, and ballast condition are all interrelated and present when performing calm water maneuvers. These results provide a way to look at scale effects, and how such influences correlate during simulations and other scaled tests. Both turning circles and zig-zags were performed as presented by Hayden, et.al. (2006).

### *Regular Wave Runs*

Regular wave dynamic stability runs were performed at the conditions of interest. The model was held stationary from a punt at the edge of the basin while the desired wave field was allowed to build. The model operator would set the autopilot heading, and bring the props up to speed using the pre-determined throttle command. Model tenders in the punt would hold the model at the desired heading relative to the waves, and then release the model on command from the model operator once there was sufficient wave coverage in the basin. The tracker data, model and wave data collection, and video would start prior to model release in order to record intital conditions. The model would accelerate away from the punt after release. The operator would make a verbal and computer collection note ("Model Mark") when the model was on speed and heading.

The model would be allowed to translate the basin using the autopilot and throttle commands until capsize occurred or it was necessary to stop the model because of basin limitations. Additional personnel would observe the model and make notes of surf, broach, wave captures, bow roots, or other roll events indicative of dynamic instabilities. The model operator would declare end of run to the video and data personnel. Example of a tracker image for a capsize event (Run 396) in following seas at Fn=0.4, λ/L=1.25, H/λ=1/10 is shown in Figure 4. Evidence of the surf, broach, capsize event can be evidenced by the curved trajectory at the end of the run.

All pre-defined test conditions were performed a minimum of one time. If crititcal dynamic stability behavior was present for a condition, then that condition would be repeated. If a capsize or dangerous roll was observed, then the conditon would be repeated three or more times. If the model consistently capsized, then that condition would be labeled as a capsize condition. If dangerous roll consistently occurred, but capsize did not always occure, then that condition would be classified as "In Danger of Capsize". "Dangerous Roll" was classified as any maximum roll greater than 75% of the positive area under the GZ curve.

## RESULTS

The results of the test were presented as performance matrices which summarized the run numbers, maximum rolls, wave conditions, and comparison to FREDYN results for each test condition. Maximum roll matrices are presented for both load condition in Tables 5 and 6. Each roll value corresponds to an individual run. Individual capsizes and dangerous rolls are indicated at each cell with color coded text. The cell was classified based upon the predominate behaviour at that cell condition.

The comparison to FREDYN 9.3 results is presented in Tables 7 and 8. It can be seen that FREDYN generally overpredicts the capsize event for the typical surface combatant.

## UNCERTAINTY ANALYSIS

Uncertainty analysis as applied for this report is based upon the ISO Uncertainty Guide (1995). The analysis consists of two parts: (1) Type A evaluation and (2) Type B evaluation. For this report, all uncertainties are defined at the 95 % confidence limit. Typically, these experiments were highly unsteady and random in character, and the standard deviations were not typically computed. Consequently, most of the uncertainty was determined by Type B evaluation method.

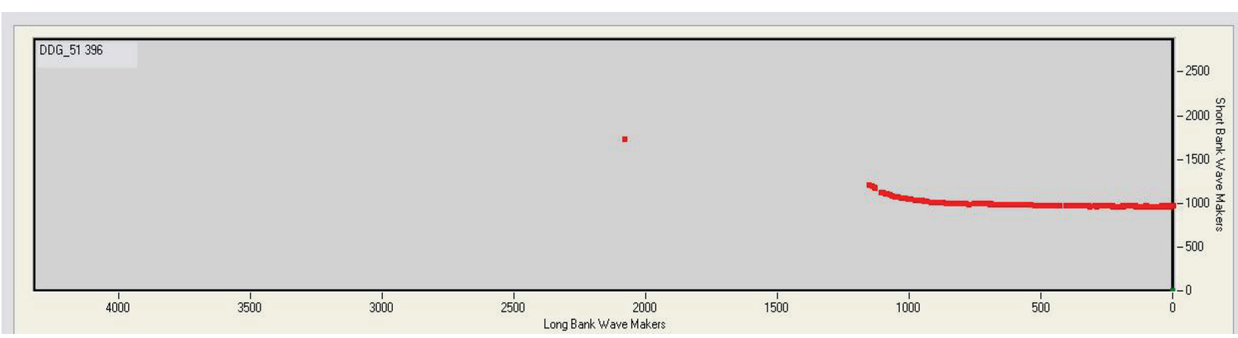


**Figure 4. Example Tracker Plot for Run 396.**

**Table 4. Uncertainty Estimates for Instrumentation.**

| | | | | Type A Uncertainty * | | | Type B | Total | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Parameter** | **Units** | **Min** | **Max** | **N** | **Std Dev** | **U95** | **U95** | | **(% Max)** |
| Acceleration, bow transverse | g | -1 | +1 | 321 | 0.00668 | 0.0007 | 0.0081 | 0.0082 | 0.82 |
| Acceleration, bow vertical | g | -1 | +1 | 321 | 0.00379 | 0.0004 | 0.0010 | 0.0011 | 0.11 |
| Acceleration, cg longitudinal | g | -1 | +1 | 321 | 0.00049 | 0.0001 | 0.0020 | 0.0020 | 0.20 |
| Acceleration, cg transverse | g | -1 | +1 | 321 | 0.00649 | 0.0007 | 0.0033 | 0.0033 | 0.33 |
| Acceleration, cg vertical | g | -1 | +1 | 321 | 0.00236 | 0.0003 | 0.0108 | 0.0108 | 1.08 |
| Acceleration, stern transverse | g | -1 | +1 | 321 | 0.00694 | 0.0008 | 0.0098 | 0.0098 | 0.98 |
| Acceleration, stern vertical | g | -1 | +1 | 321 | 0.00337 | 0.0004 | 0.0209 | 0.0209 | 2.09 |
| Angle, Pitch | deg | -50 | +50 | 321 | 0.177 | 0.0198 | 0.64 | 0.64 | 1.28 |
| Angle, Roll | deg | -90 | +90 | 321 | 0.370 | 0.0413 | 0.77 | 0.77 | 2.67 |
| Angle, Rudder | deg | -30 | +30 | 321 | 0.029 | 0.0033 | 0.80 | 0.80 | 2.67 |
| Heading | deg | 0 | 360 | 321 | 0.733 | 0.0818 | 1.00 | 1.07 | 0.28 |
| Model Speed | m/s | 0.55 | 2.19 | 321 | 0.00836 | 0.0009 | 0.12 | 0.12 | 5.66 |
| Propeller Shaft Speed | rpm | 264 | 1093 | 321 | 4.28 | 0.48 | 1.78 | 1.84 | 0.17 |
| Rudder Angular Rate, Max. | deg/s | -67.5 | +67.2 | | | | 1.61 | 1.61 | 2.40 |
| Wave Height #1 | mm | -381 | +381 | | | | 2.29 | 2.29 | 0.60 |
| Wave Height #3 | mm | -381 | +381 | | | | 3.42 | 3.42 | 0.90 |
| Wave Height #4 | mm | -381 | +381 | | | | 2.61 | 2.61 | 0.69 |
| Wave Height #5 | mm | -381 | +381 | | | | 3.22 | 3.22 | 0.85 |
| Wave Height #6 | mm | -381 | +381 | | | | 3.40 | 3.40 | 0.89 |
| Wave Height #8 | mm | -381 | +381 | | | | 1.89 | 1.89 | 0.50 |

## CONCLUSIONS

The regular wave, dynamic stability results yield a very consistent result with respect to performance at any particular operational condition. The operational areas of concern are well defined by the "Danger of Capsize" and "Capsize Condition" cells. There are no cells at separate locations from the concentrated concern areas at Fn=0.4. There is one capsize cell at Fn=0.3 for a stern quartering condition, for the 100kt wind limiting KG. There are no "Capsize Condition" cells for the righting arm limiting KG condition.

These results could be used to create operational guidance for the ship being evaluated. The matrices indicate that if the ship speed is operationally limited to Fn=0.2 and below for extreme following seas, then there is very limited possibility of a dynamic stability event.

Additionally if other tests in irregular seas are to be performed, then the irregular seas will most likely need to contain wave components which are near the same steepness as that observed for regular wave testing. The results indicate that wave steepnesses near $H/\lambda=1/10$ will be required, and that these conditions will have to be run at the speed and heading indicated by regular wave results.

## ACKOWLEDGEMENTS

The authors would like to acknowledge the many contributions of naval architects, electronic and mechanical engineers and technicians whom have improved NSWCCD dynamic stability testing capabilities since the early evolutions. The technical efforts from Code 51 and 55 personnel have gradually built upon the previous effort. The contributions of each and all is greatly appreciated in this effort.

## REFERENCES

Hayden, D.D., Bishop, R.C., Park, J.T., Laverty, S.M., 2006, Model 5514 Capsize Experiments Representing the Pre-Contract DDG51 Hull Form At End of Service Life, Report No. NSWCCD-50-TR-2006/20, Carderock Div, NSWC.

ISO 1995, "Guide to the Expression of Uncertainty in Measurement," 1995, International Organization for Standardization (ISO), Geneva, Switzerland.

**Table 5. Roll Angle Matrix for Intact 100kt Wind Limiting KG = 8.55m, EOSL Load Condition.**

| λ/L | λ/h | Fn | χ (deg) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 15 | 30 | 45 | 60 | 75 | 90 | 105 |
| 0.75 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 10 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | 26.2, 25.8 | 11.6, 12.2 | | | |
| | | 0.3 | | | 32.0, 30.8 | 37.9, 34.2 | 19.2, 21.0 | 17.2, 18.7 | | |
| | | 0.4 | | | 76.1, 43.2, 90, 68.0, 61.9, 90, 90 | 90, 90, 67.4, 59.8, 61.8 | 26.6, 27.0 | | | |
| 1.00 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | 20.2, 21.9 | 21.0, 23.4 | | | |
| | | 0.4 | | | | 32.1, 31.9 | 32.0, 31.9 | | | |
| | 10 | 0.0 | 25.6 | | | | | | 28.1 | |
| | | 0.1 | | | 22.2 | | 14.3, 15.7 | 15.3, 12.9 | | |
| | | 0.2 | | | 34.6, 32.8 | 20.4, 18.9 | 19.4, 11.3 | 20.1, 18.9 | | |
| | | 0.3 | | 29.6, 29.0 | 32.8, 42.1 | 27.5, 25.9 | 26.4, 26.9 | 21.8, 25.4 | | |
| | | 0.4 | | 90, 90, 90, 90 | 90, 90, 90, 90 | 37.2, 33.4 | 38.2, 31.1 | 25.9, 34.6 | | |
| 1.25 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | 24.4, 21.9 | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | 19.0 | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | 19.0 | | | | |
| | | 0.3 | | | 29.9 | 25.8, 27.5 | 26.8 | | | |
| | | 0.4 | | | 42.1, 42.0 | 40.8, 42.2 | 33.3, 34.4 | | | |
| | 10 | 0.0 | 28.4 | | | | | | 30.5 | |
| | | 0.1 | | 34.3 | | 32.5 | 30.6 | 30.1 | 27.6 | |
| | | 0.2 | | 26.9 | 35.3 | 39.1 | 36.7 | 34.8 | | |
| | | 0.3 | | 33.3 | 38.7, 40.7 | 58.3, 48.1 | 45.1, 45.0 | 39.8 | | |
| | | 0.4 | 64.5, 90, 90 | 90, 90, 90, 90 | 90, 90, 90, 90 | 74.4, 90, 90, 90 | 69.0, 67.4, 90, 90, 61.2, 54.8 | 42.6 | | |

**Table 5(Cont). Roll Angle Matrix for Intact 100kt Wind Limiting KG = 8.55m, EOSL Load Condition.**

| λ/L | λ/h | Fn | χ (deg) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 15 | 30 | 45 | 60 | 75 | 90 | 105 |
| 1.50 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | 29.3 | | | | |
| | | 0.4 | | | | 37.5 | 37.0 | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | 14.9 | | 32.0 | | | | |
| | | 0.3 | | 21.8 | 30.0 | 35.2 | 41.4 | | | |
| | | 0.4 | | | 37.2 | 43.2 | 43.5 | | | |
| | 10 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |

**Table 6. Roll Angle Matrices for Righting Arm Limiting KG = 8.22m, EOSL Load Condition.**

| λ/L | λ/h | Fn | χ (deg) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 15 | 30 | 45 | 60 | 75 | 90 | 105 |
| 0.75 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 10 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | 32.5, 34.5 | 36.4 | 39.5 | | | |
| | | 0.4 | | | 48.1, 45.4 | 45.7, 44.7, 44.2, 41.7, 45.7 | 45.7 | | | |
| 1.00 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 10 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | 23.6 | 35.5 | 45.8 | | | | |
| | | 0.4 | | 43.3, 48.6 | 45.2 | 52.3, 46.8 | | | | |

**Table 6 (Cont.). Roll Angle Matrices for Righting Arm Limiting KG = 8.22m, EOSL Load Condition.**

| λ/L | λ/h | Fn | χ (deg) 0 | 15 | 30 | 45 | 60 | 75 | 90 | 105 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.25 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 10 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | 11.5 | 24.2 | 32.5 | 43.6 | 47.4 | 42.2, 45.6 | | |
| | | 0.4 | 52.0, 39.3 | 44.6, 41.9 | 46.1, 42.6 | 44.3, 45.0, 43.9 | 46.32 | 41.8, 28.5, 43.3 | | |

**Key for Tables 5 and 6**

| Key: | | |
|---|---|---|
| | 36.6 | Max Roll Angle < 49.4 deg (75% of GZ curve) |
| | 55.2 | Max Roll Angle > 49.4 deg: in danger of capsize (capsize, dangerous roll) |
| | 90.0, 54.3, 48.1 | Capsize condition (capsize, dangerous roll, acceptable roll) |

**Table 7. Test Versus FREDYN Results for Intact 100kt Wind Limiting KG = 8.55m, EOSL Load Condition.**

| λ/L | λ/h | Fn | χ (deg) 0 | 15 | 30 | 45 | 60 | 75 | 90 | 105 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.75 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 10 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | $C_f$ | $C_f$ | | | |
| | | 0.3 | | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.4 | | | $C_f$ | $C_f$ | $C_f$ | | | |

**Table 7(Cont.) Test Versus FREDYN Results for Intact 100kt Wind Limiting KG = 8.55m, EOSL Load Condition.**

| λ/L | λ/h | Fn | χ (deg) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 15 | 30 | 45 | 60 | 75 | 90 | 105 |
| 1.00 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | $C_f$ | $C_f$ | | | |
| | | 0.4 | | | | $C_f$ | $C_f$ | | | |
| | 10 | 0.0 | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | |
| | | 0.1 | | | $C_f$ | | $C_f$ | $C_f$ | | |
| | | 0.2 | | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.3 | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.4 | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| 1.25 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | $C_f$ | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | $C_f$ | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | $C_f$ | | | | |
| | | 0.3 | | | $C_f$ | $C_f$ | $C_f$ | | | |
| | | 0.4 | | | $C_f$ | $C_f$ | $C_f$ | | | |
| | 10 | 0.0 | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ |
| | | 0.1 | | $N_f$ | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | |
| | | 0.2 | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.3 | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.4 | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| 1.5 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | $C_f$ | | | | |
| | | 0.4 | | | | $C_f$ | $C_f$ | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | $C_f$ | | $C_f$ | | | | |
| | | 0.3 | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | | |
| | | 0.4 | | | $C_f$ | $C_f$ | $C_f$ | | | |
| | 10 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |

**Table 8 Test Versus FREDYN Results for Righting Arm Limiting KG = 8.22m, EOSL Load Condition.**

| λ/Λ | λ/η | Fn | χ (δεγ) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 15 | 30 | 45 | 60 | 75 | 90 | 105 |
| 0.75 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 10 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | $C_f$ | | | |
| | | 0.3 | | | $N_f$ | $C_f$ | $C_f$ | | | |
| | | 0.4 | | | $C_f$ | $C_f$ | $C_f$ | | | |
| 1.00 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | $C_f$ | | | |
| | 10 | 0.0 | $T_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | |
| | | 0.1 | | | | | $C_f$ | $C_f$ | | |
| | | 0.2 | | | | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.3 | | $N_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.4 | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| 1.25 | 20 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | | | | | |
| | | 0.3 | | | | | | | | |
| | | 0.4 | | | | | | | | |
| | 15 | 0.0 | | | | | | | | |
| | | 0.1 | | | | | | | | |
| | | 0.2 | | | | $C_f$ | $C_f$ | | | |
| | | 0.3 | | | | $C_f$ | | | | |
| | | 0.4 | | | | $C_f$ | $C_f$ | | | |
| | 10 | 0.0 | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ |
| | | 0.1 | | | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | |
| | | 0.2 | | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.3 | $N_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |
| | | 0.4 | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | $C_f$ | | |

**Key for Table 7 and 8**

| | | |
|---|---|---|
| **Key:** | | Max Roll Angle < 49.4 deg (75% of GZ curve) |
| Model Test | | Max Roll Angle > 49.4 deg: in danger of capsize |
| Results | | Consistent capsize condition. |
| | $\mathbf{C_f}$ | FREDYN predicted capsize. |
| FREDYN | $\mathbf{N_f}$ | FREDYN predicted no capsize. |
| Prediction | $\mathbf{T_f}$ | FREDYN prediction terminated. |