An Initial Investigation Toward Understanding Scale Effects in Dynamic Stability Predictions

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Abstract: In order to further the dynamic stability community's understanding of direct assessment results and to inform development and validation of simulation tools, an argument is made to pursue a study of scale effects on large amplitude ship motions. Results are presented of a very limited numerical simulation study that tests the effect on motion response in high sea states when the resistance force, wake fraction, rudder lift behavior, and hull cross-flow drag are modeled at model scale and full scale. Small differences in predicted motion responses were observed for steep seas, but not lower-period seaways of the same significant wave height. It is concluded that further study and discussion of scale effects in dynamic stability should continue.

Key words: Maneuvering; Simulation; Intact Stability, Dynamic Stability, Scale Effects

1. Introduction

The direct assessment of dynamic stability performance relies either on model tests or simulations that have been validated against model tests. However, this paradigm makes the assumption that the dynamic stability behavior as determined from a Froude-scaled model test represents the behavior of the full-scale ship. But while this assumption has been noted in the dynamic stability community, leading to guidance that model experiments use sufficiently large models (see IMO, 2006 guidance, for example), the specific impact has not been examined. The likely reason for this is that the toolset to do so has not been available. Full-scale heavy weather trials cannot be exactly reproduced at model scale, so the required approach is to test the assumption numerically. Only recently have advances in computing power and numerical simulation models allowed such research to be embarked upon.

There is reasonable suspicion that there are scale effects, at least for certain failure modes, given that the dynamic stability problem is a maneuvering-in-waves problem. There are Reynolds scale effects in calm water maneuvering performance as measured by turning circle quantities (see ITTC (1999), for example). The question that arises is whether or not Reynolds number differences that affect large maneuvers appreciably influence dynamic stability performance.

Beyond suspicion of existence, there is strong motivation to test for scale effects: Scale physical model experiments must be interpreted appropriately and numerical models need to account for scale effects where they may drive the solution. And the first step toward improving the stability community's understanding in this area is to commence a dialogue on the subject, which is the intent of the present paper.

2. Possible Scale Effects

An examination of the aspects of the physics subject to scale effects provides insight into where there may be some influence on dynamic stability predictions. With Froude-scaled model tests, the primary discussed mismatch is in the Reynolds number. Dynamic sta-

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bility model experiments rely on large waves and, occasionally, high ship speed, which leads to models that often don't exceed 3–4 m in length. This further exacerbates the Reynolds number mismatch. The following aspects will, therefore, be influenced:

- *Ship Resistance* — The well-known effect of relatively higher resistance at model scale leads to more required thrust at a given speed. The primary effects of this are possible different operating point on the propeller and increased flow over the rudders. Given the importance of rudders on ship control in waves, this could have a noticeable effect on dynamic stability predictions.
- *Viscous wake* — The inflow to the propellers and rudders is likely to be different than full scale, which will influence the propeller operating point and lift of the rudders.
- *Propeller performance* — The scales at which the model experiments are run require small propellers. The difference in blade Reynolds numbers may end up being large enough that the thrust coefficients are significantly different from full scale. Therefore, while the previously mentioned scale effects may drive the propeller to a different advance coefficient, J, the thrust coefficient, K_T, could likewise be different. Perhaps more importantly, the slope of the J-K_T curve could be different, leading to different speed loss in waves.
- *Rudder lift characteristics* — The lift slope as a function of angle of attack is a function of Reynolds number, as shown by Hoerner (1965). The stall angle is similarly affected. This scale effect must be considered in conjunction with the anticipated increased inflow due to the relatively higher thrust required out the propeller. Also, some model testers adjust rudder geometry in order to overcome these scale effects.
- *Hull lift and cross-flow drag* — Circulatory hull lift and/or viscous separation due to the ship being at a drift angle is likely to be affected by a Reynolds number mismatch. The change in lift and cross-flow drag characteristics will have an effect on the hull's maneuvering performance.
- *Bilge keel boundary layer* — The primary mechanism of roll damping in a typical ship is the bilge keels. The velocity over the bilge keels, particularly for the cross-flow separation drag component, plays a strong role in the damping moment. This means that the thickness of the boundary layer will have a strong influence on the damping behavior, and, subsequently, the roll motion. The effect of Reynolds number differences is difficult to characterize, because the influence is very different in the case of laminar flow at model scale vs. turbulent flow. If the flow is laminar, then the relative boundary layer thickness is very similar to the full-scale boundary layer thickness. However, if the model-scale flow is turbulent, then the boundary layer is much thicker than at full scale.

Beside the Reynolds number mismatch with a Froude-scaled model test, there is also a cavitation number mismatch. At higher speeds, this can lead to differences in the cavitation and ventilation behavior on the propellers and rudders.

Will all of these noted possible effects, there are also likely subtle differences that may not be anticipated to have an influence on dynamic stability, but may be illuminated as the study of dynamic stability scale effects progresses (presuming the numerical tool models those physics). On the other hand, there are many scale effects that may be cancelling in terms of their influence on dynamic stability.

3. Proposed Approach

The proposed approach for studying the impact of scale effects is two-pronged: First, use a simulation tool that comprehensively addresses all or most of the suspected relevant Reynolds number-dependent forces to predict ship responses over a wide range of conditions (speed, heading, and environment). This is to provide an overall assessment of the importance of including scale effects in predictive models.

Second, sensitivity studies should be performed to isolate (if possible) those forces that are the largest contributors to any observed differences in the "comprehensive" study. The reason to do this, beyond the desire for a more full understanding, is to focus the development of numerical models in the relevant areas and avoid the expense (both developmental and computational) of unnecessarily complex models and/or input development.

The use of sensitivity studies to guide understanding of predictive needs is not new. For example, the 22nd ITTC Manoeuvring Committee (1999) noted that sensitivity analysis for calm water maneuvering predictions would identify the terms most in need of accuracy. One example cited was the study by Vassalos, *et al.* (1995) that found that the linear coefficients Y_v Y_r, N_v, N_r are the most critical for steady turning motion.

3.1 Numerical Tool

The numerical tool selected to execute this proposed study is the US Navy's new maneuvering-in-waves simulation code, Tempest (Belknap and Reed, 2010). This tool has been developed with the objective of balancing the needs of higher fidelity modeling for high sea states with computational efficiency, thereby making it a well-suited candidate for an initial dynamic stability scale effects sensitivity study.

Tempest is able to capture many scale effects through a combination of the implemented models and user-supplied input. These include:

- Calm water resistance force (user-supplied)
- Wake fraction and thrust deduction (user-supplied)
- Propeller performance characteristics (user-supplied)
- Rudder lift slope variation as a function of Reynolds number (automatic)
- Baseline linear hull lift coefficients: Y_v, N_v, Y_r, N_r (user-supplied values allow for Reynolds number dependence)
- Sectional cross-flow drag coefficients (automatic Reynolds number dependence or via user-supplied coefficients)
- Cross-flow drag longitudinal attenuation coefficients (user-supplied values allow for Reynolds number dependence)

The details of the hull lift and cross-flow drag model can be found in Hughes, *et al.* (2011). Figure 1 illustrates the modeled automatic handling of Reynolds number dependence for the cross-flow drag coefficients. However, the preferred approach for a scale effects study is to compute model-scale and full-scale hull lift and cross-flow drag coefficients directly for the subject hull using a RANS tool.

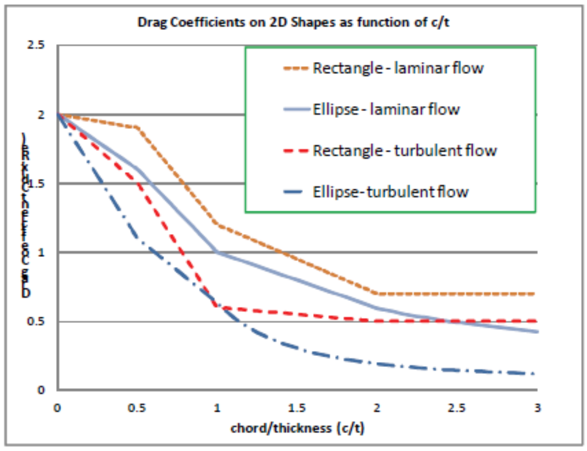


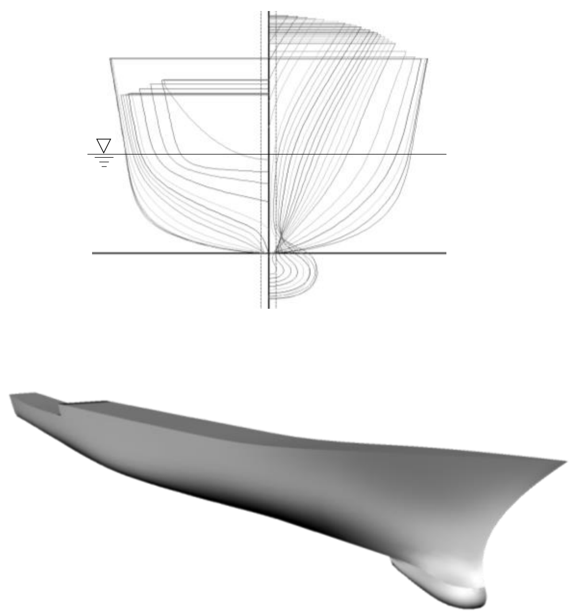
Fig. 1: Cross-flow drag coefficients for different section shapes in sub-critical and super-critical flow regimes (from Hughes, *et al.*, 2011).

4. Present Study

Prior to the application of the full proposed approach in a complete scale effects study, an initial limited investigation was performed. This present study addresses a small part of the second prong in the proposed approach by examining the sensitivity to only the following scale-dependent variations for a 1/46.6-scale model:

- Calm water resistance — C_f scaled via ITTC friction line
- Wake fraction — modified heuristically from w = 0.05 at model scale to w = 0.01 at full scale
- Rudder lift slope — automatically handled
- Cross-flow drag coefficients — use automatic Reynolds-number variation for elliptical sections

The ship selected for this initial study was the widely studied destroyer geometry represented by NSWCCD Model 5514 (a geo-sim of Model 5415 and a 46.6-scale representation of a full-scale destroyer). The geometry is shown in Figure 2, where it can be seen there is no deckhouse.



a)

b)

Fig. 2: Present study's ship geometry (M5514) in (a) body plan and (b) perspective view.

The ship was run at a high KG value, producing a calm-water righting arm curve that peaks near 40 degrees of heel, as shown in Figure 3.

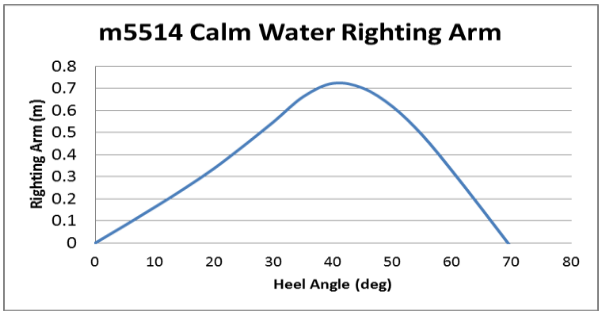


Fig. 3: M5514 calm water righting arm for present study.

4.1 Run Matrix

The primary condition variations present in the run matrix are significant wave height, modal period, and relative wave heading (30° increments from 0–180°). In this initial study, only 5 & 10 kt "ordered speeds" (i.e. speed that would be attained in calm water given the propeller RPM settings) were included. The wave environments were run with spreading in order to provide a realistic operating scenario. A visualization of this spreading is shown in a screen capture of sample Tempest simulation output in Figure 4. The matrix of wave environments was designed to run three nominal steepnesses (H_s/λ_m) of 1/20, 1/40, and 1/60 at H_s = 7.5m & 11.5m. This leads to the environment matrix shown in Table 1.

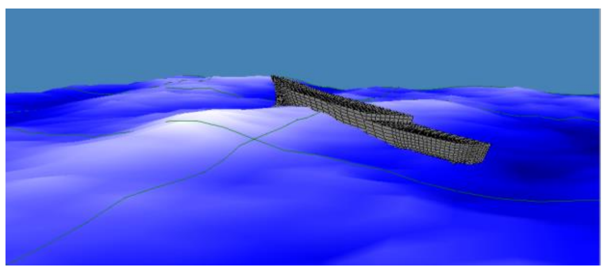


Fig. 4: Screen capture of simulation showing short-crested irregular sea environment.

Table 1: Wave Environment Matrix

H_s	T_m #1	T_m #2	T_m #3
7.5 m	10 s	14 s	17 s
11.5 m	12 s	17 s	20.5 s

4.2 Simulations

The wave spectra were discretized into 224 wave components and each simulation run for 10 minutes exposure time (after an 80-s ramp-up period). The full run matrix (6 environments x 7 headings x 2 speeds) was repeated 30 times with a different random wave phase seed each time, with model- and full-scale runs using the same set of 30 phase seeds.

5. Results

The simulation results were analyzed for “non-rare” motion statistics (mean, minimum, maximum, and standard deviation) and for motion quantile levels to provide a means of comparing the motion peaks distributions. Example results are plotted in figures 5–11.

Figures 5 and 6 show the non-rare roll motions for all conditions tested. Each sub-plot represents a different wave environment. From these results, it appears that the model scale results (solid lines) are nearly identical to the full-scale results (dashed lines) for all seaways except for the steepest. But even for the steep seaways, differences are not large and are not consistent between speeds and headings.

Other non-rare motion responses for the steep 11.5 m seaway are shown in figure 7. From these plots, it can be seen that, while pitch and yaw rate do not appear sensitive to the modeled scale effects, significant yaw differences are seen at some headings. Though it may seem peculiar that yaw can show large differences while yaw rate does not, it is an indication that the large amplitude yaw increase may be accompanied by an increase in yaw period.

Figures 8, 9, and 10 provide examples of more complete measures of roll response in the form of quantile comparisons. The differences (or lack thereof) between model scale and full scale motions are illuminated in Q-Q plots, shown beneath each quantile plot. These particular examples show that there can be differences not only in the extreme responses, but also in the overall distribution of peaks.

Finally, Figure 11 shows the 99th percentile pitch response for the steepest 11.5 m seaway. Even though the non-rare motions were nearly identical (see figure 7), the “once-every-hundred” peak begins to show some difference at certain headings.

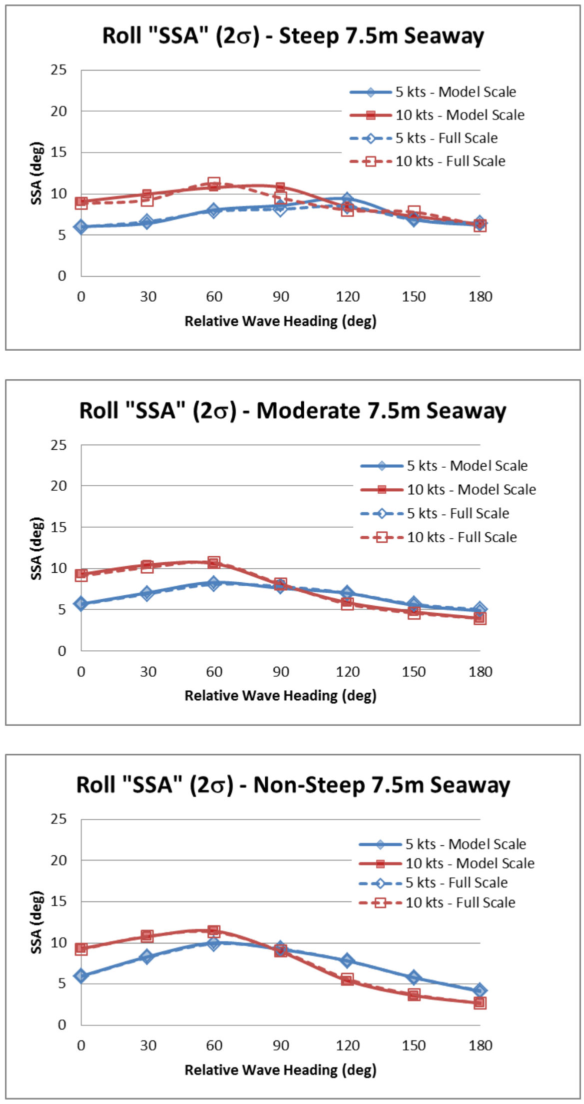


Fig. 5: “Non-rare” statistics of roll motion at H_s = 7.5 m at 5 kt (blue) and 10 kt (red) for model scale (solid) and full scale (dashed), shown at three modal periods: top) T_m = 10 s; middle) T_m = 14 s; bottom) T_m = 17 s

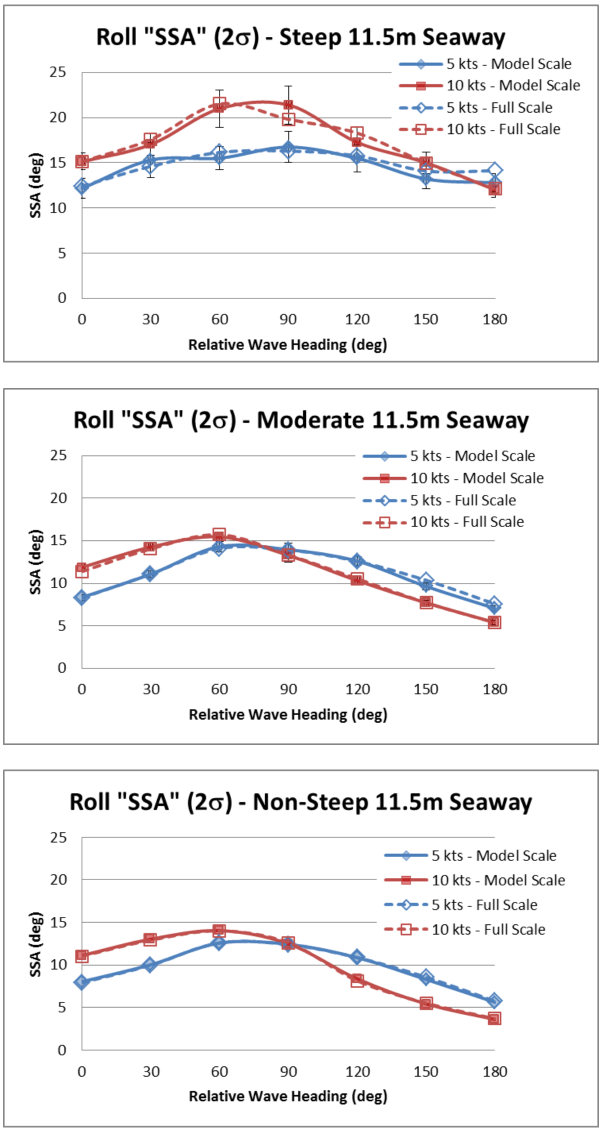


Fig. 6: "Non-rare" statistics of roll motion at H_s = 11.5 m at 5 kt (blue) and 10 kt (red) for model scale (solid) and full scale (dashed), shown at three modal periods: top) T_m = 12 s; middle) Tm = 17 s; bottom) Tm = 20.5 s

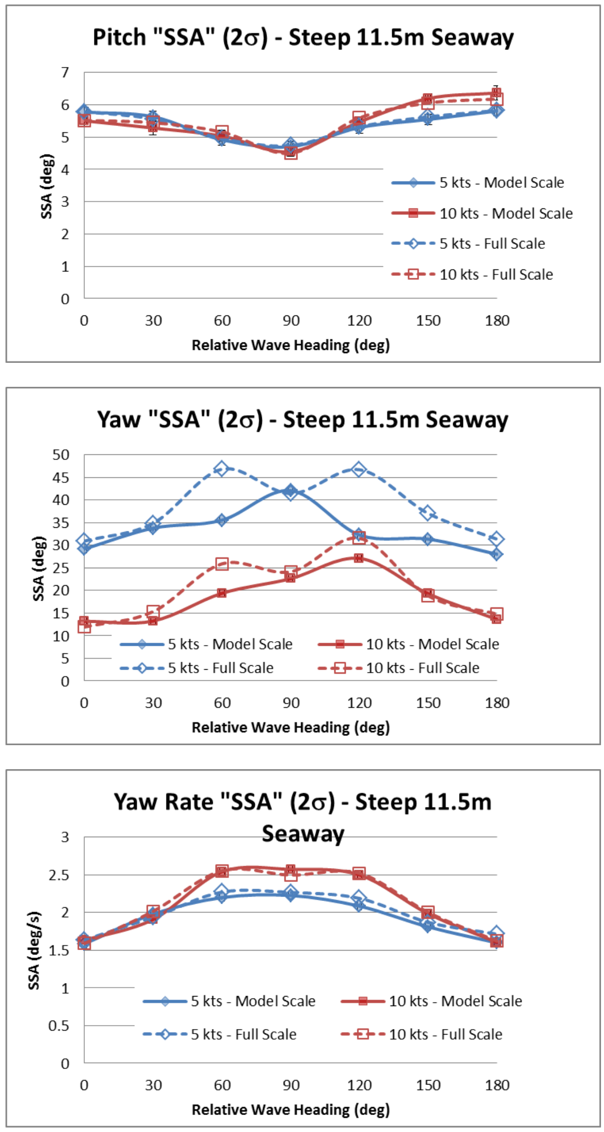


Fig. 7: "Non-rare" statistics of pitch (top), yaw (middle), and yaw rate (bottom) for H_s = 11.5 m, Tm = 12 s at 5 kt (blue) and 10 kt (red) for model scale (solid) and full scale (dashed).

6. Conclusions

The present study was extremely limited in that the scale effects tested were few and the matrix of conditions did not explore a wide range of speeds.

The results indicate that different motions can be realized in steep seas when even rudimentarily accounting for scale effects. However, the observed differences were not significant. No patterns were able to be identified between speed and heading.

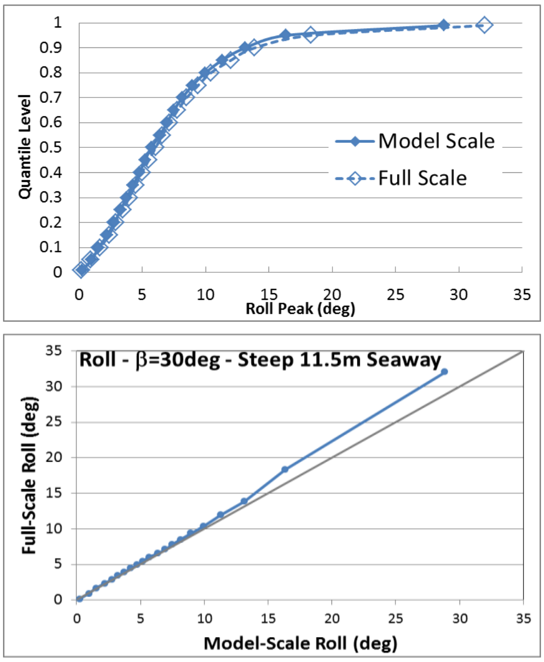


Fig. 8: Roll quantile comparisons for H_s = 11.5m, Tm = 12s at 5 kt, 30° relative wave heading, between model scale and full scale. Quantile plot shown at top and Q-Q plot at bottom.

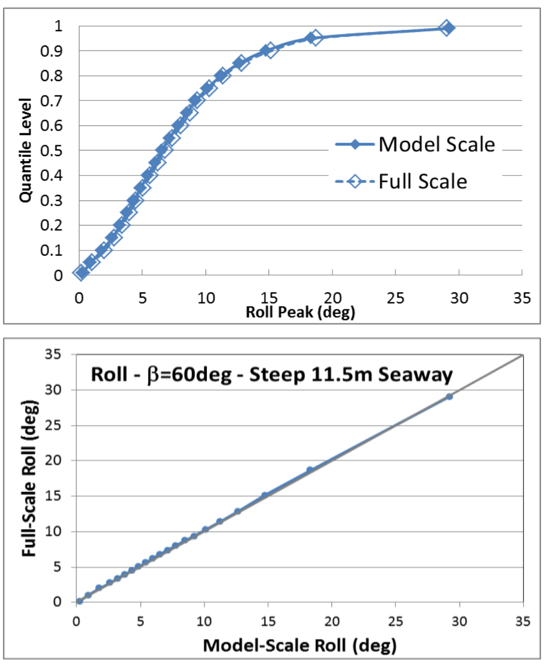


Fig. 9: Roll quantile comparisons for H_s = 11.5m, Tm = 12s at 5 kt, 60° relative wave heading, between model scale and full scale. Quantile plot shown at top and Q-Q plot at bottom.

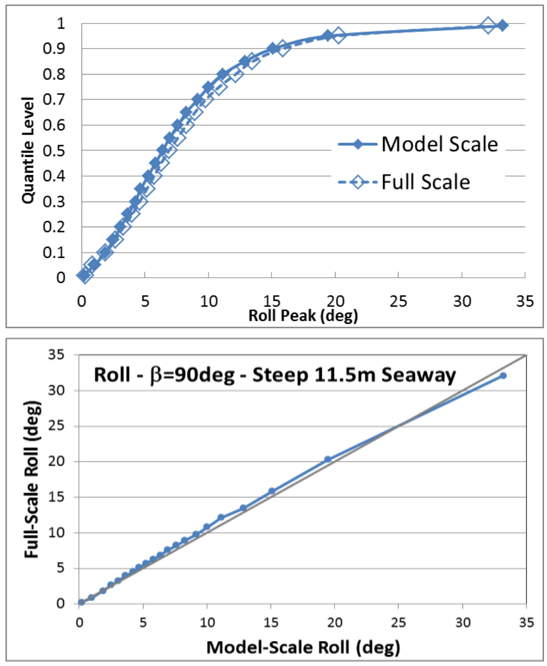


Fig. 10: Roll quantile comparisons for H_s = 11.5m, T_m = 12s at 5 kt, 90° relative wave heading, between model scale and full scale. Quantile plot shown at top and Q-Q plot at bottom.

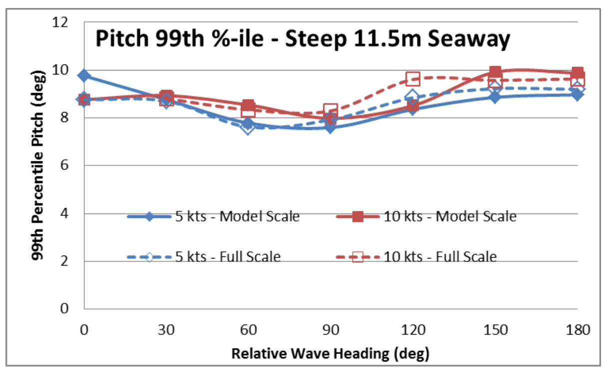


Fig. 11: "Rare" statistics of roll motion for H_s = 11.5 m, T_m = 12 s at 5 kt (blue) and 10 kt (red) for model scale (solid) and full scale (dashed).

6.1 Future Work

Additional study is required to determine the relative importance of modeling scale effects in simulation tools. Not only must the ship types and simulation conditions (speeds, headings, environments) be further expanded, the prediction tools must capture more completely the force components subject to scale effects.

Also, further work is needed in considering the statistical treatment of results. With the current approach, while the ambient seaways are identical, the study is only quasi-deterministic in that the encountered waves will differ once deviations in track or speed occur.

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