Linear Seakeeping High Sea State Applicability

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ABSTRACT

The small motion assumption of linear seakeeping codes is well known. The validity of this assumption is investigated by comparisons with a body exact non-linear seakeeping code over a range of significant wave height. A metric based on relative motion is proposed to quantify the validity of the assumption and indicate up to what point linear seakeeping is appropriate.

Keywords: *Linear Seakeeping; numerical simulations.*

1. INTRODUCTION

Despite the advent of relatively computationally fast non-linear time domain seakeeping programs, there is still some use for linear strip-theory seakeeping programs. Frequency domain programs can produce seakeeping predictions for many speeds, relative wave headings, and seaways in seconds of computation. This is especially useful for including seakeeping in early design analysis of alternatives and calculating mission operability. Time histories based on linear response amplitude operators (RAOs) are also fast to compute and provide representative motions for ship system design/evaluation.

The main assumptions of linear strip-theory seakeeping codes are well known. The first is that calculations are preformed about the mean undisturbed waterline. Hydrostatics, radiation, diffraction, and incident wave forces are all calculated on the submerged portion of the hull at the mean undisturbed waterline. This is also stated as a "wall sided" and "small motion" assumptions. These descriptions explain in a physical sense what using the mean undisturbed waterline to define the submerged hull actually means. "Wall sided" indicates that the hydrostatic properties are not changing as the ship moves. "Small motion" indicates that the submerged geometry used for radiation, diffraction, and incident wave force calculations can be considered constant. O'Dea and Walden (1985) examined linear seakeeping with respect to bow flare and wave steepness.

The other main assumption of linear strip-theory seakeeping relates to the independence of the two dimensional strips. The strips are assumed to be independent but in actuality flow from one will influence flow from strips further aft. As a result low speed strip-theory is limited to Froude numbers less than 0.3-0.35. Higher speed strip-theories have been formulated. This paper does not address the validity of using low speed strip-theory above Froude numbers of 0.3-0.35.

Lastly, as a direct result of having a constant submerged volume, the equations of motion can be solved for a unit wave height and linearly scaled to higher wave heights. This is most obviously seen with heavily damped heave and pitch motion. However, roll has non-linear damping and most linear seakeeping programs have some iterative or computational scheme to account for this and do not scale roll linearly with wave height.

However, seakeeping predictions in very small waves, where linear seakeeping assumptions are valid, are not very useful. Fortunately, the assumptions can be stretched and produce useful results at wave heights of interest. This paper discusses a metric to identify when the linear seakeeping assumptions are more than stretched but broken.

2. COMPARISON APPROACH

The validity of linear scaling of results will be determined by comparing linear strip theory results with non-linear time domain results for the same hull form, loading condition, and seaways. Heave, pitch, and roll root mean square (RMS) values will be compared for a range of wave heights. The comparison will be made as a ratio of the RMS motion value at a given wave height over the RMS motion value of the lowest wave height considered. For linear response, that ratio is a straight line when plotted against wave height. Non-linear response will deviate from that line.

Motions will be calculated at 15 knots (Fr=0.2062) for headings from head to following seas in 30 deg increments. While this is not a complete matrix, it avoids higher Froude numbers and provides enough headings for a preliminary evaluation. The wave heights considered range from 3.25m to 12m in 1.75m increment. This is from mid-Sea State 5 to mid-Sea State 8 following STANAG 4194 (NATO 1983). The wave heights corresponds to 0.5 to 1.84 times the draft. A 14 second modal period is used for all the wave heights, so the steepness increases with wave height. The waves are long-crested. The spectra shape is Bretschneider.

The hull form used for this study is a generic naval combatant that has been widely studied in the public domain (DTMB model 5415) (Longo and Stern, 2005). See Figure 1 for a view of geometry and Table 1 loading condition details at full scale.

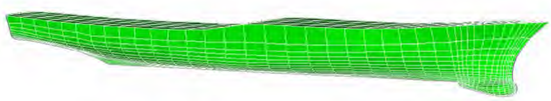

Figure 1: Geometry of model 5415

Table 1: Full scale principle dimensions of DTMB 5415.

Parameter	Units	
Length between Perpendiculars	m	142.0
Beam	m	18.87
Draft, baseline	m	6.51
Trim (+bow down)	m	0.00
Displacement	tonnes	9381.8
LCG (aft FP)	m	72.14
KG	m	7.86
GM	m	1.63
Roll Gyradius	m	7.05
Pitch Gyradius	m	35.5
Yaw Gyradius	m	35.5

This hull form is a traditional monohull with a small amount of flare forward. As most of the hull is "wall sided" the expectation is that linear strip theory should be appropriate at a much higher wave height than hull forms with more variation.

The simulation tools used for this study are Navy Ship Motion Program (SMP95) (Conrad, 2005; Meyers and Batis, 1985; Meyers et al., 1981) and Large Amplitude Motion Program (LAMP) (Lin et al., 1990, 1994). SMP95 is a linear strip-theory seakeeping code first developed in 1981 that uses the Salvensen-Tuck-Faltinsen strip-theory (Salvensen et al., 1970) with modified forward-speed terms. It uses Frank's close-fit method (Frank, 1967) to calculate radiation forces. Roll damping is estimated from appendage geometry using Ikeda-Tanaka-Himeno (1978) and Kato (1958) empirical formulae. Non-linear roll damping is included by an iterative process to match the calculated response with roll angle associated with the roll damping estimate used to calculate the response. SMP95 calculates motions, velocities, and accelerations at center of gravity and defined points, as well as, relative motion between points on the hull and the incident wave.

LAMP is a time domain ship motion and wave loads simulation code that was developed by Science Applications International Corporation (SAIC) beginning in 1991 to complement linear frequency domain codes. LAMP calculates three dimensional wave-body hydrodynamics using a potential flow approach. The basic hydrodynamic calculations include non-linear Froude Krylov forces and non-linear hydrostatics as well as linear potential flow calculations. Roll damping, appendage lift and other viscous and vortical forces are estimated using empricial formulae and/or tuned coefficient models. LAMP can calculate combined seakeeping and maneuvering, and includes rigid and elastic beam models for computing hydrodynamic loads. LAMP calculates motions, velocities, and accelerations at center of gravity and defined points, as well as relative motion between points on the hull and the incident wave.

3. COMPARISON RESULTS

The results are non-dimensionalized by dividing by the value associated with the 3.25m significant wave height. The non-dimensional wave height ranges from 1.0 to 3.69. If the motions scale linearly with wave height, they should follow the same range. Figures 2 to 8 show the comparison of non-linear (LAMP) and linear (SMP95) seakeeping predictions. In Figures 2 and 8, the roll data are not presented due to values being very small in head and following seas.

LAMP heave and pitch results are very close to the linear seakeeping line over the entire wave height range. The differences are most notable at head (0 deg), bow (30deg), and following (180 deg) seas above non-dimensional wave height 2.5 (1.25 times draft). Pitch behavior in beam seas is not linear as values are small. LAMP and SMP95 are very close in dimensional values as well.

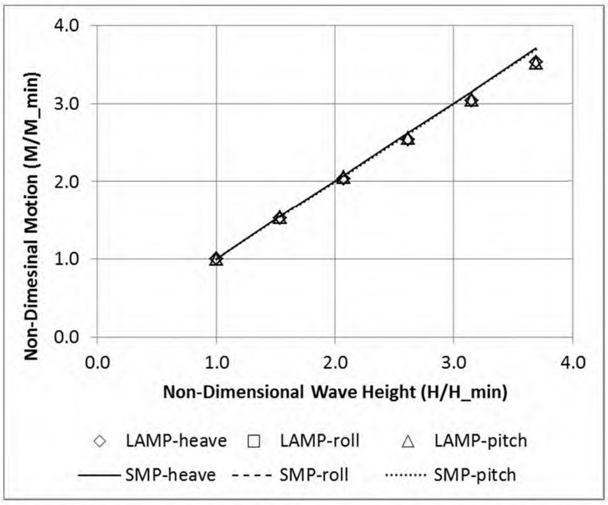

Figure 2: Comparison of non-linear and linear seakeeping at Fr=0.21 and head seas (0 deg).

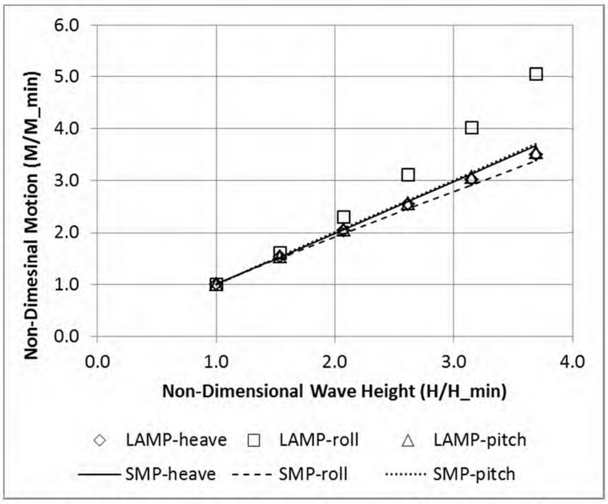

Figure 3: Comparison of non-linear and linear seakeeping at Fr=0.21 and bow seas (30 deg).

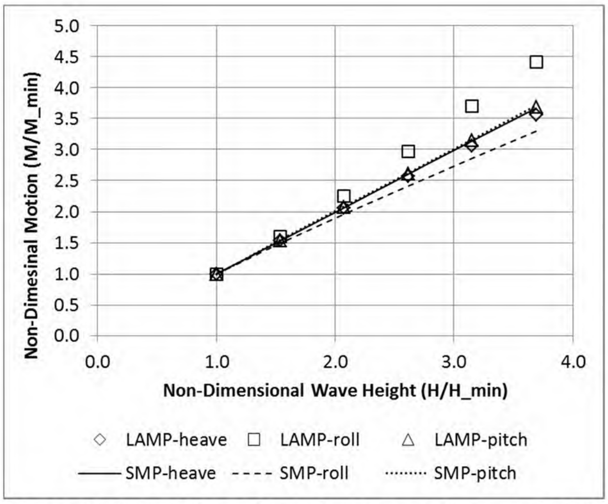

Figure 4: Comparison of non-linear and linear seakeeping at Fr=0.21 and bow seas (60 deg).

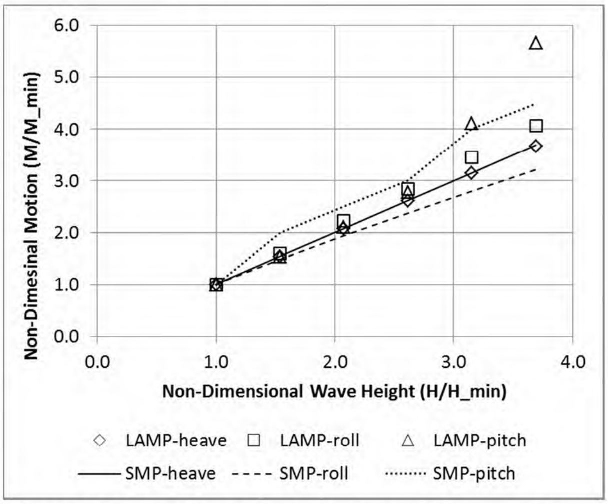

Figure 5: Comparison of non-linear and linear seakeeping at Fr=0.21 and beam seas (90 deg).

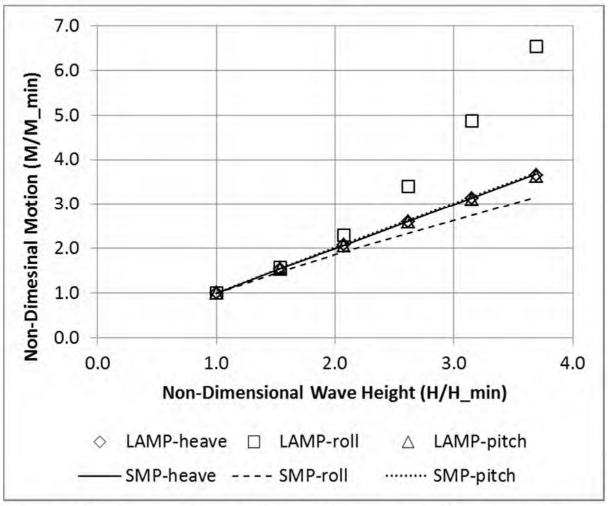

Figure 6: Comparison of non-linear and linear seakeeping at Fr=0.21 and quartering seas (120 deg).

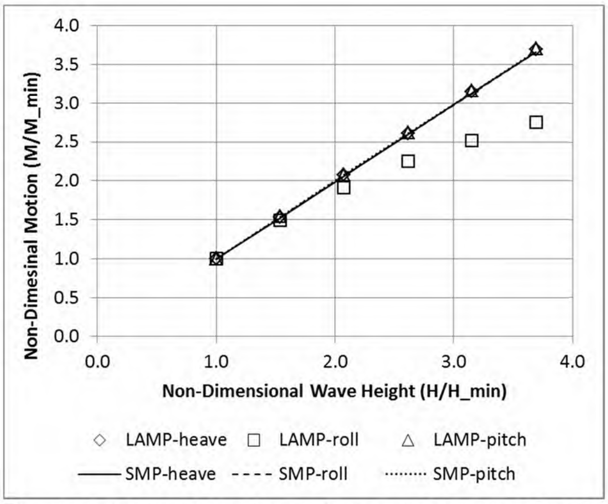

Figure 7: Comparison of non-linear and linear seakeeping at Fr=0.21 and quartering seas (150 deg).

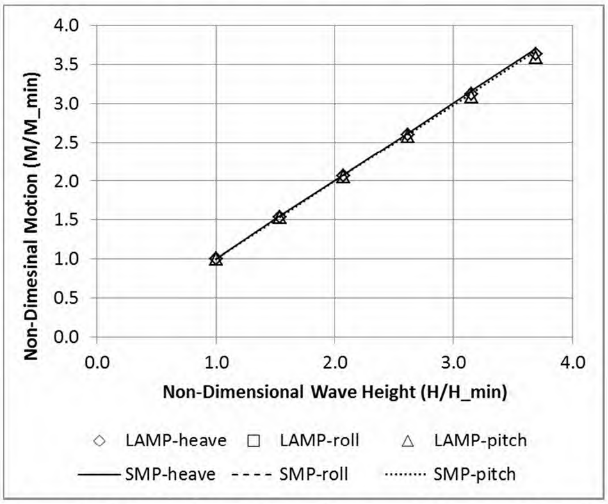

Figure 8: Comparison of non-linear and linear seakeeping at Fr=0.21 and following seas (180 deg).

Both LAMP and SMP95 roll results vary from linear behavior as expected. LAMP results have noticeable curvature as the wave height increases. SMP95 results are fairly linear with a different slope than 1:1 with wave height. LAMP roll results are almost twice the SMP95 roll values in dimensioanl values. This is explained as difference in roll damping models and appendage suite.

4. APPLICABILITY METRIC

Grigoropoulos et al. (2003) indicates strip theory is appropriate for displacement monohulls under Fn=0.3. However, the RoPax ferry did not perform as well as expected. While the geometry is vertical above the waterline, the below waterline shape has significant taper. DTMB model 5415 has a relatively large bilge with nearly vertical sides at the waterline along most of the length. A typical oil tanker has vertical sides for most of it's length and depth. Hull form considerations lead to a metric that quantifies the validity of linear seakeeping based on changes of waterplane area and relative motion.

An informal metric is that linear seakeeping is appropriate if the relative motion is less than half the draft; essentially to the top of the turn of the bilge. The rationale being this is the wall sided portion of the hull and the concern is motion relative to wave, not absolute motions. This metric is somewhat vague in terms of relative motion statistic, e.g., RMS, 1/10th highest, and point location.

Following Meyers et al. (1981) and applying the Rayleigh distribution, the probability of relative motion, σ, exceeding half the draft (critical distance D) can be found by

$$P = e^{-D^2 / 2\sigma^2} \tag{1}$$

The probability where the linear and non-linear results diverege becomes the limit of linear seakeeping applicability. Even so, this is somewhat subjective in terms of location of points at which to evaluate relative motion and selection of critical distance, e.g., half the draft.

This study proposes using points at 0.25LBP and 0.75LBP, centerline, and baseline to evaluate relative motion with respect to incident wave. The quarter length points bracket parallel middle body locations while representing some of the fore and aft geometry changes. The critical distance is the average of the distance from the mean waterline to where the station becomes decidedly non-vertical. This definition accommodates different hull geometries from RoPax ferry to oil tanker. For this case, the critical distance is half the draft (3.251m).

Also, note that the probability changes with speed and heading, so some minimum probability should be selected as the limit of applicability. Figures 9 to 12 show the probability of the SMP95 relative motion exceeding half the draft for cases that showed a difference between LAMP and SMP95. The forward point is the limiting point and as wave heading move aft of beam, the forward point line moves towards the aft point line and becomes coincident.

Looking at head seas, Figure 2 and Figure 9, LAMP heave and pitch are approximately 2% less than linear value near non-dimensional wave height of 2 with a probability 0.14 for the forward point. The probabilities at bow seas are less for similar motion differences. Other headings have lower probabilities and less difference in motions for the same wave height. Roll shows more non-linearity, but within 10% difference at 2.0 non-dimensional wave height.

The threshold value to exceed, allowable motion difference, and relative motion point location are all inter-related and acceptability limits cannot be set independently. So taking the relative motion point location as the foward point and accepting 2% difference bewteen linear and non-linear results sets the threshold probability at 0.14. So for other destroyer-like hull forms, if the probability of a forward relative motion point is less than 0.14, the difference between linear and non-linear response is less than 2%. Other relative motion points and acceptable differences would have other associated probabilities.

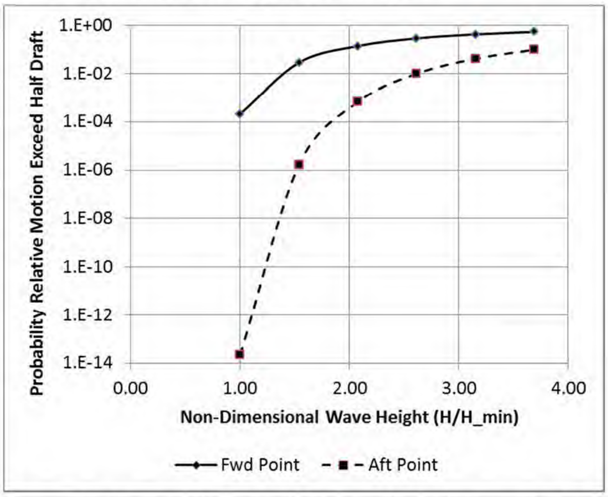

Figure 9: Probability of relative motion at bow and stern exceeding half the draft at Fr=0.21 and head seas (0 deg).

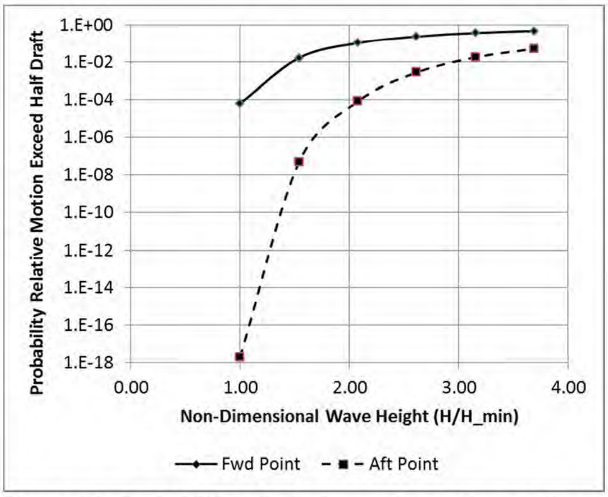

Figure 10: Probability of relative motion at bow and stern exceeding half the draft at Fr=0.21 and bow seas (30 deg).

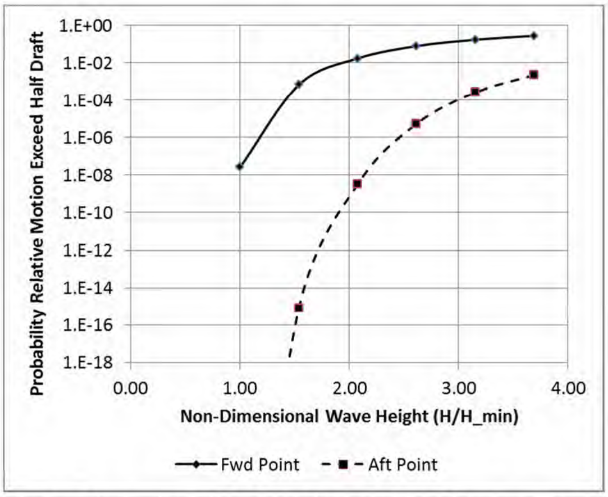

Figure 11: Probability of relative motion at bow and stern exceeding half the draft at Fr=0.21 and bow seas (60 deg).

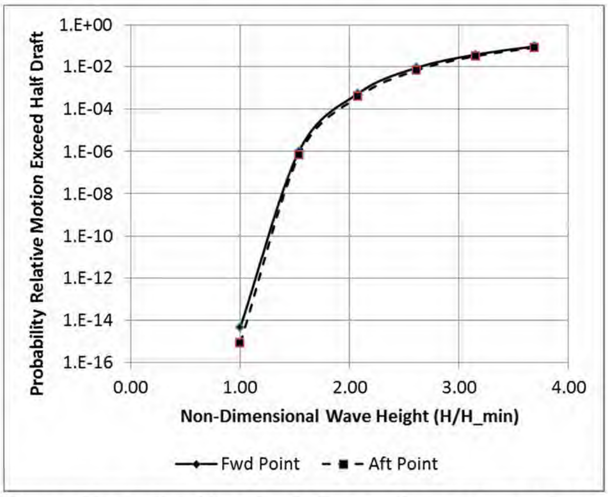

Figure 12: Probability of relative motion at bow and stern exceeding half the draft at Fr=0.21 and following seas (180 deg).

5. CONCLUSIONS

This study proposed a metric to quantify the applicability of linear strip-theory seakeeping. Motions were calculated for DTMB model 5415 using SMP95 and LAMP for a range of wave heights, a single speed, and multiple headings. The motions were compared to see where non-linear effects were apparent and important to the root mean square of the motions. A metric based on the probability of the relative motion exceeding a critical distance was proposed to define the range of applicability of linear strip-theory seakeeping predictions. This approach shows promise but needs to be expanded to other speeds and hull forms to determine general applicability. Other statistics such as average of 1/10th highest may provide more discrimination than root mean square statistic. Additionally, there may be some complementary metric based on variation in waterplane area that would improve selection of critical distance.

6. ACKNOWLEDGEMENTS

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