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Operational Seakeeping Considerations in LCU Deployment

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Abstract

The current class of Landing Craft Utility (LCU) has been in service in the U.S. Navy since the 1960s. Primarily used to land heavy vehicles, equipment, personnel, and cargo ashore in an amphibious assault, its basic design has served well over the last half century of use. However, certain loading combinations impacted by weight creep of particular cargoes have recently come to challenge established operational stability limits. The stability criteria currently employed came from traditional open ocean stability studies and therefore may not be optimal for the typical coastal transits of these specialized vessels. This study examines the intact transverse static and dynamic stability of the LCU in order to determine more appropriate criteria for short-range transits close to shore. The analysis mainly uses the Program of Ship Salvage Engineering (POSSE) software and the standard Ship Motion Program (SMP) to model a stochastic sea state, simulate the LCU's loading conditions, and predict the craft's dynamic response in various sea state conditions. The LCU's static transverse stability is derived by the POSSE software in terms of righting arm diagrams for different loading conditions, while the SMP software determines the dynamic transverse stability. The SMP analysis is based on seakeeping theory, using sea spectra model techniques to determine the LCU's roll angle dynamic responses. Based upon these simulation results, the study evaluates the current stability criteria and arrives at several dynamic stability recommendations and operational limits for loading conditions of interest.

Introduction and Method of Analysis

Motivation

Once thought of as being outdated by the introduction of the Landing Craft Air Cushion (LCAC), the Landing Craft Utility (LCU) 1610 class has continued to be a mainstay in U.S. Navy and Marine Corps amphibious operations through the present day (Schmitz, 2001). Of the 72 LCUs built in the 1960s and 1970s for the Navy, over 30 are still in service today (Colton, 2015). Recently, the contract for detailed design and construction of the LCU 1700, a newer version of the current LCU which was designed in the late 1950s, was awarded (Eckstein, 2018). While plans are to have this newer version of the familiar LCU provide a one-for-one replacement of those vessels currently in service, the continued need for full operational performance of current LCUs has not diminished and will need to be sustained over the next decade during this changeover period.

The LCU, a small displacement craft, is primarily used in amphibious operations to transport troops and military equipment, such as wheeled vehicles and tanks, and other types of cargo ashore. Launched from amphibious assault ships, its primary objective is to safely and expeditiously land and/or transport these items along the beachfront. While capable of long range transits and sustained operations of over a week, typically these vessels are deployed in limited duration coastal operations wherein short crested waves and not long period swells dominate the local seagoing environment (Bottleson, 2001).

While the cargo carrying capacity of the LCU 1610 has not significantly changed over the years—as often is the case due to loss of design margin in conventional warships over their life cycle resulting from ship alterations, modifications, and upgrades—its utility is impacted by another issue related to weight (Pedatzur, 2016). Impressive weight creep, occurring in some of its primary cargoes, such as the M1A1 Main Battle Tank, directly affects desired loading requirements by maxing out payload capacity. This weight gain, stemming from up-armoring of tanks and other vehicles, or replacing “designed for” cargo with more hefty versions of their predecessors, has reportedly pushed the limits of operational performance with respect to seakeeping at certain loading conditions (Eckstein, 2016).

With respect to this, ship stability and associated seakeeping considerations for the safe operation of the current LCU 1610 in coastal waters under normally occurring conditions are investigated herein.

Background

Ship stability is a basic principle of naval architecture. In general, the broader topic can be divided into transverse stability and longitudinal stability. The first of these, transverse stability, which can be described as the ship’s ability to return to an equilibrium position when perturbed by an external force that generates a moment about the centerline axis of the vessel, is of typically greater interest to ship designers due to the greater length to beam ratio of most ships. Longitudinal stability, the ability of the ship to resist trim, the difference in forward and aft drafts, is generally of a secondary order.

A particular ship’s stability is influenced by many internal factors, including displacement, load distribution, and underwater volume, as well as additional external influences such as wind speed, sea state conditions, turning angle, and speed. These factors, expressed as numerical parameters, contribute to the generation of the ship’s stability curves. Stability curves describe the ship’s transverse stability over a wide range of heeling angles and provide information about the required righting arm and moments in order to return the ship to the initial equilibrium state when it has been disturbed by a particular heeling angle. These curves are then used to derive the stability criteria of a ship for a particular set of parameters, such as the heeling angle, the righting arm, and the area under the curves, which are expressed in terms of mathematical limitations of the associated parameter values. Thus these stability criteria provide a ship or vessel with an operational guide based on the environmental and other varying inputs, such as cargo driven changes in displacement, that influence these curves. Compliance with such criteria ensures a ship’s positive stability (i.e., the ship’s ability to restore itself to its initial position), in contrast to negative stability, which refers to the ship’s tendency to overturn.

The stability criteria currently used for the LCU are mainly based on the *Procedures Manual for Stability Analysis of U.S. Navy Small Craft* (Koelbel, 1977, pp. 11–40). This manual provides a transverse dynamic stability analysis for small displacement vessels based on a partially empirical procedure, which makes use of stability curves, and provides stability criteria by focusing on the ship’s restoring moment. The ship restoring moment is the moment produced by the misalignment of the gravity and buoyancy forces and contributes to the ship’s return to initial equilibrium position.

A primary assumption used in the analysis is of vessels making open ocean transits. These conditions are associated with higher wind velocities, yet the majority of LCU missions occur in coastal waters exhibiting much lower wind velocities (Joint Chiefs of Staff, 2009). This then raises the question of whether or not the current stability criteria are in fact optimal for use with the LCU 1610 in its predominately coastal missions at desired loading conditions. Therefore, it is postulated that these criteria may be overly conservative, resulting in a negative impact on LCU operational envelopes. Specific stability criteria for the LCU missions are not currently documented, but it has been reported that as a result of perceptions in potential reduced stability conditions, operational limitations are in place for the LCU.

Objectives

The main objective of this study is to investigate the suitability of stability criteria currently used for the LCU through rigorous analysis. This analysis examines the intact stability of the craft in conditions experienced during coastal missions. More specifically, this analysis focuses on LCU performance in short-range coastal transits from amphibious assault ships to the beach carrying different equipment loads and personnel. A further objective is to contribute to a guideline for the entire LCU fleet based on the conditions and characteristics of its typical coastal missions. One key aspect in this is the weight creep of the primary cargo load. Additionally, since existing stability criteria have been primarily developed based on data obtained from larger ships operating in different environments, they may not be adequate in addressing current operational concerns for this class of vessel and must be reviewed for suitability.

Tasks

The following tasks were undertaken in a systematic way in order to address the objectives of this work:

- Determination of the ship's static stability and dynamic response
- Evaluation of the LCU seakeeping performance stability on the basis of the obtained simulation results
- Development of recommended operational envelopes for the LCU deployment during typical coastal water missions
- Categorization of the currently used LCU stability criteria

Assumptions

This study followed three basic assumptions. The assumptions listed as follows were deemed both necessary in order to proceed with the analysis and reasonable so that the results could be used as a basis for further refinement:

- The ship's center of gravity does not change with changes in the angle of heel.
- The ship's center of buoyancy is always defined as the geometric centroid of the ship's underwater hull area.
- The shape of the ship's underwater hull area will continue to change with changing angles of heel.

Approach

The approach used in this work was comprised of the following steps. For brevity, we present here only the steps taken and follow with the fundamental results. Further technical details can be provided upon request and are documented in a recently completed Naval Postgraduate School master's thesis and related technical report (Roussopoulos, 2017).

Data Analysis

The first step was to analyze the existing static stability criteria. Following a classic approach, five criteria were considered, namely,

- Wind action and rolling
- Lifting heavy weights over the side
- Crowding of personnel to one side
- High-speed turning
- Topside ice (Sarchin & Goldberg, 1963, pp. 429–433)

As expected, some of these criteria were not applicable to this case and, thus, resulted in no additional usable information. From the static stability criteria that were found to be applicable, wind action and rolling was the most limiting. In all realistic loading cases and with environmental conditions considered, the LCU passed the criterion.

The next step was to initiate the analysis for dynamic stability. To that end, it was decided to use a six degree of freedom motions program, Standard Ship Motion Program (SMP), with several loading conditions and a variety of sea states (Herbert-ABS, 2012, pp. 10–34; Conrad, 2015, pp. 1–16).

The following loading conditions were used in the modeling:

- Lightship
- LCU with half cargo deadweight
- LCU with full cargo deadweight

Several sea spectra models, as indicated here, were used in the investigation:

- Pierson-Moskowitz spectrum model
- Bretschneider spectrum model
- JONSAWP spectrum model
- Ochi-Hubble spectrum model

In addition to long-crested or unidirectional seas, we also considered short-crested seas which are better suited for operations in coastal regions and the littorals (IHS Markit, 2017). Figures 1 and 2 illustrate sample input and response parameters used in portions of the SMP analyses. Detailed results at varying load conditions and wave spectra are found in the appendix.

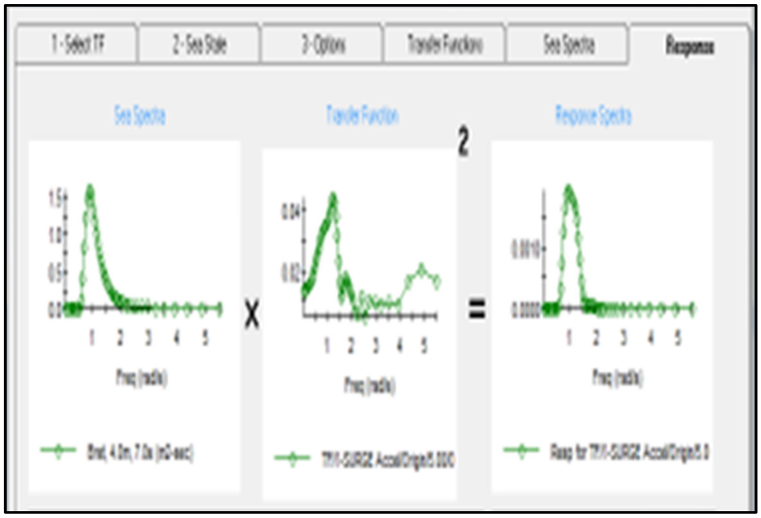

Figure 1. Sample Input for SMP Ship Response Calculator

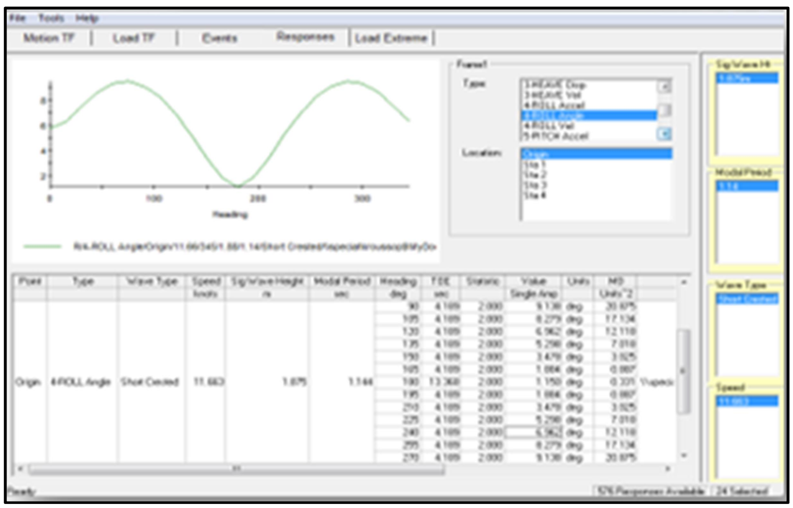

Figure 2. Sample of SMP Ship Response Results

Ship Model

This study used the LCU 1644 model, as shown in Figure 3, as a representative case for study of the LCU. Some basic characteristics of this particular version of the LCU 1610 class craft are as follows:

LCU 1627 General Characteristics (McCreight, 1998, pp. 8–9, 12–13):

- Length (Overall): 41.1 m
- Length (Between Perpendiculars): 40.84 m
- Beam: 8.8 m
- Depth 2.44 m
- Maximum Speed: 5.66 m/s (11 knots)
- Maximum Range: 2,222.4 Km (1200 Nautical Miles)
- Economic Speed: 4.12 m/s (8 knots)
- Maximum Load: 127 Metric Tones

- Crew Members: 16
- Propulsion system: 4 Detroit 6-71 diesels 519.007 KW (696 hp)

Figure 3. LCU 1644 Awaiting Loading by Beachmaster Unit
(U.S. Navy Photo)

Engineering drawings and detailed characteristics necessary to accurately model the LCU 1644 and its loading conditions using the Program of Ship Salvage Engineering (POSSE) were provided by Naval Sea Systems Command (Herbert-ABS, 2013, pp. 75–79, 115–119, 124–125). Figures 4 and 5 depict the LCU hull geometry and sample loading case as modeled in the POSSE program.

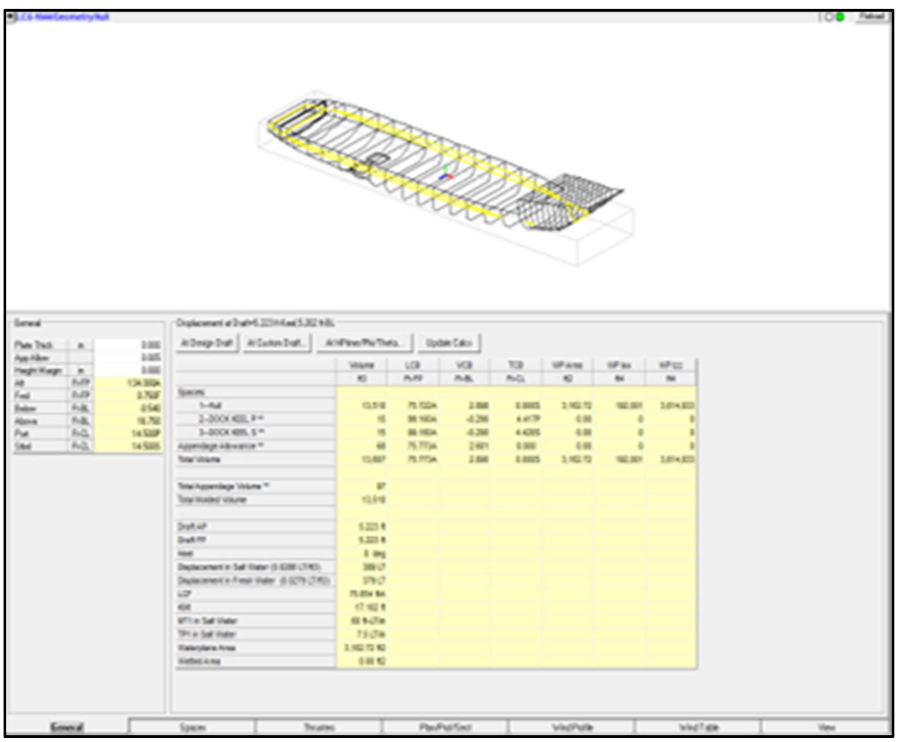

Figure 4. LCU Hull Geometry in POSSE

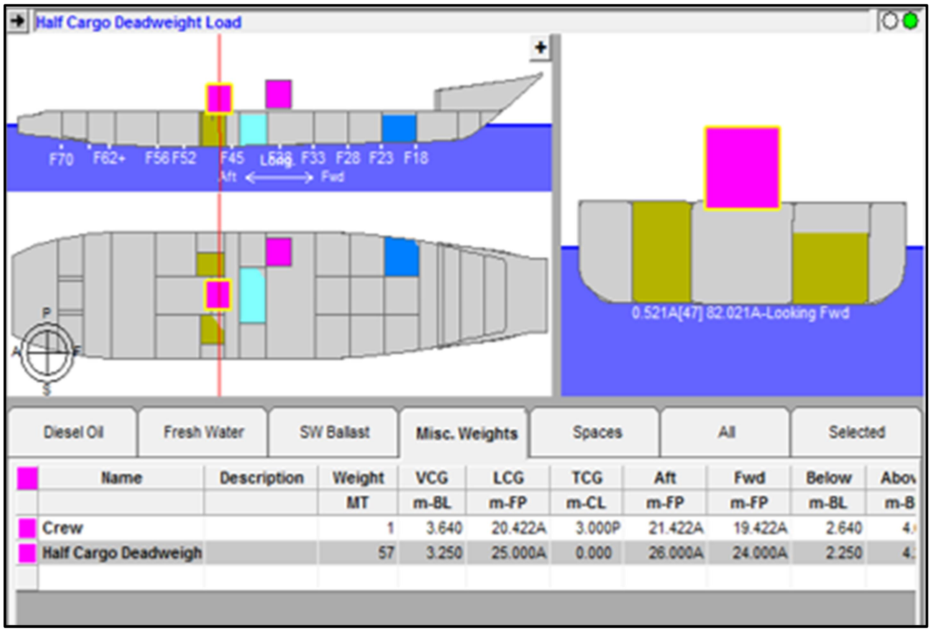

Figure 5. Lightship With Half Cargo Deadweight Loading Condition

Results and Discussion

Findings

Static Stability Assessment

The static stability of the LCU was considered adequate in all loading cases and all sea states. Calculations were performed for the lightship condition as well as LCU with half cargo deadweight and LCU with full cargo deadweight cases. The corresponding total displacement of these cases was 257, 314 and 371 metric tons, respectively. Static stability was based on the Navy's wind-rolling criterion, which was met throughout the operational trade space of the LCU. It was found that the LCU meets the minimum requirements of the reserve area as well as the maximum wind heeling arm. Numerical results were compared with analytical predictions and the agreement was found to be excellent.

Dynamic Stability Assessment

Dynamic stability of the LCU was studied for a variety of random seas and for all loading conditions as for the static stability case. The full range of LCU operational speeds was considered. Random seas results were obtained with Bretschneider two-parameter spectra and the Ochi-Hubble six-parameter spectral family. The Bretschneider family is used extensively in most standard dynamic stability and seakeeping studies and is typically found in deep waters. Two parameters, the significant wave height and the spectral peak, were utilized in order to provide coverage from developing to decaying seas. The Ochi spectral family is more common in coastal areas where a local wind-driven sea is superimposed to a long range swell. In addition, both long-crested and short-crested formulations were used for all spectra. Short crested seas are more realistic models of actual conditions in real life and are composed of a collection of long-crested unidirectional seas with a standard cosine-squared spreading. Care is taken to ensure that the total energy contained in the seaway is preserved in order to get meaningful comparisons.

Due to the large number of sea state conditions, ship speeds, loading conditions, and headings considered, we summarize the results in a set of operational recommendations as shown in Table 1. It should be emphasized that these results are preliminary and further studies are needed to arrive at more conclusive recommendations. Such sensitivity studies along with specific operational recommendations will be presented in follow on studies and accompanying technical reports.

Table 1. Ship Speed and Heading Recommendations for Typical Loading Conditions at Various Sea States

Given Variables \ Selected Variables		Sea Heading (Degrees)	Ship Speed (Knots)	
Lightship, and Half Cargo Deadweight Loading Cases			Sea Heading 0–120 and 240–360	Sea Heading 120–240
	Sea State 2	-	-	-
	Sea State 4	Avoid sea headings 60 – 90 and 270 – 300	Reduce or maintain speed close to 4	Increase or maintain speed close to 11
	Sea State 6	Avoid sea headings 60 – 90 and 270 – 300	Reduce or maintain speed close to 4	Increase or maintain speed close to 11
Full Cargo Deadweight Loading Case			Sea Heading 0–135 and 225–360	Sea Heading 135–225
	Sea State 2	-	-	-
	Sea State 4	Avoid sea headings 60 – 90 and 270 – 300	Reduce or maintain speed close to 4	Increase or maintain speed close to 11
	Sea State 6	Avoid sea headings 60 – 90 and 270 – 300	Reduce or maintain speed close to 4	Increase or maintain speed close to 11

The operational recommendations for the various loading conditions and sea states presented in Table 1 can be visualized via polar diagrams provided as Figures 6 and 7. These figures show schematically the recommended actions by the LCU operators for different loading conditions in sea states 4 and 6, and for the full range of sea headings in 15 degree increments. Such diagrams need to be refined and superimposed to specific geographical areas of operations and expected sea states in order to arrive at a recommended route within adequate safety constraints and the operational requirements at hand.

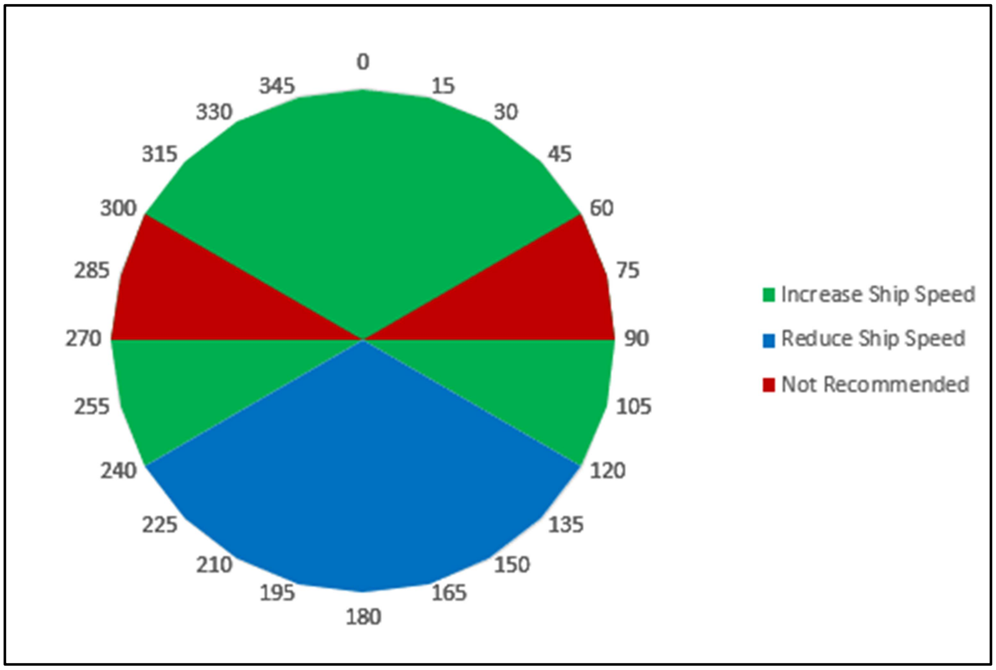

Figure 6. Sample Operational Diagram for LCU Lightship and Half Cargo Deadweight Loading Conditions in Sea States 4 and 6

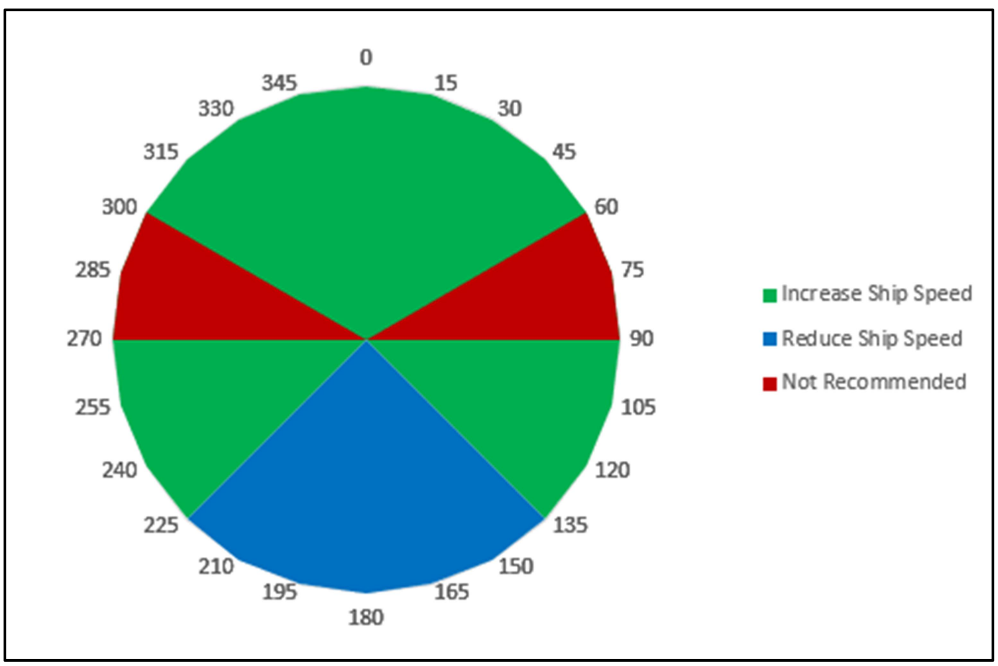

Figure 7. Sample Operational Diagram for LCU Full Cargo Deadweight Loading Conditions in Sea States 4 and 6

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Appendix

This appendix contains some of the detailed results supporting the conclusions described in the main body of the paper.

Bretschneider Spectrum Roll Angle Response for Lightship Loading Case

Table 2. Roll Angle Responses in Bretschneider (Tm = 7 sec) Short-Crested Sea Waves for LCU Lightship

Sea Heading (Degrees)	LCU Heeling Angle (Degrees)											
	Sea State 2				Sea State 4				Sea state 6			
	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s
0	0.43	0.56	0.75	0.88	2.65	3.49	4.65	5.48	7.02	9.19	12.19	14.36
15	0.51	0.65	0.82	0.95	3.20	4.02	5.13	5.95	8.44	10.55	13.42	15.56
30	0.70	0.83	0.99	1.12	4.36	5.16	6.17	6.96	11.34	13.38	16.04	18.13
45	0.90	1.01	1.16	1.28	5.56	6.28	7.20	7.95	14.26	16.14	18.60	20.62
60	1.06	1.15	1.28	1.38	6.53	7.13	7.92	8.60	16.57	18.19	20.38	22.26
75	1.16	1.23	1.32	1.41	7.15	7.59	8.20	8.77	18.03	19.28	21.08	22.71
90	1.20	1.23	1.29	1.36	7.36	7.60	8.01	8.44	18.53	19.33	20.63	21.91
105	1.16	1.16	1.18	1.23	7.16	7.18	7.36	7.63	18.05	18.33	19.05	19.88
120	1.06	1.02	1.01	1.03	6.54	6.35	6.30	6.41	16.61	16.34	16.44	16.80
135	0.90	0.84	0.80	0.79	5.58	5.19	4.96	4.92	14.13	13.51	13.06	13.00
150	0.71	0.62	0.56	0.54	4.39	3.86	3.51	3.37	11.41	10.16	9.13	8.95
165	0.52	0.42	0.36	0.33	3.24	2.63	2.23	2.04	8.53	6.97	5.95	5.45
180	0.43	0.33	0.26	0.23	2.70	2.04	1.64	1.45	7.13	5.43	4.37	3.87

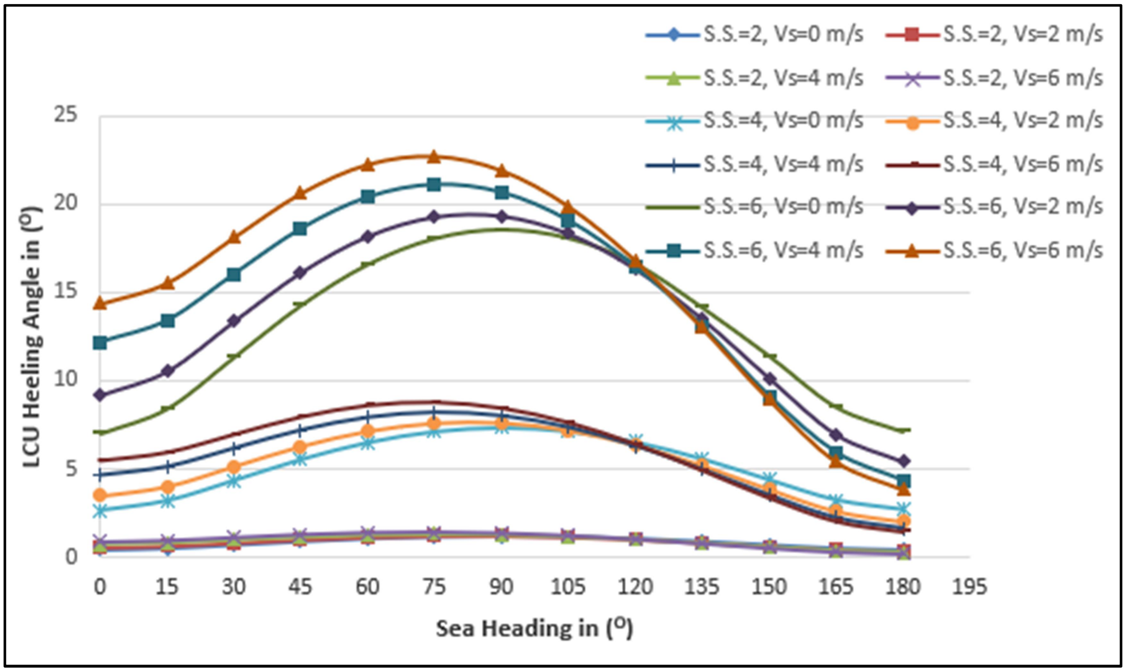

Figure 8. Heeling Angle Versus Sea Heading in Bretschneider (Tm = 7 sec) Short-Crested Sea Waves for LCU Lightship

Table 3. Roll Angle Responses in Bretschneider (Tm = 15 sec) Short-Crested Sea Waves for LCU Lightship

Sea Heading (Degrees)	LCU Heeling Angle (Degrees)											
	Sea State 2				Sea State 4				Sea state 6			
	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s
0	0.16	0.19	0.24	0.28	0.99	1.18	1.47	1.74	2.64	3.15	3.92	4.64
15	0.18	0.21	0.26	0.30	1.12	1.31	1.59	1.86	2.98	3.49	4.24	4.94
30	0.23	0.26	0.30	0.34	1.41	1.60	1.86	2.11	3.75	4.25	4.95	5.63
45	0.28	0.30	0.34	0.38	1.73	1.90	2.14	2.38	4.59	5.05	5.69	6.32
60	0.32	0.34	0.38	0.41	1.99	2.14	2.34	2.55	5.30	5.68	6.23	6.79
75	0.35	0.36	0.39	0.42	2.17	2.27	2.43	2.60	5.76	6.04	6.46	6.93
90	0.36	0.37	0.38	0.40	2.23	2.28	2.38	2.51	5.93	6.06	6.34	6.69
105	0.35	0.35	0.35	0.37	2.17	2.17	2.21	2.29	5.77	5.76	5.89	6.10
120	0.32	0.31	0.31	0.31	2.00	1.94	1.93	1.96	5.31	5.17	5.14	5.23
135	0.28	0.26	0.25	0.25	1.73	1.63	1.58	1.57	4.60	4.35	4.21	4.19
150	0.23	0.21	0.19	0.19	1.41	1.29	1.21	1.18	3.76	3.44	3.23	3.14
165	0.18	0.16	0.15	0.14	1.12	0.99	0.91	0.87	3.00	2.64	2.42	2.32
180	0.16	0.14	0.13	0.12	1.00	0.87	0.79	0.75	2.66	2.31	2.10	2.00

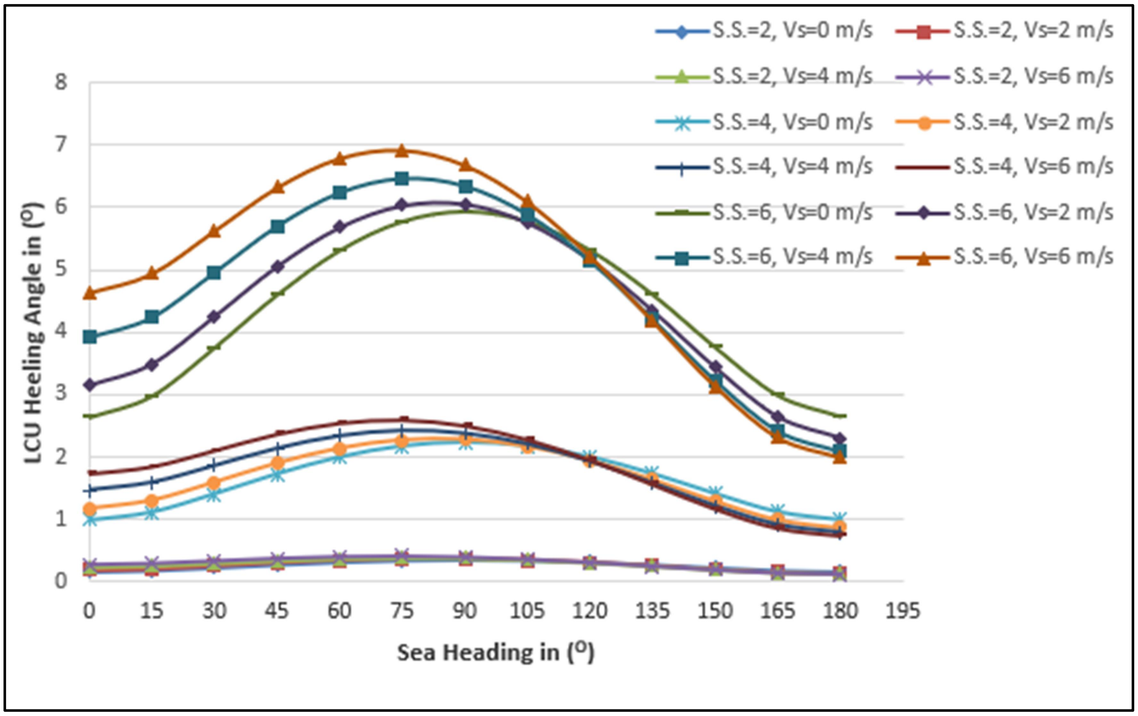

Figure 9. Heeling Angle Versus Sea Heading in Bretschneider (Tm = 15 sec) Short-Crested Waves for LCU Lightship

Bretschneider Spectrum Roll Angle Response for LCU Plus Half Cargo Deadweight Loading Case

Table 4. Angle Responses in Bretschneider (Tm = 7 sec) Short-Crested Sea Waves LCU Carrying Half Cargo Deadweight

Sea Heading (Degrees)	LCU Heeling Angle (Degrees)											
	Sea State 2				Sea State 4				Sea state 6			
	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s
0	0.51	0.72	0.98	1.16	3.14	4.48	6.06	7.14	8.13	11.36	15.32	18.11
15	0.62	0.83	1.08	1.25	3.85	5.13	6.65	7.70	9.80	12.89	16.71	19.48
30	0.87	1.06	1.29	1.45	5.30	6.50	7.91	8.92	13.06	15.98	19.63	22.40
45	1.11	1.29	1.50	1.65	6.73	7.82	9.12	10.09	16.19	18.89	22.38	25.16
60	1.32	1.46	1.64	1.77	7.86	8.79	9.94	10.83	18.57	20.97	24.22	26.89
75	1.45	1.55	1.69	1.80	8.56	9.28	10.22	10.99	20.04	22.03	24.88	27.29
90	1.49	1.55	1.64	1.72	8.81	9.26	9.93	10.51	20.54	22.02	24.29	26.26
105	1.45	1.45	1.49	1.54	8.57	8.72	9.08	9.44	20.06	20.92	22.45	23.83
120	1.32	1.27	1.26	1.27	7.88	7.71	7.75	7.87	18.61	18.76	19.43	20.12
135	1.12	1.03	0.98	0.96	6.76	6.30	6.04	5.97	16.24	15.63	15.42	15.46
150	0.87	0.75	0.67	0.64	5.34	4.63	4.17	3.97	13.14	11.81	10.87	10.44
165	0.64	0.49	0.40	0.36	3.91	3.05	2.49	2.23	9.94	8.00	6.59	5.94
180	0.52	0.37	0.27	0.22	3.22	2.28	1.67	1.39	8.32	6.03	4.44	3.71

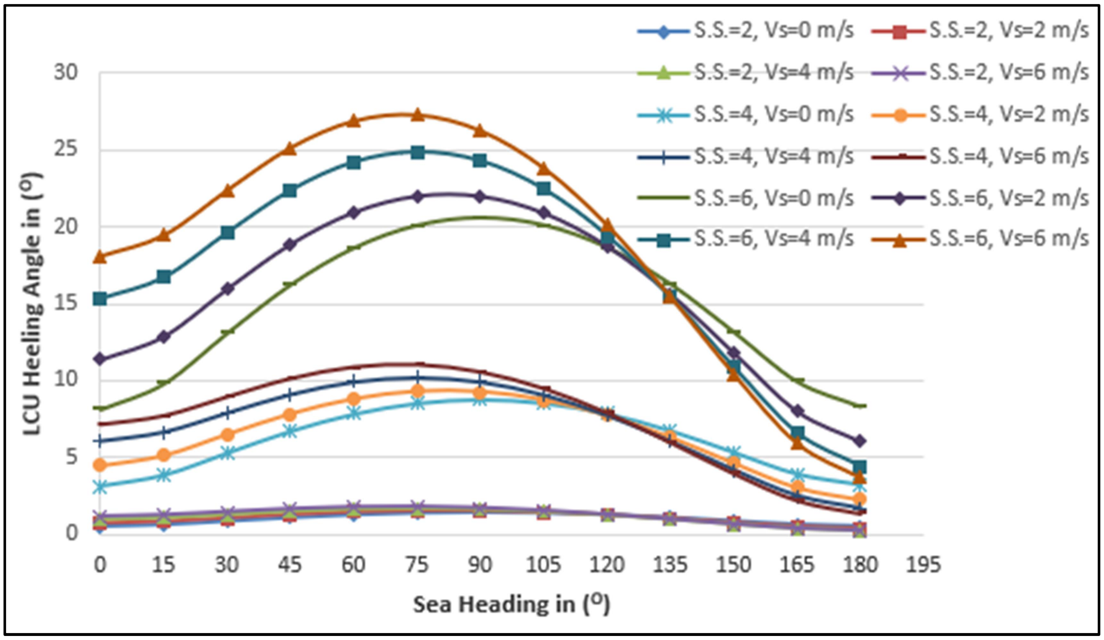

Figure 10. Heeling Angle Versus Sea Heading in Bretschneider (Tm = 7 sec) Short-Crested Waves for LCU Carrying Half Cargo Deadweight

Table 5. Roll Angle Responses in Bretschneider (Tm = 15 sec) Short-Crested Sea Waves for LCU Carrying Half Cargo Deadweight

Sea Heading (Degrees)	LCU Heeling Angle (Degrees)											
	Sea State 2				Sea State 4				Sea state 6			
	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s
0	0.17	0.22	0.30	0.36	1.07	1.39	1.84	2.24	2.86	3.70	4.88	5.96
15	0.20	0.25	0.32	0.38	1.24	1.55	1.98	2.38	3.28	4.12	5.26	6.31
30	0.26	0.31	0.37	0.43	1.60	1.90	2.31	2.68	4.23	5.03	6.11	7.10
45	0.32	0.36	0.42	0.48	1.98	2.26	2.63	2.99	5.24	5.97	6.96	7.89
60	0.37	0.41	0.46	0.51	2.31	2.54	2.86	3.18	6.06	6.68	7.54	8.39
75	0.41	0.43	0.47	0.51	2.52	2.69	2.94	3.20	6.59	7.05	7.75	8.46
90	0.42	0.43	0.46	0.49	2.59	2.68	2.85	3.05	6.78	7.04	7.53	8.07
105	0.41	0.41	0.42	0.44	2.52	2.53	2.61	2.73	6.60	6.65	6.91	7.25
120	0.37	0.36	0.36	0.37	2.31	2.24	2.24	2.29	6.07	5.92	5.95	6.09
135	0.32	0.30	0.29	0.29	1.99	1.85	1.79	1.78	5.25	4.92	4.76	4.73
150	0.26	0.23	0.21	0.20	1.61	1.43	1.32	1.28	4.25	3.79	3.51	3.40
165	0.20	0.17	0.15	0.14	1.25	1.05	0.93	0.88	3.31	2.80	2.49	2.36
180	0.17	0.14	0.12	0.12	1.09	0.89	0.78	0.73	2.89	2.37	2.07	1.95

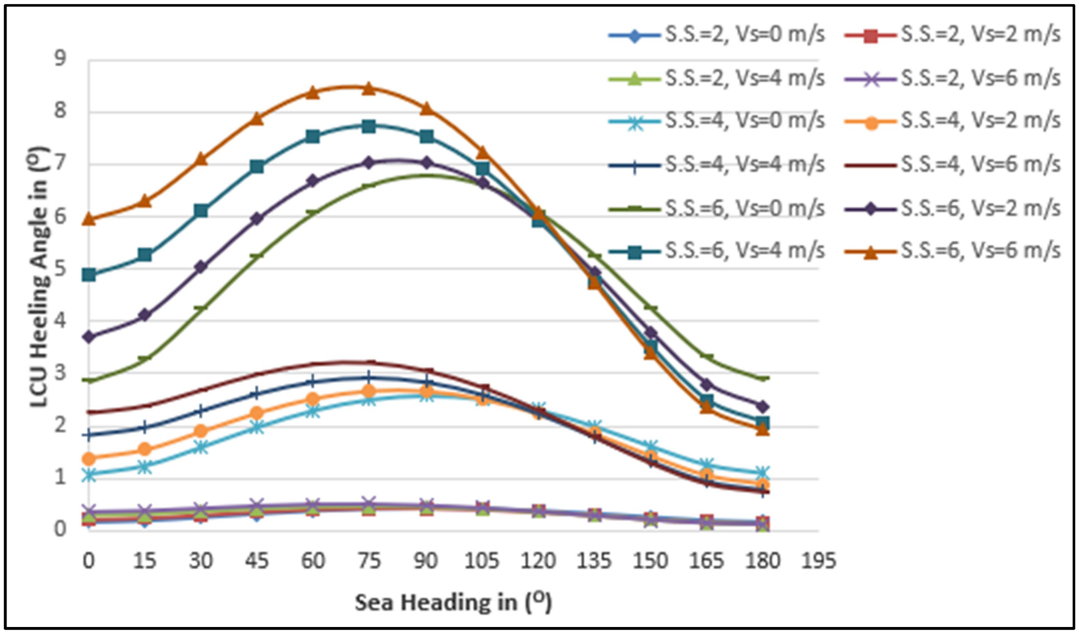

Figure 11. Heeling Angle Versus Sea Heading in Bretschneider (Tm = 15 sec) Short-Crested Waves for LCU Carrying Half Cargo Deadweight

Roll Angle Responses in Bretschneider Spectrum for LCU Plus Full Cargo Deadweight Loading Case

Table 6. Roll Angle Responses in Bretschneider (Tm = 7 sec) Short-Crested Sea Waves for LCU Carrying Full Cargo Deadweight

Sea Heading (Degrees)	LCU Heeling Angle (Degrees)											
	Sea State 2				Sea State 4				Sea state 6			
	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s
0	0.62	0.94	1.21	1.39	3.76	5.67	7.31	8.44	9.28	13.49	17.68	20.65
15	0.77	1.07	1.32	1.52	4.64	6.40	7.98	9.19	11.07	15.00	19.14	22.29
30	1.08	1.35	1.58	1.80	6.33	7.90	9.39	10.73	14.44	18.06	22.17	25.60
45	1.39	1.63	1.83	2.06	7.92	9.34	10.76	12.18	17.53	20.90	24.99	28.59
60	1.64	1.84	2.00	2.23	9.12	10.37	11.68	13.09	19.81	22.88	26.85	30.45
75	1.81	1.95	2.06	2.27	9.86	10.90	12.00	13.32	21.19	23.88	27.53	30.92
90	1.86	1.94	1.99	2.17	10.12	10.86	11.68	12.81	21.65	23.85	26.95	29.95
105	1.81	1.82	1.82	1.95	9.87	10.28	10.73	11.59	21.21	22.79	25.11	27.51
120	1.65	1.60	1.54	1.62	9.14	9.17	9.21	9.76	19.85	20.68	22.01	23.63
135	1.40	1.29	1.19	1.22	7.96	7.60	7.25	7.45	17.60	17.56	17.76	18.47
150	1.09	0.94	0.82	0.79	6.39	5.69	5.03	4.88	14.55	13.60	12.71	12.50
165	0.79	0.61	0.47	0.41	4.74	3.76	2.93	2.55	11.26	9.43	7.68	6.75
180	0.64	0.45	0.29	0.23	3.90	2.75	1.84	1.41	9.55	7.13	4.88	3.75

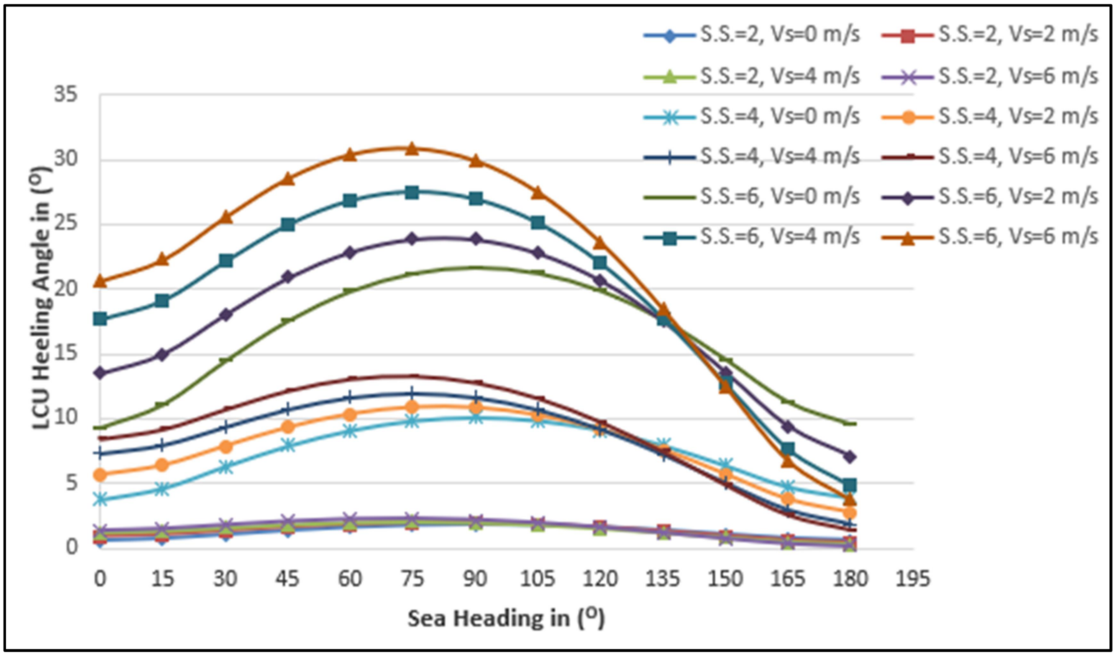

Figure 12. Heeling Angle Versus Sea Heading in Bretschneider (Tm = 7 sec) Short-Crested Waves LCU Carrying Full Cargo Deadweight

Table 7. Roll Angle Responses in Bretschneider (Tm = 15 sec) Short-Crested Sea Waves for LCU Carrying Full Cargo Deadweight

Sea Heading (Degrees)	LCU Heeling Angle (Degrees)											
	Sea State 2				Sea State 4				Sea state 6			
	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s	Vs=0 m/s	Vs=2 m/s	Vs=4 m/s	Vs=6 m/s
0	0.19	0.28	0.36	0.45	1.20	1.71	2.26	2.77	3.18	4.49	5.94	7.28
15	0.23	0.31	0.39	0.47	1.42	1.90	2.43	2.95	3.72	4.98	6.37	7.74
30	0.30	0.38	0.45	0.54	1.87	2.32	2.80	3.35	4.88	6.04	7.33	8.73
45	0.38	0.45	0.51	0.60	2.35	2.75	3.19	3.73	6.06	7.10	8.28	9.67
60	0.45	0.50	0.56	0.64	2.74	3.08	3.44	3.97	6.99	7.87	8.91	10.25
75	0.49	0.53	0.57	0.64	2.99	3.24	3.52	3.99	7.57	8.26	9.11	10.31
90	0.51	0.53	0.55	0.61	3.08	3.23	3.40	3.79	7.77	8.23	8.83	9.83
105	0.49	0.49	0.50	0.54	3.00	3.03	3.10	3.38	7.58	7.77	8.08	8.82
120	0.45	0.43	0.42	0.45	2.75	2.67	2.64	2.81	7.00	6.91	6.92	7.39
135	0.38	0.36	0.33	0.34	2.36	2.20	2.08	2.14	6.08	5.73	5.49	5.66
150	0.31	0.27	0.24	0.23	1.89	1.66	1.49	1.46	4.92	4.38	3.96	3.89
165	0.23	0.19	0.16	0.15	1.44	1.18	1.00	0.93	3.78	3.13	2.67	2.47
180	0.20	0.15	0.13	0.12	1.23	0.96	0.79	0.72	3.25	2.55	2.11	1.93

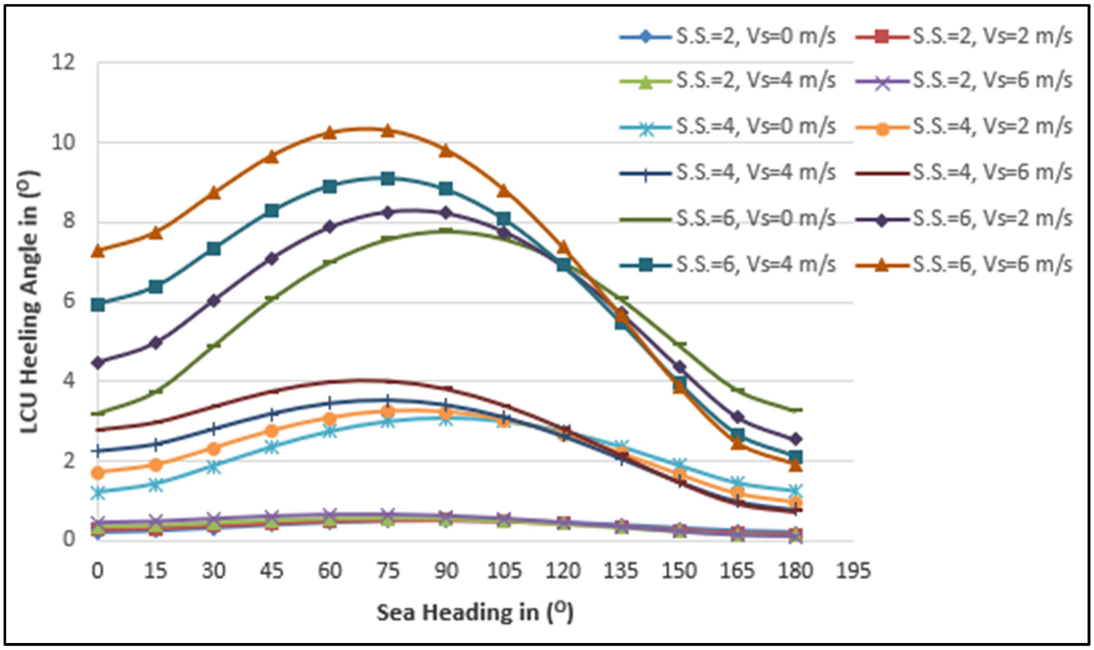

Figure 13. Heeling Angle Versus Sea Heading in Bretschneider (Tm = 15 sec) Short-Crested Waves LCU Carrying Full Cargo Deadweight

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