A statistical representation of landing craft yaw response to surf zone conditions

Stanley Keith Martin

Follow this and additional works at: https://scholarsjunction.msstate.edu/td

Recommended Citation
Martin, Stanley Keith, "A statistical representation of landing craft yaw response to surf zone conditions" (2020). Theses and Dissertations. 263.
https://scholarsjunction.msstate.edu/td/263

This Dissertation is brought to you for free and open access by the Theses and Dissertations at Scholars Junction. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Scholars Junction. For more information, please contact scholcomm@msstate.libanswers.com.
A statistical representation of landing craft yaw response to surf zone conditions

By

Stanley Keith Martin

A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in Civil Engineering
in the Department of Civil & Environmental Engineering

Mississippi State, Mississippi

May 2020
A statistical representation of landing craft yaw response to surf zone conditions

By

Stanley Keith Martin

Approved:

________________________

John J. Ramirez
(Major Professor)

________________________

Seamus F. Freyne
(Committee Member)

________________________

William H. McAnally
(Committee Member)

________________________

Jane McKee Smith
(Committee Member)

________________________

Greg W. Burgreen
(Committee Member)

________________________

Farshid Vahedifar
(Graduate Coordinator)

________________________

Jason M. Keith
Dean
James Worth Bagley College of Engineering
Yaw response of landing craft transiting the surf zone is a significant concern for U.S. military forces engaged in amphibious landing operations. However, this subject is not well understood and few investigations have been dedicated to its study. The present investigation used laboratory conditions to investigate and determine variables important to the yaw response of shallow-hulled landing craft. Using a sloped wave basin outfitted with wave gauges and a motion capture system, a unique dataset was obtained regarding the six degree of freedom motion of the landing craft model under a variety of wave conditions. The dataset was analyzed with both linear and nonlinear data analysis techniques. The results of these analyses illustrated variables significantly impacting shallow-hulled landing craft yaw response and were used to develop a statistical representation of landing craft utility (LCU) yaw response.
DEDICATION

To my wife, Anita, for her support and patience while this idea matured. Without you I would have quit long ago. And to Mr. Tom McKenna who sparked the idea for this work.
ACKNOWLEDGEMENTS

Anyone who tells you a dissertation is solitary endeavor has never worked on a major research effort. Your name may be in blank next to the word author or PhD candidate and, yes, you do a lot of heavy lifting/thinking. However, you have company on that journey from the family members who cover the mundane day-to-day tasks to the co-workers who take some of your normal workload so you can concentrate, to the dissertation director who patiently guides you through the cycles of success and failure. There are lots of people to acknowledge so if I miss someone it’s probably because my brain is addled in throws of trying to finishing the writing. First and foremost, I thank my heavenly father. Every breath, every heartbeat, every synapse firing is a gift from Him and as painful as this process seemed at times it was a “get to” provided by Him. Thanks to Mary Bryant and Catie Dillon for running the waves calculations, helping with the basin setup, and all for all those “mad” Matlab skills. Thanks to the deep draft navigation group for taking so much of the simulation workload off me so I could concentrate on my dissertation. A huge thank you to Kiara Pazan. You provided invaluable technical support more times than I can count. And finally thanks to Jackie Pettway for refusing to let me quit when all seemed lost.
TABLE OF CONTENTS

DEDICATION.................................................................................................................. ii

ACKNOWLEDGEMENTS.................................................................................................. iii

LIST OF TABLES .................................................................................................................. vi

LIST OF FIGURES ................................................................................................................ vii

CHAPTER

I. INTRODUCTION............................................................................................................. 1

1.1 Brief discussion of U.S. Military amphibious operations ........................................ 1

1.2 Research objectives .................................................................................................. 3

1.3 Approach ..................................................................................................................... 4

II. LANDING CRAFT IN THE SURF ZONE ..................................................................... 6

2.1 Vessels ......................................................................................................................... 6

2.2 Wave and surf zone characteristics ............................................................................. 7

2.3 Challenges and hazards in amphibious transits ........................................................... 14

2.4 Design considerations for amphibious craft ................................................................. 15

2.5 State of research of surf zone condition impacts on amphibious craft ....................... 17

2.6 Comparison of the present research effort with past research ................................... 20

III. EXPERIMENT COMPONENTS AND DATA COLLECTION .................................... 24

3.1 Experiment scaling ..................................................................................................... 24

3.2 Experiment space ....................................................................................................... 28

3.3 Data collection lane and berthing area ....................................................................... 35

3.4 Scale landing craft model ........................................................................................... 39

3.5 Wave gauges ............................................................................................................... 47

3.6 Water level consistency ............................................................................................. 51

3.7 Six degree of freedom data collection system ............................................................. 52

3.8 Data collection syncing .............................................................................................. 57

3.9 Experimental wave conditions .................................................................................... 59

3.10 Data collection and processing ................................................................................ 61

3.10.1 Collection method ............................................................................................... 61

3.10.2 Processing .............................................................................................................. 66
IV. DATA ANALYSIS METHODS .................................................................68

4.1 Approach to data analysis ...............................................................68
4.2 Variables affecting yaw response ...................................................69
4.3 Morison equation discussion .........................................................70
4.4 Data extraction techniques ............................................................73
  4.4.2 Polygon method .................................................................74
  4.4.3 Motion capture only method ....................................................76
4.5 Water Surface Elevation Data analysis – Polygon data extraction ........77
4.6 Data analysis – McCapS data extraction .........................................81
  4.6.1 Cross spectral analysis ..........................................................81
  4.6.2 Linear regression analysis ......................................................84
  4.6.3 Polynomial regression analysis ..............................................86

V. MODEL DEVELOPMENT ......................................................................95

5.1 Description of nonlinear mathematical model/analysis ......................95
5.2 Uncertainty in the cross-spectral analysis .......................................101
5.3 Linear model description ...............................................................103
5.4 Final Model .................................................................................107
5.5 Uses of the model .........................................................................113

VI. CONCLUSIONS ..............................................................................114

6.1 Experimental results ......................................................................114
6.2 Statistical response model .............................................................115
6.3 Limitations of model ....................................................................116
6.4 Future research ............................................................................117

REFERENCES .......................................................................................121

APPENDIX

A. HEADING REGRESSION PLOTS .........................................................125

B. RESIDUAL YAW DISTRIBUTION PLOTS .........................................130

C. MODEL VALIDATION PLOTS ............................................................135

D. IRREGULAR WAVE MODEL COMPARISON PLOTS .........................150
LIST OF TABLES

Table 2.1 LCM dimensions, prototype vs. model .................................................. 20
LIST OF FIGURES

Figure 2.1  Wave Orbital Motion Effects on a Ship (Graphic from Pearson Prentice Hall, 2006) 9
Figure 2.2  Shape of Wave Orbital Motion in Deep Water (Graphic Courtesy Dr. Jane M. Smith, USACE) ........................................................................................................... 10
Figure 2.3  Wave Orbital Shape Differences between Deep and Shallow Water (Graphic from Shore Protection Manual, USACE) ......................................................................... 10
Figure 2.4  Head, following, beam, and quartering seas, respectively (Graphic Courtesy U.S. Naval Academy) ........................................................................................................... 16
Figure 2.5  Six degrees of freedom for vessel motion (Graphic Courtesy U.S. Naval Academy) ..................................................................................................................... 17
Figure 2.6  DUKW-21 Concept Vehicle ................................................................................. 18
Figure 3.1  LSTF basin in use (sediment traps in the foreground) .................................... 29
Figure 3.2  Plan view diagram of LSTF layout .................................................................. 30
Figure 3.3  LSTF sediment traps ...................................................................................... 31
Figure 3.4  Berm across the LSTF .................................................................................. 32
Figure 3.5  Berm ramp under construction .................................................................... 33
Figure 3.6  Completed Ramp .......................................................................................... 33
Figure 3.7  MTS Wave Generators ................................................................................... 34
Figure 3.8  Layout of Data Collection Area for Round 1 .................................................. 36
Figure 3.9  Layout of Data Collection Area for Rounds 2 and 3 ....................................... 36
Figure 3.10 Data Collection/Calibration Zone .................................................................. 37
Figure 3.11 Berthing Area .............................................................................................. 39
Figure 3.12 1:32 Scale Landing Craft Utility Model – side view .................................... 42
Figure 3.13 1:32 Scale Landing Craft Utility Model – plan view .................................................43
Figure 3.14 1:32 Scale Landing Craft Utility Model – stern view .............................................44
Figure 3.15 1:32 Scale Landing Craft Utility Model – view of stern cover and stern reflectors ..45
Figure 3.16 Remote Control for Landing Craft Utility Model .....................................................46
Figure 3.17 Akamina Wave Gauge ...............................................................................................49
Figure 3.18 Instrumentation bridge ..............................................................................................50
Figure 3.19 Control building ........................................................................................................50
Figure 3.20 View of LSTF basin from control building .................................................................51
Figure 3.21 LSTF Water Level Gauge ..........................................................................................52
Figure 3.22 Qualisys Oqus 300 Camera ......................................................................................53
Figure 3.23 Calibration Wands ....................................................................................................55
Figure 3.24 Calibration Process .....................................................................................................55
Figure 3.25 Camera field of view tested but not used .................................................................56
Figure 3.26 Final camera locations and field of view for Round One .........................................57
Figure 3.27 Triggering Mechanism ...............................................................................................58
Figure 3.28 Wave Signals (Graphic from Mary Bryant, USACE) ..................................................60
Figure 3.29 Wave spectrum (bottom) and signal (top) for Wave ID 2 ..........................................60
Figure 3.30 Beginning of Model Transit .....................................................................................64
Figure 3.31 Model Midway through Transit .................................................................................65
Figure 3.32 Model Approaching Beach .......................................................................................65
Figure 3.33 Water Removal from Hull .........................................................................................66
Figure 4.1 Free Body Diagram of LCU – Plan View .................................................................68
Figure 4.2 LSTF basin data polygons ..........................................................................................74
Figure 4.3 LCU Cg position with respect to water surface elevation .........................................75
Figure 4.4 LCU Cg track through wave gauge polygons .............................................................76
Figure 4.5  Yaw vs Rising Water Level (wave trough to crest) .............................................78
Figure 4.6  Yaw vs. Falling Water Level (wave crest to trough) ............................................79
Figure 4.7  Yaw vs. Water Surface Elevation Change, Polygon 10 ..........................................80
Figure 4.8  Cross-Spectral Analysis of an LCU Model Transit ................................................84
Figure 4.9  Example of Cross Covariance of Heading and Yaw ..............................................85
Figure 4.10 Yaw vs Heading with a 0.5 second lag .................................................................86
Figure 4.11 Third order regression on rotated yaw and heading data for Wave ID5 ..................87
Figure 4.12 Residual Yaw Distribution - Wave Id 2 ............................................................89
Figure 4.13 Residual yaw vs initial wave steepness with a lag of 0.5 s .................................91
Figure 4.14 Residual yaw vs. initial wave steepness with a lag of 1 s .................................92
Figure 4.15 Second residual yaw data set vs. depth ..........................................................93
Figure 5.1  Flow Chart of Cross-Spectral Analysis .................................................................100
Figure 5.2  Concatenated Wave Gauge Data versus MoCapS z-data (Wave ID2) .................103
Figure 5.3  Linear regression of initial wave steepness to median yaw ..................................106
Figure 5.4  Negative heading regression equation comparison ..........................................108
Figure 5.5  Positive heading regression equation comparison ..............................................108
Figure 5.6  Model of Wave ID 2 – Negative Headings .........................................................110
Figure 5.7  Model of Wave ID 2 – Positive Headings ..........................................................111
Figure 5.8  Model of Wave Id 2, Irregular Waves, Seed 1 – Negative Headings ....................112
Figure 5.9  Model of Wave Id 2, Irregular Waves, Seed 1 – Positive Headings .......................112
Figure 6.1  U.S. Marine Corps personnel exiting an LCU (picture courtesy of the U.S. Navy) 120
Figure A.1  Third order regression on rotated yaw and heading data for Wave ID2 ............126
Figure A.2  Third order regression on rotated yaw and heading data for Wave ID3 ............126
Figure A.3  Third order regression on rotated yaw and heading data for Wave ID5 ............127
Figure A.4  Third order regression on rotated yaw and heading data for Wave ID11 ............127
Figure D.2  Model of Wave id 2, Seed 1 – Positive Headings .............................................. 152
Figure D.3  Model of Wave id 2, Seed 2 – Negative Headings ............................................. 153
Figure D.4  Model of Wave id 2, Seed 2 – Positive Headings ............................................... 154
Figure D.5  Model of Wave id 2, Seed 3 – Negative Headings .............................................. 155
Figure D.6  Model of Wave id 2, Seed 3 – Positive Headings ............................................... 156
Figure D.7  Model of Wave id 3, Seed 1 – Negative Headings ............................................... 157
Figure D.8  Model of Wave id 3, Seed 1 – Positive Headings ............................................... 158
Figure D.9  Model of Wave id 3, Seed 2 – Negative Headings ............................................... 159
Figure D.10 Model of Wave id 3, Seed 2 – Positive Headings ............................................... 160
Figure D.11 Model of Wave id 3, Seed 3 – Negative Headings ............................................... 161
Figure D.12 Model of Wave id 3, Seed 3 – Positive Headings ............................................... 162
Figure D.13 Model of Wave id 5, Seed 1 – Negative Headings ............................................... 163
Figure D.14 Model of Wave id 5, Seed 1 – Positive Headings ............................................... 164
Figure D.15 Model of Wave id 5, Seed 2 – Negative Headings ............................................... 165
Figure D.16 Model of Wave id 5, Seed 2 – Positive Headings ............................................... 166
Figure D.17 Model of Wave id 5, Seed 3 – Negative Headings ............................................... 167
Figure D.18 Model of Wave id 5, Seed 3 – Positive Headings ............................................... 168
Figure D.19 Model of Wave id 17, Seed 1 – Negative Headings ............................................. 169
Figure D.20 Model of Wave id 17, Seed 1 – Positive Headings ............................................. 170
Figure D.21 Model of Wave id 17, Seed 2 – Negative Headings ............................................. 171
Figure D.22 Model of Wave id 17, Seed 2 – Positive Headings ............................................. 172
Figure D.23 Model of Wave id 17, Seed 3 – Negative Headings ............................................. 173
Figure D.24 Model of Wave id 17, Seed 3 – Positive Headings ............................................. 174
Figure D.25 Model of Wave id 18, Seed 1 – Negative Headings ............................................. 175
Figure D.26 Model of Wave id 18, Seed 1 – Positive Headings ............................................. 176
Figure D.27 Model of Wave id 18, Seed 2 – Negative Headings ........................................... 177
Figure D.28 Model of Wave id 18, Seed 2 – Positive Headings.............................................. 178
Figure D.29 Model of Wave id 18, Seed 3 – Negative Headings .............................................. 179
Figure D.30 Model of Wave id 18, Seed 3 – Positive Headings.............................................. 180
CHAPTER I
INTRODUCTION

1.1 Brief discussion of U.S. Military amphibious operations

The United States Military has been conducting amphibious operations since the inception of the country. In March of 1776, the first American amphibious operation was conducted. It was a bloodless affair in which the Colonial forces landed on one of the Bahama Islands near Fort Montagu which they captured. Fort Nassau, the other fort on the island was captured the next day allowing the Americans to secure the town and the island’s military stores excluding the gunpowder [1].

The Battle of New Orleans was a famous, successful American defense against a British Amphibious operation after the end of the War of 1812. The Americans conducted two very successful amphibious landings at the Battle of York (capital of colonial province of Upper Canada) and the Battle of George (across the Niagara River from Youngstown, New York) capturing a British held town and fort, respectively [1].

Approximately fifty amphibious landings were conducted by the Union Army during the American Civil War. One of the most notable of these landings was the Second Battle of Fort Fisher in January 1865 near Wilmington, North Carolina. The fort was considered the largest, most powerful fort at the time and sometimes referred to as the “Gibraltar of the South”. The Union forces were able to take the fort through simultaneous land and amphibious assaults. [1]. At the very beginning of the Spanish-American War, American forces assaulted the beaches of
Guantanamo Bay and Santiago in Cuba [2]. However, it is World War II’s (WWII) Allied Normandy Invasion and U.S. Pacific Island hopping campaigns that spring to mind when most people think of amphibious operations.

Over time the types of craft used to perform these landings have changed, but the broad mission has remained the same: get personnel and material onto the beach as efficiently and safely as possible. The safety and efficiency of any landing is directly related to the surf conditions that exist at the time of the surf zone transit and the response of the craft to those conditions.

The small size and draft of amphibious craft means they are not seaworthy in the traditional sense of the word [3]. And yet these craft are operated in regions of the ocean where some of the most hazardous hydrodynamic conditions exist. In WWII the predominant number of amphibious craft casualties were caused by the “perils of the sea” [3] and not by direct interaction with the enemy. Fifty percent of boat losses at Iwo Jima resulted from either swamping or broaching that occurred as the craft attempted to climb the steep beach of volcanic ash [3]. Almost 700 craft were lost or damaged at the Normandy beachhead due to wave heights of approximately eight feet. The first two months of the operations at Normandy were studied and it was discovered [3] the tonnage of material transported to the beach was inversely proportional to the wave height. This is not to say that operational results during WWII were all negative.

The Allies recognized early in WWII that knowledge of surf conditions (winds, waves, currents, and tides) would play an important role in the success of the war effort and studied them extensively. They obtained superior, accurate knowledge of these conditions and this contributed significantly to amphibious operational successes at Normandy and Sicily. The Allies were able
to land craft in conditions considered too extreme by their adversaries and therefore gained an additional advantage that many times proves crucial to successful military operations in contested environments, the element of surprise.

Amphibious operations are by their very nature mission critical to the United States Military. The first few waves of landings are often the initialization of much larger operations with objectives farther inland. These operations can be forcible entry or Humanitarian Assistance and Disaster Relief (HADR). In either case the timing of an operation is crucial and delaying amphibious transits until conditions are more favorable is oftentimes not an option. Commanders must weigh the importance of a mission compared with the risk to personnel, material, and the craft itself.

Improved understanding and methods of predicting vessel response to surf zone forcings could lead to improved craft design. The current research could also improve the development of Go/No-Go thresholds for landings most likely in the form of an improved Modified Surf Index [3]. These improvements will lead to fewer craft casualties, increased safety to military personnel, and overall improved mission success rates.

1.2 Research objectives

Current amphibious operational planning has no means of representing yaw response of displacement landing craft in the surf zone. Very little research has been conducted in the area of landing craft motion vessel response in the six degrees of freedom (6DoF) in the surf zone. Those studies that did examine craft motion in the surf zone were either restrained by towing carriages or considered only concept craft unrepresentative of the current fleet. The present investigation asserts there are specific surf zone parameters (e.g., wave height, steepness, craft heading, etc) which impact the yaw response of shallow-hulled landing craft. Yaw is one of the
6DoF used to describe a ship’s responses to waves. The objective of the present research is to develop a statistical representation of the yaw response of a Landing Craft Utility (LCU) as it transits an idealized surf zone. The mathematical relationship is developed through a robust analysis of physical model data collected during scale model experiments of LCU transits across a sloped wave basin. The mathematical relationship developed is in the form of a statistical model and is evaluated based on vessel model tracks obtained during the experimental transits.

Ship motion in a wave environment is described using the 6DoF: Surge, sway, heave, pitch, roll, and yaw. Surge, sway, and heave are translational movements in which all points on the ship move along an individual ship axis. Roll, pitch, and yaw represent movements rotating about one of the three ship’s axes and are also called Euler Angles. The present research considers the rotation for roll, pitch, and yaw to be about the x, y, and z ship axes, respectively.

Existing vessel motion formulations are defined based on response to deep water waves where wave parameters such as steepness and breaking are only effected by wind forcing. In the surf zone bathymetric variability impacts the wave shape and speed through the processes of refraction, shoaling, breaking, and nonlinear interactions.

1.3 Approach

Collecting landing craft response data in the surf zone at an actual beach is difficult and presents a number of challenges. There are many variables that change not just daily but oftentimes minute to minute. Tide and wind forcings which drive wave development are affected by storm and frontal passage. Winds can have magnitudes and directions which are different at midday from their values in the morning or evening. The landing craft itself has a human operator who may not make the transit from deep water to the beach on the same line from transit to transit and all the while the environmental conditions are changing and effecting how he or she
will navigate the surf zone. Bathymetric conditions in high-wave environments also evolve over scales of hours, and the bathymetry in turn modifies the local wave conditions.

In order to better understand the basic processes affecting landing craft yaw movement, the number of variables was reduced as was the range of their variability. First and foremost, the experiments were moved from the prototype environment to the laboratory. All experiments were carried out in the U.S. Army Engineer Research and Development Center’s (ERDC) Large-Scale Transport Facility (LSTF) using a 1:32 scale model of the Landing Craft Utility (LCU). A full description of the experimental and data collection techniques used to collect the LCU response data is detailed in Chapter 3. Chapter 2 contains the results of the literature review of research carried out regarding landing craft as well as a discussion of surf zone processes with respect to wave parameters including shoaling, wave shape, and breaking. The statistical model used in this research is described in Chapter 4. The data analysis techniques and results of the data analysis is detailed in Chapter 5 with Chapter 6 is comprised of the conclusions and a summary.
CHAPTER II
LANDING CRAFT IN THE SURF ZONE

In many cases, landing craft are transported in the well decks of larger ships to the Area of Operation (AO), the first broad component of an amphibious operation. Once the transport ship arrives in the AO, the landing craft then makes multiple transits between the transport ship and beach, moving material and personnel. The U.S. military has used and continues to use these craft for humanitarian missions such as providing disaster relief. However, the primary mission of these craft is to transport material and personnel from ship-to-shore in contested environments with the objective of attacking and capturing land-based objectives.

2.1 Vessels

The U.S. military uses a range of craft in landing operations including the AAV, the LCAC, and the LCU. The Assault Amphibious Vehicle (AAV) is primarily used to transport personnel from ship-to-shore. The AAV is an armored, tracked vehicle which travels at significantly slower speeds (6-7 knots) than other craft in the fleet. On the other end of the speed spectrum is the Landing Craft Air-Cushion (LCAC) which travels at speeds well over 30 knots. As its name implies the LCAC travels over land and sea on a cushion of air and does not have a hull like a conventional water craft. The LCAC is used to transport equipment and personnel.

The landing craft used for the present research is the Landing Craft utility (LCU) a shallow-drafting craft. It drafts six feet empty and seven feet at the stern with a 1:65 trim when loaded. This craft is the workhorse of the U.S. military’s amphibious fleet and is what comes to
mind when most people consider what an amphibious craft looks like as it most closely resembles the Landing Craft Vehicle and Personnel (LCVP) used in the Normandy invasion. The LCU travels at maximum speeds between 11 and 12 knots and is used to move personnel and equipment.

2.2 Wave and surf zone characteristics

Waves are the primary environmental threat to amphibious craft transits. This is especially true in the surf zone where wave refraction, shoaling, and breaking are affected by the bathymetry along the vessel approach. While the shape and size of surf zone waves are affected by changes in water depth, the period is not due to the conservation of the number of waves [6].

Waves in the surf zone are generated by winds local to the beach and winds or storms from far offshore as well. The winds can be a result of frequently occurring simple pressure gradients or of much sharper gradients associated with frontal passage and/or storms in the same local and far offshore locations. The energy transferred to the waves is directly proportional to the square of the velocity of the wind, the duration of the wind, and the fetch over which the wind blows. Swell is also a wind-generated wave, an undulation of the sea surface, but is produced by storms far offshore, not by winds at the site. While traversing deep water, the swell does not behave in a particularly violent manner and is often masked by shorter-period wind waves [3]. The swell propagates away from the area of wind forcing. As swell enters intermediate and shallow water depths (defined as depths less than half the wave length) the wave height increases significantly and can produce higher, steeper, and sometimes violent surf conditions. Storm forecasting is a good tool in determining wave conditions in the surf zone as a result of swell. However, it is important to note— for amphibious operational planning purposes—the swell associated with the storm can originate hundreds of miles from the AO and can arrive well in
advance of the storm. Timing is critical to avoid the surf conditions related to the storm-generated swell.

In deep water, water particle velocity and pressure fluctuations are zero near the bottom. This is not the case in the surf zone where the water is much shallower. Here wave transformation is influenced by the slope of the bottom as well as bed roughness attributed to bed material, including sand grains or bedforms that range from small ripples to large dunes. These characteristics are directly responsible for wave shoaling and dissipation in the near shore. The bathymetric gradients affect the wave direction and height differently based on wave period and wave orientation relative to the bottom contour [6]. Contours parallel to the shoreline represent the simplest case, a two-dimensional problem and is the one considered in the present research.

In the surf zone the depth of the water is significantly shorter than the wavelength of the incoming waves in deep water. The ratio of depth to wavelength where the waves begin to “feel” the bottom is approximately one half [12]. Figures 2.1-2.3 illustrates the orbital motion associated with waves. Figure 2.1 shows how the motion might affect a toy boat in deep water. Figure 2.2 illustrates the decrease in size of the deepwater orbital motion from the surface to the sea bottom. Finally, the changes in wave orbital motions associated with the transition from deep water into shallow water are depicted in Figure 2.3. Note how the shape of the motion goes from circular in deep water, where the ratio of depth to wavelength is greater than 0.5, to elliptical in shallow water, where that same is ratio is less than 0.04. Also, notice that the orbital motion does not decay to zero in shallow water and the elliptical shape flattens with an overall movement parallel to the direction of wave propagation. In linear wave theory, as is being considered in the present research, the elliptical orbits are closed. In higher order theories these orbits are not closed, but there is an onshore mass transport.
Figure 2.1  Wave Orbital Motion Effects on a Ship (Graphic from Pearson Prentice Hall, 2006)
Figure 2.2  Shape of Wave Orbital Motion in Deep Water (Graphic Courtesy Dr. Jane M. Smith, USACE)

Figure 2.3  Wave Orbital Shape Differences between Deep and Shallow Water (Graphic from Shore Protection Manual, USACE)
Waves begin to shoal as they encounter shallower water and break as the steepness of the wave exceeds a specific threshold or criteria. This process repeats itself continuously as the waves approach the beach and the depths continue to decrease. Therefore, the shoaling and breaking of the waves in the surf zone are directly affected by the bathymetry in the surf zone and the decrease in depth near the beach. The point of breaking is not an exact location for all waves in an irregular wave train as each incoming wave is different [6].

Breaking waves can be divided into three categories: plunging, spilling, and surging. Plunging breakers release a large amounts of energy over a short period of time. This type of breaking wave occurs when the wave shoals to produce an advancing, vertical wall of water followed by the crest curling far over the preceding trough and descending violently into it where the water surface is essentially horizontal. Air is explosively expelled behind the breaking wave. The plunging breaker is the most dangerous to landing craft.

The spilling breaker peaks like the plunging breaker but not the point where a vertical wall of water is produced. At the point of breaking the topmost portion of the crest curls over and then simply crumbles into the preceding trough. As this process occurs the wave becomes an advancing line of foam. The energy of a spilling wave dissipates gradually to the beach. This type of breaker is the most desirable to amphibious craft.

The surging breaker is a less common type of breaking wave. Initially the wave begins to form as the plunging breakers with the crest advancing faster than the base. At some point near the beach, however, a reversal occurs such that the base of the wave now advances much faster than the crest and surges up the beach as a wall of water which may or may not resemble white water. The controlling factor is the backwash of water back towards the sea. If high backwash exists the base of the wave is kept from overtaking the crest and therefore a plunging breaker is
produced. However, if the backwash is low, a surging breaker will be produced. The surging breaker is most detrimental to craft that have landed and have the ramp down in an unloading/loading operation.

The type of breaker formed is affected by the factors such as local wind forcing, irregular bathymetry or beach slope, and other waves reflected from obstacles [11]. These factors can disrupt transformation processes at one or more points along a crest and inhibit the breaking process. When this occurs a wave which is developing into a plunging breaker can transform into a spilling or surging breaker depending on the location of the disruption.

A process which affects the wave direction in the surf zone—the wave angle relative to the bottom contours—is refraction. Refraction is a direct result of the bathymetry in the surf zone. Wave celerity is the speed a wave propagates and is a function of the water depth. Wave celerity decreases as wave depth decreases. For a wave entering the surf zone at an angle other than normal to the bathymetry contours, the portion of the wave that reaches shallower water first is slowed relative to the portion in deeper water. The result is a bending of the wave crest causing it to become more aligned with the bottom contours and beach. If the zone of shallower water is sufficiently large in the cross shore direction, the wave will arrive at the beach with the crest nearly parallel to the shoreline. Refraction has a direct impact on amphibious craft landing axes as the craft operator prefers to transit the surf zone normal to the wave crests to decrease the probability of broaching.

Waves can also refract with regard to current as with a tidal inlet. The extent to which the refraction occurs depends on the strength of the current, the period of the incident wave, and the angle between the current and the wave [12].
Submarine ridges and submarine canyons also refract waves and as with currents depend on the angle and period of the waves. Submarine ridges focus the wave energy where the ridge intersects the shoreline thereby increasing wave heights locally. Headlands refract waves in a similar manner. Conversely, submarine canyons cause the wave energy to diverge and results in lower wave heights at the point where the canyon joins to the shoreline [12].

Longshore or littoral currents form as a direct result of waves breaking at an angle to the beach. Breaker height and the sine of the breaking wave angle relative to shore normal affect these currents in a proportional manner. Longshore currents are commonly found along straight beaches. For the present research longshore currents are neglected in part due to the somewhat small angle of the wave crests with respect to the beach that were considered in the experiments. However, longshore currents have been recorded at speeds of 3-4 knots for wave heights of 8 ft [11] and, therefore, should be considered an area of future research for vessel motion.

The period of the breaking wave is very important as it will affect several factors that affect amphibious craft: shoaling, refraction, and wave celerity. The effects on shoaling and refraction have already been discussed in preceding paragraphs. The primary direct effect is the rapidity with which wave impacts to the craft occur. Shorter period breaking waves strike the craft in quick succession and affect the ability to orient the craft. Longer period breakers allow the craft to plow through and arrive on the beach between breakers [11].

Beach slope plays a significant role in breaker formation as it represents changing depth and thereby a changing rate of wave shoaling and breaking. The U.S. military classifies beach slope in three categories: steep, moderate, and gentle. A steep beach has gradient of more than 1:15. With this gradient, plunging breakers dominate and spilling breakers are rarely observed. Beaches with gradients ranging from 1:15 to 1:30 are considered moderately sloped. The surf
zone for this slope classification usually has at least one offshore bar. Spilling breakers are more common than plunging breakers with slopes in this range. Spillers dominate on gently sloped beaches which range in gradient from 1:30 to 1:300. Several offshore bars typically exist in the surf zone for this slope classification.

2.3 Challenges and hazards in amphibious transits

In addition to the obvious hazards of enemy resistance, amphibious craft must traverse the surf zone where conditions are highly energetic and can be extremely variable. Any of the factors or combination of factors discussed in the previous section can result in a craft casualty. A casualty is defined as any event which removes a craft from operation either temporarily or permanently. The three most common casualties are swamping, hanging on bar, or broaching on a bar or beach.

Swamping results most commonly from plunging breakers. The casualty does not occur due to the wave impact alone. It is the combination of the wave impact and the same wave overtaking the craft. This scenario causes the craft operator to lose steerage since the craft is essentially surfing the wave with possible end results of colliding with another craft or broaching.

Hanging on a bar is simply a result of the craft crossing an offshore bar and grounding or broaching due to insufficient depth. The risk of this type of casualty is greatest when breaker heights are low as higher breakers will allow the craft to clear the bar.

The most significant risk to the craft is broaching. Broaching involves the craft being pushed—usually due to wave forcings—onto the beach with a heading parallel to the beach [11]. This scenario can develop while the craft is at the beach with the ramp down or can be a result of the craft being turned by repeated wave impacts. In this position, the craft is subjected to repeated, sometimes violent, wave impacts on its beam. If the surf levels are of significant height,
these conditions can cause the craft to capsize endangering personnel and cargo or a grounding requiring assistance from another craft or heavy equipment on the beach.

The heading of the vessel provides another level of complexity especially when coupled with the incident angle of the waves on the craft. This set of parameters includes the effects of head seas, following seas, beam seas, and quartering seas (see Figure 2.4). Head seas are defined as waves with a primary direction opposite to that of a vessel’s course. Waves running at a 90° angle to vessel course are considered beam seas. Following seas have an angle of incidence in the same direction as the course of the vessel. Finally, a 45° angle of incidence defines quartering seas. As stated above the operator would prefer to transit the surf zone perpendicular to the wave crests and have sufficient speed to outpace the wave and plow through it. This angle of attack presents the least of amount of freeboard to the incident wave.

2.4 Design considerations for amphibious craft

Today’s amphibious craft are designed by highly skilled and knowledgeable naval architects using cutting edge design tools and scale model tests. However, while the scale model tests are performed in irregular wave environments using wave tanks and generators [4], the waves used in testing are deep water waves which have wavelengths smaller than the water depth and are affected negligibly by the sea bottom [6]. The vessel response in these types of conditions is predominantly linear in nature. These wave conditions are more akin to open ocean conditions where ship responses in the six degrees of freedom (6DoF) (see Figure 2.5) have been studied extensively and are well-understood. This method of testing is well-suited for vessels that traverse the deep ocean. However, it does not take into account surf zone forces or reproduce the 6DoF responses that occur in the surf zone. Amphibious craft such as the LCU used in this
research are not tested in surf zone conditions until sea trial testing of the prototype craft is conducted [5].

Therefore the design with regard to 6DoF surf zone response is not significantly informed by pre-production scale modeling. Data gathered during the sea trials is only used to determine if the craft meets operational parameters. These data are significantly dependent on sea and weather conditions and are therefore highly variable. Using these data to predict craft response is difficult at best because no two datasets are alike with regard to forcings: waves, wind, longshore current, and the like.

Figure 2.4 Head, following, beam, and quartering seas, respectively (Graphic Courtesy U.S. Naval Academy)
2.5 State of research of surf zone condition impacts on amphibious craft

While significant research has been devoted to the study of surf zone wave conditions, limited research has been conducted with regard to the response of amphibious craft to surf zone forces during a landing operation. Surf limits validated to field data do not exist for amphibious craft. The surf limits developed for landings [11] are extremely crude and existing guidance [11] is based on landing failures in the field correlated with simplistic wave measurements.

Only a handful of groups have attempted to advance the understanding of amphibious craft response in the surf zone. All of these efforts experienced notable limitations. These studies have been limited to an air-cushioned vehicle, a concept, tracked supply craft, and the Landing Craft Utility (LCU).
Marquardt [7] tested a 1/7th scale DUKW-21 concept vehicle (see Figure 2.6) both in a wave tank at the Naval Surface Warfare Center Carderock Division (NSWCCD) and in the surf zone at Dania Beach, FL. The tests at NSWCCD measured heave and pitch response to spilling and plunging waves over an experimental beach. Three types of experiments were conducted at Dania Beach: sea-to-land transit, land-to-sea, and surf zone. In the surf zone experiments, the vehicle position was maintained in the surf zone for five separate data collections. The work gives insight into methods for determining vessel response. The part of the work which could be considered most applicable to the present study occurred during the surf zone experiments where the vehicle was exposed to the irregular wave environment of an actual surf zone. However, the results were specific to the DUKW-21. The hull form of the vehicle is not similar to any of the shallow-draft hulls used by U.S. Military forces.

![Figure 2.6 DUKW-21 Concept Vehicle](image)

Dhanak [8] studied wave response of an air-cushioned vehicle, the surface effect ship (SES). However, air-cushioned vehicles respond in a significantly different manner to wave
conditions than traditional shallow-hulled vehicles. Therefore, the results of this work cannot be used to describe the response of hulled craft.

Quintero et al. [9,10] studied the effects of breaking waves on a shallow draft landing craft. Quintero used a 1:20 scale model that corresponded approximately to a prototype Landing Craft Mechanized six (LCM6) with regard to beam and draft. With respect to length overall (LOA), the model fell between the LCM6 and the Landing Craft Mechanized eight (LCM8). See table 1 for the prototype and scale model specifications of the model and the LCM6 and LCM8.
Table 2.1  LCM dimensions, prototype vs. model

<table>
<thead>
<tr>
<th>Dimension</th>
<th>LCM 6</th>
<th>LCM 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prototype</td>
<td>1:20 scale</td>
</tr>
<tr>
<td>Length Overall</td>
<td>56 ft (17.1m)</td>
<td>2.8 ft (0.85m)</td>
</tr>
<tr>
<td>Beam</td>
<td>14 ft (4.3 m)</td>
<td>0.7 ft (0.21m)</td>
</tr>
</tbody>
</table>

A flap-type wave maker was used in the Naval Surface Warfare Center, Carderock Division’s (NSWCCD) 140-ft-long basin. The model was attached to a towing carriage that was held in fixed positions within the basin to simulate the impacts of breaking waves perpendicular to craft direction -head seas- in the surf zone. The towing carriage restricted the degrees of freedom DoF that could be considered: pitch, heave, and surge. Only regular waves were considered in these experiments. Quintero et al determined that there was a large second-order response in the surf zone especially in the pitch of the craft in spilling and plunging waves. Quintero [10] confirmed the lack of study of craft response in the surf zone.

2.6  Comparison of the present research effort with past research

The current research effort eliminates several of the variables that were encountered in other efforts. Variables such as wind forcing and variable bathymetry in the longshore dimension are not considered. Controlled bathymetric variability in the cross-shore directions is included. The human response factor related to piloting the craft has been reduced to a negligible amount through the use of pre-programmed model speeds and rudder settings at midships. Limiting or removing these variables during the experiments ensured the predominant
forcing was the wave environment. Waves for the experiments are generated in a laboratory environment which allows for significant control of the variability in the wave field.

The research contained herein while similar to Quintero’s work is significantly different and unique. It removes the constraints of a towing carriage on the 6DoF and focuses on a DoF other than those in Quintero’s work, namely yaw. In addition, the craft is transiting the surf zone as a free running model rather than being held in place.

It is also important to note in past research efforts the data collected was input into existing formulations for determining vessel response relationships which were not explicitly stated in the documentation of the work. Quintero’s work, for example, held the craft’s position fixed such that the underkeel clearance of the craft was a function of the incident waves traveling past the craft. Therefore, bathymetric effects due to craft propulsion were not considered. With the bathymetry neglected to some extent, he was then able to use relationships –Response Amplitude Operators (RAO) – developed for deep water ship motion. RAOs are transfer functions that give the frequency response of the vessel motion to the wave amplitude(s). RAOs are developed for each of the 6 DoF by solving the equations of motion (EoM) for the displacement, \( x(t) \), for a given DoF.

The general form of the EoM for ship motion is given by [13]:

\[
 a(\omega)\dddot{x} + b(\omega)\dot{x} + c(\omega)x = F_o \sin (\omega t + \varepsilon)
\]  

(2.1)

where \( a(\omega) \) is the coefficient for mass, \( b(\omega) \) is the damping coefficient, \( c(\omega) \) is the hydrostatic restoring coefficient, \( \omega \) is the wave frequency, \( F_o \) is amplitude of the wave forcing, and \( \varepsilon \) is the phase angle. The mass coefficient generally represents more than just the mass of the vessel
\[ a(\omega) = \text{vessel mass} + \text{added mass} \quad (2.2) \]

where the added mass term represents the mass of water moved by the vessel as it moves in a given direction. The damping term represents the resistance to motion provided by the water. Expanding the EoM to the 6DoF \[14\]

\[
\sum_{k=1}^{6} \left[ (M_{jk} + A_{jk})\ddot{x}_k + B_{jk}\dot{x}_k + C_{jk}x_k \right] = F_j
\quad (2.3)
\]

where \( M_{jk} \) are the components of the ship's mass matrix which includes the moments of inertia (MoI), \( A_{jk} \) and \( B_{jk} \) are the components of the added mass and damping coefficient matrices, respectively, \( C_{jk} \) are the hydrostatic restoring coefficients, and \( x_k \) is the displacement in each DoF. Also, the coefficients \( A_{jk} \) and \( B_{jk} \) are frequency dependent, specifically the encounter frequency of the craft with waves \[15\] which is given by

\[
\omega_e = \omega_w \left( 1 - \frac{\omega_w V}{g} \cos \mu \right)
\quad (2.4)
\]

where \( \omega_w \) is the wave frequency, \( V \) is the vessel velocity, \( g \) is the acceleration due to gravity, and \( \mu \) is the wave angle \[16\].

Developing the EoM in this way allows for coupling which exists between groups of DoF. Yaw \((x_6)\) is coupled with sway \((x_2)\) and roll \((x_4)\) such that the above EoM for yaw is given by

\[
A_{61}\ddot{x}_2 + B_{62}\dot{x}_2 + (A_{64} - I_{46})\ddot{x}_4 + B_{64}\dot{x}_4 + (A_{66} + I_6)\ddot{x}_6 + B_{66}\dot{x}_6 = F_6
\quad (2.5)
\]
As yaw is a nonrestoring DoF, note the absence of the hydrostatic restoring coefficient.

A discussion of the development of an EoM for the current research will be undertaken in the approach section of the data analysis chapter, Chapter 4.

Finally, it is important to understand that even when regarding deep water wave ship motion responses, a dearth of research exists regarding the yaw DoF. In *The Principles of Naval Architecture* [17], it is noted that yaw is less understood than the other DoF particularly due to the difficulties involved in model testing and data collection. The experimental conditions required include a large basin compared to the size of the vessel model, quartering seas, and a self-propelled model with freedom of movement in all 6DoF.
CHAPTER III
EXPERIMENT COMPONENTS AND DATA COLLECTION

This chapter details how the data were collected and the initial data processing. The experiments carried out in this research effort were conducted at a 1:32 scale as dictated by the size of the wave basin and the constraints of the wave generators. A free running remote control model was used with a pre-programmed speed and rudder angle. A free running model is preferred for seakeeping experiments as per the recommended guidelines from the International Towing Tank Conference [16, 18]. Included in this chapter are descriptions and discussions of scaling effects, the experimental space, the vessel model, the data collection components including the syncing system, and the matrix of wave conditions used for the experiments.

3.1 Experiment scaling

Determining the proper scales for physical model experiments is of significant concern. In seakeeping experiments, extremely careful measurements have to be made of both the wave conditions and corresponding model responses in order to ensure predictions of prototype response from model results are as accurate as possible [16].

Scaling for physical models involving ships include consideration of surface tension, resistance related to energy dissipated in wave-making due to the forward or sternward transit of the vessel, and resistance related to frictional effects of the vessel moving through the water. As this research specifically included the surf zone, the effects on the wave propagation processes were also considered.
Using dimensional analysis, it has been shown that wave-making resistance of a ship depends primarily on the Froude and Reynolds numbers [20]. This resistance is defined as the energy required to move water out of the way as the hull moves through the water which creates a bow wave. Wave-making resistance is different from the frictional resistance resulting from the tangential fluid forces acting on the hull as the ship moves through the water.

Prototype-scale wave-resistance is governed by two different laws. The scale of the present experiments was not small enough for viscous effects to be significant. Furthermore, satisfying the Reynolds criterion would require using a model fluid with a kinematic viscosity scaled based on the length scale. Using a geometric length scale of 10, for example, would require a model kinematic viscosity of $1/30^{th}$ that of the prototype fluid [19]. Therefore, it is not possible nor is it necessary to simulate both in a model experiment and, one of these two similarities or similitude must be selected in order to scale the model.

To determine the similitude criterion which governs the scaling used in a physical model, the ratio of the inertial forces to another family of forces (viscous, gravity, etc) must be determined. That ratio must be same for the model and prototype scales in order to preserve the similarity between the scales [20].

Froude similarity stresses the ratio between the inertial forces acting on a water particle and the weight of that particle. Of the elementary forces available, gravity is the primary influencing force with regard to waves which is governed by the Froude number given by

$$ F_g = \frac{V}{\sqrt{gL}} $$

(3.1)

Where $V$ is the velocity, $g$ is the acceleration due to gravity, and $L$ is the length.
On the other hand, Reynolds similarity preserves the ratio of inertial forces on a water particle to the viscous forces acting on that particle. This similarity is important in boundary layer problems, drag forces, or any problem where viscous forces are dominant.

Simultaneous Reynolds and Froude similarity can be achieved only at full scale (1:1), so modeling at reduced scale requires compromises. Ship motions are usually modeled by enforcing Froude scaling and minimizing viscous scale errors by ensuring that model Reynolds Numbers are in the turbulent range [20].

In the highly energetic environment of the surf zone, Reynolds numbers are well over the threshold between laminar and turbulent flow and, therefore, attempting to maintain Reynolds similarity would not have been appropriate for the LCU research effort. Coupled with the fact that waves are significantly affected by gravity, Froude similarity/scaling was chosen for the experiments performed in this study.

The time scale can be determined using the principles of dimensional analysis starting with the Froude similarity criterion

\[ N_V = \sqrt{N_g N_L} \]  \hspace{1cm} (3.2)

where

\[ N_V = \frac{V_m}{V_p} \]  \hspace{1cm} (3.3)
which is the scale ratio of velocities where m and p subscripts represent model and prototype, respectively. The gravity and length terms, $N_g$ and $N_L$, follow the same convention. And as velocity can be represented as the length over time

$$N_V = \frac{N_L}{N_t}$$

Solving for the scale ratio of the time, $N_t$, yields

$$N_t = \sqrt{N_L}$$

Therefore, the time scale is the square root of the length scale for Froude similarity criterion. The LCU experiments were performed at the 1:32 length scale, so 1.0 second in the model represented 5.66 seconds at the prototype scale.

The LCU model was constructed at an undistorted spatial scale of 1:32. This scale of the LCU model was chosen based on the size of the LSTF basin in comparison with the wave conditions which could be generated. The scale of the LSTF wave tank was undistorted, as well. Hughes [19] demonstrated through a mathematical treatment that in order to correctly model wave refraction the scale of the model must remain undistorted. In his treatment of wave refraction, he demonstrated the vertical length scale ratio and wavelength scale ratio must be equal. This implies an undistorted scale is necessary for correctly reproducing wave shoaling at the model scale. In the same text, Hughes referenced publications by Whalin and Chatham [21] and Kamphuis [22] which showed an undistorted scale is also essential for correctly modeling wave diffraction.
In order to minimize scale effects of surface tension on free-surface flow behavior, the depth of the water in the model should be greater than approximately 20 mm [23]. The current effort met this criterion by necessity because the draft of the LCU model was 72 mm. To avoid grounding the model and thereby damaging it, the minimum underkeel clearance (UKC) across all experiments was approximately 25 mm with the exception of one irregular wave signal condition, which was not analyzed as part of the current research effort. Adding the UKC to the model draft yields a water depth of 97 mm, which is well above the 20 mm threshold. Furthermore, it has been shown that surface tension effects have little effect on experimental results involving ships [16, 23].

The scales of movement in the direction of each of the 6DoF, including the yaw angle, were 1:32 as these are spatial parameters. The wave heights used in the experiment were also 1:32 to coincide with the scale of the LSTF basin. Forces, which involve accelerations and velocities require the time scale as part of the calculation. Therefore, force and velocity calculations are not 1:32. As was mentioned above, the time scale is the square root of the length scale in physical modeling. Therefore, in the force and velocity calculations the length variables are divided by 32 (for a 1:32 scale model) and the time variables are divided by 5.66 to resulting in 1:32 scale forces and velocities.

3.2 Experiment space

The facility used for the LCU surf zone transit experiments was the Large-Scale Sediment Transport Facility (LSTF) (Figure 3.1) in the Hudson Building at the ERDC. This facility is operated by the ERDC Coastal and Hydraulics Laboratory (CHL).
As the name suggests, this facility has traditionally been used to study the impacts of waves and currents on sediment transport in littoral environments [24]. No sediment was in the basin for the present experiments. The LSTF basin (Figure 3.2) has a fixed, concrete bed with a slope of 1:30. The slope terminates at a concrete wall on the landward side. The wave generators represent the “offshore” region and the top of the sloping bed is the “landward” region. Four synchronized wave generators are positioned at the seaward boundary of the basin. The wave generators are oriented at a 10° angle to shorenormal and can be rotated to provide waves with up to a 20° angle of attack. The dimensions of the fixed, concrete bed are 21m in the cross-shore direction and 31m in the longshore direction. The overall dimensions of the basin are 30m in the cross-shore and 50m in the longshore. Sediment traps (Figure 3.3) located at
downdrift longshore boundary of the basin account for the remaining dimensions of the facility (left side in Figure 3.2).

Figure 3.2  Plan view diagram of LSTF layout
A berm was constructed using three rows of 5.1cm-thick, 0.9m² concrete paving stones (Figure 3.4). The stones were stacked four layers high for a total berm height of 0.2m. The berm ran the longshore dimension of the fixed, concrete bed. The location of the berm within the LSTF is displayed in a later section of the current chapter. The purpose of the berm was to shoal the waves and induce wave breaking in order to produce surf zone conditions [6] in the LSTF basin. Berms are typical nearshore, morphological features which occur naturally, parallel to the shore and primarily occur near the point of wave breaking. Nearshore bars tend to grow and move offshore during storm events with large steep waves (winter), and they move onshore a weld to the coast during long-period swell events (summer). The vertical face of the berm had a strong potential to reflect the incoming waves. To mitigate wave reflection, a ramp was
installed on the seaward side of the berm (Figure 3.5 and Figure 3.6). The ramp was constructed of 4 by 8 ft (1.22m by 2.44m) pieces of marine plywood attached to frame constructed of 5.1cm x 15.24cm treated lumber which was anchored to the concrete bed using screws specifically made for this purpose.

Figure 3.4   Berm across the LSTF
Figure 3.5  Berm ramp under construction

Figure 3.6  Completed Ramp
The wave generators were manufactured by MTS Systems Corp (Figure 3.7) and are capable of generating unidirectional, long-crested waves. Wave reflections off the wall behind generators are minimized by rubble mound wave absorbers located behind the generators. The wave heights used in the model ranged from 3.6cm to 8.6cm with periods ranging from 1.1-1.8s. Using the model scale of the LCU experiments discussed above, these model waves translate to prototype wave heights and periods of 1.14-2.74m and 6.2-10.2s, respectively. The wave generators are piston-type and capable of generating regular and irregular waves. When used together, the generators create waves with a 30.5-m-long wave front.
3.3 Data collection lane and berthing area

The data collection lane (see Figure 3.8 and Figure 3.9) was drawn on the floor of the LSTF. The two figures collectively represent three phases of testing—which will be discussed later in the chapter—with phase one represented by Figure 3.8 and phases two and three represented by Figure 3.9. This lane delineated the range of long shore motion of the craft and served as a guide when calibrating the camera system. A berthing area holds the vessel model at a fixed starting point for experiments and assists in providing a consistent initial heading for the experiments.

Using the field of view (FoV) from the motion capture capture system (MoCapS) used for collecting vessel response data, a data collection lane was developed and painted on the floor of the LSTF basin (Figure 3.10). It was determined from preliminary experiments that actual model transits would not vary more than a boat length or two at most, so a centrally located boat lane was developed. The boat lane is 3.05m in width and is centered in the FoV. The purpose of the lane was two-fold. First, Qualisys recommends the camera system be calibrated twice per day during use. With water in the basin it is difficult to ensure adequate coverage with the calibration wand without a guide. The painted lane provides this guide and shows the approximate FoV used for the experiments. The painted line closest to the instrumentation bridge also provided a point of reference for setting up the berthing area representing the starting point for all LCU transit experiments.
Figure 3.8  Layout of Data Collection Area for Round 1

Figure 3.9  Layout of Data Collection Area for Rounds 2 and 3
Consistency in any experimental program is important to ensure gradients in data collected are the result of a desired phenomenon and not a change in a parameter meant to be held constant. For the present experiments one of the parameters being measured was yaw which is strongly dependent on heading relative to waves impacting the craft. Therefore it is important that the starting location and initial model heading are consistent across all LCU experiments so the ending location of each run is a result of wave impacts and not the initial heading or location. Because the wave environment affects the vessel motion while the model is in the berthing area, exact starting location and heading are virtually impossible to maintain across all experiments without impacting the wave field. However, it is possible to maintain the consistency of these parameters in an approximate sense through the use of a berthing area. A consistent starting
location improves the data analysis relating wave impacts to vessel motion. Maintaining a consistent initial heading ensures that the approximate same portion of model beam is presented to the wave field at the beginning of each experiment. This reduces the probability the vessel track is impacted by varying initial headings. Again this is done in the approximate sense as more robust initial protection of the vessel from the wave field would affect the wave field. The berthing area for the LCU model (Figure 3.11) consists of 8 steel rods set in a piece of marine plywood anchored to the floor of the basin. A piece of plywood is affixed to the top of the rods, to provide additional rigidity to the rods for a consistent berthing area. The berthing area was placed just in front of the wave generators (Figure 3.8 and Figure 3.9) along the painted lane line closest to the instrumentation bridge. The back two rods were spaced closer together so the LCU model could be held in the berthing area by holding the RC throttles in reverse until the start of the experiment. Also, the model operator waited for an initial wave crest to reach the bow of the model which provided additional control for proceeding straight out of the berth.
3.4 Scale landing craft model

This section covers the details of the landing craft model used for the current research. Included in discussions will be the craft chosen, the scale of the model, and the important physical parameters. The physical parameters will include the materials used, the propulsion and control of the model, and the center of gravity/moment of inertia locations.

The U.S. military uses a variety of landing craft for conducting amphibious operations. These craft range from the Landing Craft Air Cushion (LCAC), which rides on a cushion of air above the water surface to the Assault Amphibious Vehicle (AAV), which has a significant portion of the vehicle below the water surface as it traverses from ship to shore. However, the workhorse of amphibious fleet is the shallow-hulled LCU.
The amphibious craft chosen for this research was the Landing Craft Utility (LCU). This model was chosen because it is one of the most frequently used amphibious craft, employed by the United States Army (USA), Navy (USN), and Marines (USMC). The dimensions of the LCU ranges from 41.15m length overall (LOA) by 8.84m (beam) and drafting 2.13m loaded to 53.04m LOA by 12.8m (beam) and draft of 2.74m [25, 26], depending upon the class designation of the craft. The prototype dimensions of the model craft used in this research are 42.06m LOA, 9.45m beam, and draft of 2.13m. The scale of the model is 1:32 to fit the scale dimensions of the LSTF basin at the ERDC where the experiments took place. This scale results in the LCU model dimensions of 1.31m LOA, 0.3m beam, and a draft of 0.07m.

The model was developed by the NSWCCD in Bethesda, MD. NSWCCD has a long history of designing and testing ships for the USN and USMC [25].

The hull was constructed of fiberglass (Figure 3.12 - Figure 3.14). The shell of the model had two distinct pieces: the fiberglass hull and the lexan top. The lexan top was 0.48cm in thickness and was clear to allow for inspection of the inner hull for leakage. The craft superstructure and gunnels were permanently affixed to the lexan top with an adhesive. The gunwales were 2.54cm in thickness. The inner hull, gunnels, and craft superstructure were 3-d printed using 3D Systems Accura 60 material.

The model was trimmed using six brass weights: four affixed to the motor controller and two larger weights, one on each side of the model just forward of the motors. The four weights attached to motor controller can be seen in Figure 3.13. Of the two remaining weights, the port side weight is visible in Figure 3.13 but the starboard weight is hidden by the superstructure. In its final location, the larger port weight was laid on its side, it weighed 1.09kg, and was located 45.56cm from the stern and 12.22cm from the centerline of the model. The starboard weight was
also laid on its side, weighed 1.07 kg, and was located 45.4 cm from the stern of the model and 12.22 cm from the centerline. The four weights on the motor controller all weighed 0.23 kg. The port forward weight was located 79.69 cm from the stern and 4.89 cm from the centerline of the model. The starboard forward weight was located 79.85 cm from the model’s stern and 0.13 cm from its centerline. The port aft weight was located 4.89 cm from the centerline of the model and 74.93 cm from the stern. The starboard aft weight had a location 75.09 cm from the model’s stern and 0.13 cm from its centerline. These weight locations resulted in an even keel trim where the deck was parallel to the waterline in a still water tank. It should be noted that even keel trim condition represents an empty or ballasted condition for the craft. Therefore, even though the draft at the stern, 0.07 m, represents a loaded condition, having the even keel represents a hybrid condition. A true loaded condition would have the 0.07 cm stern draft, but would have a 1:65 trim with the draft at the bow being approximately 0.05 m.

The model was driven by two kort nozzles which are ducted propellers fitted with a non-rotating nozzle (see Figure 3.14). In simpler terms, kort nozzles are propellers with a shroud around them. The model had steering rudders aft of the nozzles and flanking rudders fore of the rudders. The propellers push water past the steering rudders to steer the craft when it is moving forward and past the flanking rudders to steer the craft when it is moving astern. Each nozzle was attached to a separate motor inside the hull and both motors were connected to a motor controller through a circuit block. The motors were powered by two 20 V, Lithium Ion drill batteries. The motor controller monitored the motor revolutions and ensured the motors were receiving sufficient power to maintain the speed designated by the remote control.
During initial trial runs in the LSTF shortly after the model was delivered by NSWCCD, water broke over the gunnels at the stern on several occasions requiring the model to be removed from the basin and dried. After the water was wiped from the deck, the deck had to be removed from the hull to soak up water which had entered the hull through fastener locations on the deck. This process was critical to keeping water away from sensitive electronics inside the hull. A two-piece cover was 3-d printed for the stern from High Impact Polystyrene (HIPS) and affixed to the model using the existing fastener holes in the deck (Figure 3.15). Adding the cover to the model significantly reduce the number of instances when the model deck has to be drained and the hull manually dried which reduced downtime between experiments.
Center of Gravity (Cg) and moment of inertia (MoI) tests were conducted on the model at NSWCCD. The tests and associated calculations included all model components which were inside its hull or affixed to its exterior during the experiments. The longitudinal coordinate of the Cg was 45.56 cm from the aft end of the model, the transverse coordinate was 0.33 cm on the starboard side of the longitudinal centerline, and the vertical coordinate was 0.89 cm below the lexan top. The roll inertia was 0.89 kg-m$^2$, the pitch interia was 1.33 kg-m$^2$, and the yaw interia was 1.36 kg-m$^2$.

Figure 3.13  1:32 Scale Landing Craft Utility Model – plan view
Figure 3.14 1:32 Scale Landing Craft Utility Model – stern view
The model was developed as a free-running, remote-controlled model. The remote control used for the LCU model was an off-the-shelf model, a Spektrum DX6e, and is traditionally used for model aircraft (Figure 3.16). Commercial remote controls specifically designed for model ships are few, and none have the ability to independently control multiple engines and multiple sets of rudders, flanking and steering, like those found on an LCU.
Carbon fiber tubes were mounted to the LCU model’s deck (Figure 3.15), spherical reflectors were attached to the top of each tube. These reflectors are used by the motion-capture system to track the model and make rigid body calculations resulting in 6DoF data for pitch, roll, and yaw. The camera system is described later in this chapter. Note the stern cover and the reflectors and their respective mountings were included in center of gravity tests performed with an inertia table at the NSWCCD. As a result, the added mass and location of these additional pieces were taken into account with regard to vessel motion. The weight and location of the added features, stern cover and reflectors, were of negligible weight when compared to the model itself and did not significantly change model response.
The remote control was programmed for three prototype speeds: 6, 8, and 10 knots. These speeds correspond to Froude scale model speeds of 1.06, 1.4, and 1.77 knots, respectively, in the model domain. Lower vessel speeds make the vessel more susceptible to forces such as wind, current, and waves [27]. The experiments were conducted at the lowest speed where the model boat’s heading and vertical motions are affected most acutely by surf zone waves. The rudders were programmed to zero degrees commonly referred to as midship.

3.5 Wave gauges

The LSTF was instrumented with wave gauges mounted on a motorized bridge (Figure 3.18). The bridge runs 21 m in a shore perpendicular direction and can be moved to any alongshore location over the concrete floor. The bridge provides a stable platform for attaching a variety of instrumentation [28]. Sixteen Akamina AWP-24-3 capacitance wave gauges (Figure 3.17) were suspended from the bridge and controlled with a computer running a data acquisition script [24] which also collects the data from the wave gauges. The script was developed using the Laboratory Virtual Instrument Engineering Workbench (LabVIEW), a visual development environment from National Instruments specifically used to develop data acquisition and analysis codes. The seaward-most gauge was located at the seaward edge of the beach slope. The spacing between successive gauges was approximately one-half of the model LCU’s LOA or 65.7cm. The locations of the wave gauges and the berm within the LSTF are illustrated in Figures 3.8 and 3.9.

The probe length (sensing wire, Figure 3.17) of each wave gauge corresponds to the maximum range of water levels that can be measured. The Akamina wave gauges collect data with a maximum error ranging from 1.2 mm to 0.55 mm for probes of lengths 1 m to 20 cm, respectively. For these experiments the probe lengths were 30 and 60 cm. These lengths mean
the maximum deviation from the still water level which can be measured is 15 and 30 cm, respectively. Drift on the Akamina gauges is negligible. Accuracy of the gauges is impacted minimally by temperature fluctuation [24].

Prior to running tests, the wave gauges required calibration. The first step in calibrating each wave gauge was to configure the output range on each gauge. After configuring the gauge, the wave gauge was calibrated by immersing the sensing wire of each gauge in still water of five different depths. The degree of immersion, which varied based on probe length, encompassed the range of water surface elevations that each gauge would encounter. The range of water surface elevations varied from gauge to gauge because the gauges were affixed to the bridge running in the cross-shore direction (Figure 3.18) and wave heights vary with water depth and distance from the wave generating. Calibrations for each gauge were calculated from a best-fit-straight line computed through the five calibration points, relating gauge output voltage to water surface elevation.
All instrumentation—including the wave gauges, wave generator, the bridge, the camera system, and the triggering mechanism—were controlled from a climate-controlled building within the Hudson Building (Figure 3.19) with a view of the basin (Figure 3.20).
Figure 3.18  Instrumentation bridge

Figure 3.19  Control building
3.6 **Water level consistency**

Consistency of the water levels was important as wave celerity, refraction, shoaling, and breaking in the transitional (depth/wavelength $\leq \frac{1}{2}$) and shallow ($d/L \leq 1/25$) water zones are dependent on water depth. Inconsistency in water depths between experiments result in inconsistent wave conditions between experiments where the signal used by the wave generators was the same.

Water levels in the LSTF basin were maintained at 67 cm on the basin gauge (Figure 3.21), which corresponded to the still water depth at the seaward edge of the beach slope which was also the location of the seaward-most wave gauge. The basin has a minor leak which
was mitigated by a small, continuous addition of water using a common garden hose. The level was checked and recorded at the beginning and middle of each day experiments were conducted.

Figure 3.21  LSTF Water Level Gauge

3.7 Six degree of freedom data collection system

A Qualisys motion capture system (QTM) was used to collect all data related to the movement of the LCU model in the 6DoF. QTM is a system comprised of high speed cameras, spherical reflectors, and a computer running the QTM software and collecting the data. The reflectors (Figure 3.15) are attached to the object being tracked, in this case the LCU model. Model Oqus 300 cameras (Figure 3.22) track the movement of the reflectors by sending out a light signal and getting a return from the spherical reflectors. The return data is captured at rates
of up to 480 Hz. The cameras were attached to the PC running the Qualisys software. The software ingests the data produced by the cameras and calculates the position/movement of object over time. If the object being tracked is rigid, the distance between individual reflectors remains constant regardless of forces acting on the body, and thus the QTM software allows the reflectors to be grouped and the body defined as a rigid body. The rigid body designation allows the software to make the rigid body calculations and outputs the data as roll, pitch, and yaw.

Figure 3.22  Qualisys Oqus 300 Camera

In order to produce accurate data, the QMS cameras were positioned in the study area to have overlapping fields of view (FoV). While two camera FoV overlap can be used in the QMS system, three camera overlapping FoV is preferred [29].
Several FoVs were tested to produce the optimal three-camera FoV. An example of an earlier FoV is shown in Figure 3.25. The early efforts at camera placement either had issues with individual cameras picking up reflections from other camera output signals or the FoV did not cover the full extent of anticipated LCU model transits. Figure 3.8 and Figure 3.26 show the final camera locations for the first round of experiments and the FoV used to develop the data collection lane for the LCU transit experiments, respectively.

The camera system was calibrated twice per day: once before testing started and once midway through the day’s testing. Since testing was performed during the summer, beginning in the early morning, the second calibration was necessary to ensure temperature changes through the day did not affect the tracking accuracy of the system. An L-shaped wand with reflectors affixed was placed at the chosen origin for the experiments on top of two concrete blocks (Figure 3.23). The calibration tool in the QMS software was then started and someone then took the calibration wand and walked back and forth through the data collection area taking care to cover the entire area (Figure 3.24). Once the camera system was calibrated it was ready for data collection.
Figure 3.23  Calibration Wands

Figure 3.24  Calibration Process
Note that for the second and third rounds of experiments the cameras and the camera system origin were moved 2 m towards the wave generators in order to include the ramp and berm in the data collection zone (see Figure 3.9). This adjustment was necessary to expand the data collection to the seaward side of the berm.

Before rounds one and two of the experiments, a LIDAR survey of the LSTF basin – which will be described below – was conducted to develop a coordinated transformation between the wave gauge and MoCapS coordinate systems. This transformation ensured the wave gauge data and camera data used the same coordinate system. The coordinate system is further discussed below in the Data Collection Syncing Section. The cameras were not repositioned between rounds two and three.

Figure 3.25 Camera field of view tested but not used
Data collection syncing

The wave and camera data collection were synchronized to analyze ship motions related to specific waves. The data syncing was performed by connecting a triggering mechanism (Figure 3.27) to the wave gauges and to the camera system. The system is comprised of the two boxes on the left side of Figure 3.27. The upper box simply opens the path between a frequency generator and the camera system and wave gauges. It also sends the signal back to the computer controlling the wave gauges for viewing purposes. The frequency generator sends a digital square wave input simultaneously to the QTM software and to one channel on the wave gauges when the left hand button on the upper box is depressed. This action commences the data collection syncing.
collection. When the LCU transit was complete, second button from the left was pushed to end data collection.

An important factor to note related to data syncing is the coordinate system for the data. The camera tracking system has its own coordinate system based on the origin set during the calibration. This calibration did not take into account the location of the individual wave gauges. Therefore, a Riegl system was used to survey the basin and wave gauges using the camera system origin. The Riegl system is a commercial LIDAR (Light Detection and Ranging) product which uses a laser to scan the topographical features. As a result, the wave gauges location with respect to the LCU model position as it was tracked during the experiments was known. The survey was performed a second time before the second round of experimentation to account for the movement of the camera system and origin 2m seaward. The camera and origin placement were maintained for round 3 of the experiments.

![Figure 3.27 Triggering Mechanism](image)

Figure 3.27 Triggering Mechanism
3.9 Experimental wave conditions

The wave signals used in the experiments were 9 min in length. Monochromatic and irregular wave fields were generated. Each monochromatic wave height was run with two different model periods, 1.1s and 1.8s. Each wave id (Figure 3.28) was run three times. Wave ids 2, 3, 5, and 9 were run as monochromatic and irregular. The remainder of the wave ids were run only as irregular signals.

The irregular wave fields used in the experiments were developed using an inverse Fast Fourier Transform (FFT\(^{-1}\)) [30] to transform a TMA Spectrum [31] to a time series of water surface elevations. As with the monochromatic wave signal wave periods of 1.1s and 1.8s were used for the irregular waves. Two additional periods of 1.4s and 2.5s were also run with irregular wave signals. A TMA Spectrum was generated for each of the selected wave heights and peak periods. A TMA Spectrum is developed in a similar fashion to that of JONSWAP in that a wave height and peak period are selected. However, the relationship for the TMA Spectrum includes an added factor that takes into account a finite depth in order to develop intermediate- or shallow-water wave signals. It is important to note that there are an infinite number of wavetrains or combinations of individual waves which satisfy the spectrum. Using a random number generator, three different wave sequence numbers (random seeds) were selected (see columns S1, S2, and S3 in Figure 3.28). Using the sequence number and the JONSWAP [32] parameters for the peak period and wave height, an inverse FFT was employed to generate three different wave signals for each wave height and peak period. By using different seeds, it was ensured that the model encountered three different wave trains with the same spectral properties. This process was repeated for each peak period and wave height chosen for testing. Each irregular wave signal was run for three repetitions. For the sake of clarity, three irregular
Wave signals were generated for each Wave ID based on S1, S2, and S3 and each one of those signals was run three times for a total of nine runs per Wave ID. An example of one of the spectra used and the wave signal resulting from the FFT\(^{-1}\) is shown in Figure 3.29.

<table>
<thead>
<tr>
<th>Wave ID</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>Hm0_prototype [m]</th>
<th>Hm0_prototype [ft]</th>
<th>Hm0_model [m]</th>
<th>Tp_prototype [s]</th>
<th>Tp_model [s]</th>
<th>f_prototype [Hz]</th>
<th>f_model [Hz]</th>
<th>MSI (app)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>194751</td>
<td>1585326</td>
<td>766294</td>
<td>2.74</td>
<td>8.99</td>
<td>0.086</td>
<td>8.0</td>
<td>1.4</td>
<td>0.13</td>
<td>0.71</td>
<td>8.45</td>
</tr>
<tr>
<td>2</td>
<td>397435</td>
<td>1807083</td>
<td>243319</td>
<td>2.59</td>
<td>8.50</td>
<td>0.081</td>
<td>10.0</td>
<td>1.8</td>
<td>0.10</td>
<td>0.56</td>
<td>8.44</td>
</tr>
<tr>
<td>3</td>
<td>659</td>
<td>546511</td>
<td>1807683</td>
<td>2.29</td>
<td>7.51</td>
<td>0.072</td>
<td>10.0</td>
<td>1.8</td>
<td>0.10</td>
<td>0.56</td>
<td>7.52</td>
</tr>
<tr>
<td>4</td>
<td>35640</td>
<td>1589831</td>
<td>426427</td>
<td>2.00</td>
<td>6.56</td>
<td>0.063</td>
<td>10.0</td>
<td>1.8</td>
<td>0.10</td>
<td>0.56</td>
<td>6.60</td>
</tr>
<tr>
<td>5*</td>
<td>23000</td>
<td>1320171</td>
<td>1338569</td>
<td>1.52</td>
<td>4.99</td>
<td>0.048</td>
<td>10.0</td>
<td>1.8</td>
<td>0.10</td>
<td>0.56</td>
<td>4.99</td>
</tr>
<tr>
<td>6</td>
<td>537667</td>
<td>7464351</td>
<td>3187556</td>
<td>1.14</td>
<td>3.74</td>
<td>0.036</td>
<td>10.0</td>
<td>1.8</td>
<td>0.10</td>
<td>0.56</td>
<td>3.65</td>
</tr>
<tr>
<td>10</td>
<td>165637</td>
<td>333388</td>
<td>570596</td>
<td>1.70</td>
<td>5.58</td>
<td>0.053</td>
<td>6.0</td>
<td>1.1</td>
<td>0.17</td>
<td>0.56</td>
<td>4.48</td>
</tr>
<tr>
<td>9*</td>
<td>23000</td>
<td>1320171</td>
<td>1338569</td>
<td>1.52</td>
<td>4.99</td>
<td>0.048</td>
<td>6.0</td>
<td>1.1</td>
<td>0.17</td>
<td>0.56</td>
<td>4.05</td>
</tr>
</tbody>
</table>

Figure 3.28  Wave Signals (Graphic from Mary Bryant, USACE)

Figure 3.29  Wave spectrum (bottom) and signal (top) for Wave ID 2
Figure 3.28 shows the wave conditions for each signal run in rounds one and two. The prototype significant wave heights, $H_{m0}$, have columns for metric and English units and the model wave heights are only given in metric units. The $T_p$ columns represent the peak wave periods and the “$f_-$” columns represent the peak frequency. The MSI column represents the modified surf index of the wave conditions which is calculated based on the method in the Joint Surf Manual published by the USN [3]. The MSI is a factor used by amphibious planners to determine wave conditions which adversely affect the landing of amphibious craft.

A third round of testing was performed. This round of experiments included another run of the monochromatic signal for Wave ID 2 (Figure 3.28) with an additional 5 cm of water added to the LSTF. Wave IDs 1, 11, and 22 were monochromatic only signals. Wave IDs 17 and 18 were run as both monochromatic and irregular signals while Wave ID 16 was run as an irregular signal only.

Each wave signal was programmed into the computer tasked with controlling the wave generators by an ERDC engineer with expert knowledge of the wave generation system.

3.10 Data collection and processing

3.10.1 Collection method

As per manufacturer suggestion the camera system was calibrated twice per day: once at before testing began and once at mid-day. The calibration determines the origin of the FoV by the placement of a calibration frame with reflectors attached to it. This origin was kept consistent by paint around blocks placed in the LSTF basin (see three squares in Figure 3.10) where the frame rested for calibration such that the blocks and –by extension– the frame were placed in the same location for every calibration.
Each experiment was comprised of six to eight inbound transits (Figure 3.31 and Figure 3.32) —offshore to the beach— during a repetition of one of the 9-min wave signals (Figure 3.28) generated by the wave generator. Each transit began with the LCU model in the berth (Figure 3.30). The boat operator held the model in place against the back of the berth by setting the throttles on the remote control full astern.

The LCU model operator started each transit once a wave crest reached the bow of the model which further ensured consistency of model heading. As the wave crest passed under the bow, the operator switched the throttles to full ahead. Once the model had cleared the berth the throttle was switched to the preset prototype speed of 6 knots and an engineer in the instrumentation building triggered the wave and model tracking data collection. Once the model cleared the FoV of the camera system, a technician on shore retrieved the LCU model and placed it back in deeper water headed seaward.

The retrieval and turning process was done manually because preliminary transits proved turning the model around at the beach using the RC allowed significant amounts of water to collect on the deck of the model. As the model turned, the beam of the model was exposed to incoming waves and these waves overtopped the gunnels of the LCU. On a prototype LCU, water on the deck is not a problem. However, the model version of the LCU has fastener holes on the deck of the model. Even though rubber washers were used with the screws which affix the deck to the hull, water that collected on the deck could find its way into the hull where electronics controlling the model are housed. Routine inspections of the inside of the hull are conducted after each 9 min testing period. When a noticeable amount of water was discovered in the hull, the deck was removed and the water was removed using microfiber towels (Figure 3.33).
Once the model reaches the model operator, it was placed back in the berthing area for the next transit and the process was repeated until the 9-min wave signal was completed. Once the transits for a wave signal were completed, the LSTF basin was allowed to still for approximately 15-20 minutes in preparation of the next wave signal and set of transits. Six to eight transits were completed for each wave signal.

Data collected by the camera system includes position (x, y, and z) and rigid body motion parameters of roll, pitch, and yaw. The raw data collected by the 16 wave gauges was water surface elevation for each timestamp. There is one file for each wave gauge. The camera data and wave data were collected at rates of 60 Hz and 61 Hz, respectively. Different rates were chose due to an issue with the triggering system.

The original test matrix was executed twice. A third round of testing was developed with different wave heights and periods: Wave IDs 1, 11, 16, 17, 18, and 22 (Table 3.1). A lone repeat from the original matrix was the monochromatic Wave ID 2 signal with an additional 5 cm of water added to the LSTF basin. The cameras and origin were moved seaward 2m for the second and third rounds of testing (Figure 3.22). As noted above this adjustment expanded the data collection to the seaward side of the berm. When the test matrix was executed the first time, the FoV/data collection area for the cameras began at approximately the landward edge of the berm. Moving the cameras seaward ensured the FoV included the ramp leading to the berm. As a result of the camera position/origin adjustment the basin was resurveyed to ensure the wave gauges and camera FoV used the same coordinate system. Having the same coordinate system for both data collection systems made data processing and analysis less complicated and less prone to errors.
Figure 3.30  Beginning of Model Transit
Figure 3.31  Model Midway through Transit

Figure 3.32  Model Approaching Beach
3.10.2 Processing

A MatLab code previously developed by Ms. Mary Bryant of ERDC for processing the data collected from the wave gauges on the LSTF bridge was modified to include the processing of the camera system data. The utility code combined the data from both the wave gauges and camera system into one MatLab data file organized in a series of structures which can be easily plotted. Data collection was triggered when the LCU model left the berth. However, the FoV for the camera system did not extend to the berth for any of the rounds of testing. As a result, the processing code was modified further to truncate all data collected before the model entered the FoV. An interpolation routine was also added to the code because the camera and wave data
were collected at two different rates of 60 Hz and 61 Hz, respectively. The interpolation process ensured one-to-one timestamp correlation between the wave and camera tracking data. This syncing of the two datasets made analyzing and interpreting the LCU model response to wave impacts more intuitive and accurate.
CHAPTER IV
DATA ANALYSIS METHODS

4.1 Approach to data analysis

With over 1400 runs focused on yaw response to surf zone waves, including monochromatic and irregular waves, some simplification was necessary. Therefore, the current research focuses on analyzing the yaw for the monochromatic waves and developing a relationship from this data between surf zone parameters and the yaw DoF. To illustrate which parameters affect vessel motion a free-body diagram is presented (Figure 4.1).

Figure 4.1   Free Body Diagram of LCU – Plan View
Forces against the direction of transit include head seas (waves), wave making resistance, and skin friction. Recall that wave making resistance corresponds to the energy required to displace water in front on the craft. Following seas and propulsion provide forces in the direction of transit. Beam seas, waves that impact the port or starboard side of the vessel at a 90° angle, and quartering seas, waves incident on the port or starboard side of the vessel at an angle other than 90°, produce sway, yaw and roll motions to varying degrees dependent upon the angle of incidence. Vertical forces include buoyance, gravity, and the change in water level and can act in either the positive (upward) or negative (downward) direction. Yawing motion is produced by the forces that are incident upon the vessel from port or starboard sides – on either the bow or the stern – and can include subsurface forces due to proximity to the bottom or a bank slope.

4.2 Variables affecting yaw response

Specific variables are analyzed in this chapter to determine the significance of the effects on the yawing motion of the LCU model. These variables include

1. Impact effective location of waves incident upon the LCU model: $C_g$, bow, and stern
2. Wave height with and without regard to impact location
3. Steepness of the waves, ratio of wave height to wavelength, impacting the LCU model
4. Under keel clearance (UKC) of the model as it transits the LSTF basin
5. Instantaneous heading of the model
6. Wavelength of the incident waves with attention given to the ratio of the wavelength to the LCU model length overall (LOA)
7. The speed of the LCU model over the course of the transit
Analyzing the effects of the individual wave impact locations along the hull of the LCU model required wave-by-wave analysis. Due to complexity and uncertainty of reconstructing the individual waves impacting the LCU model during transit and identifying the location of each wave impact, this analysis was deemed beyond the scope of the current investigation. All wave impact forces were assumed to apply at the LCU center of gravity. The same argument with regard to individual wave reconstruction applies to the analysis of the wavelength to LCU model LOA and to the speed of the LCU model during transit. A simplified wavelength analysis using the incident wave period as a surrogate was undertaken but yielded no identifiable relationship.

For the wave height analysis, the MoCaps z-data were used with the caveat of uncertainty due to the LCU model surfing the wave (discussed in Chapter 5). The uncertainty was deemed acceptable in this case as opposed to the impact location analysis or the wavelength to LOA ratio analysis. It is assumed at this level of investigation that these variables can be neglected and would be considered in future research.

Therefore, we are left with four variables: wave height, LCU heading, wave steepness, and UKC or depth. While wave height, LCU heading, and even UKC may be somewhat intuitive as having potentially significant impacts to the LCU yaw response, wave steepness may not be quite so obvious. We turn to the Morison Equation [33] to address this concern.

### 4.3 Morison equation discussion

The Morison equation describes the forces on a stationary object subjected to waves [33]:

\[ F(t) = (\rho \nabla + m_a) \frac{dU_f}{dt} + \frac{1}{2} \rho C_d dU_f |U_f| \]  \hspace{1cm} (4.1)
where $\rho$ is the density of the water, $m_a$ is the added mass, $U_f$ is the velocity of the water, and $C_d$ is the drag coefficient [33]. The equation was extended to cases where both the object and the fluid are moving [34].

\[
F(t) = \rho \nabla \frac{dU_f}{dt} + m_a \frac{d}{dt} (U_f - U_b) + \frac{1}{2} \rho C_d d(U_f - U_b) |U_f - U_b| \tag{4.2}
\]

where $U_b$ is the velocity of the body or object. The Morison equation was originally developed for determining forces on cylindrical piles. Note from basic wave theory, –using wave potential– the velocity, $U_f$, and acceleration, $\frac{dU_f}{dt}$, can be written as

\[
U_f(x = 0, z, t) = a \omega \frac{\cosh k(z + H)}{\sinh kH} \cos (\omega t - kx) \tag{4.3}
\]

\[
\frac{dU_f}{dt}(x = 0, z, t) = -a \omega^2 \frac{\cosh k(z + H)}{\sinh kH} \sin (\omega t - kx) \tag{4.4}
\]

where $H$ is the depth of the water. The position $x=0$ refers to the center of the cylinder in the lateral direction and $z$ is the vertical location on the cylinder. The wave number and wave angular frequency are $k$ and $\omega$, respectively, and are given by

\[
k = \frac{2\pi}{\lambda}
\]

\[
\omega = \frac{2\pi}{T}
\]

where $\lambda$ and $T$ are the wavelength and wave period, respectively, of the incident wave.

For the case considered in the present research, the object –the LCU– is moving in the same direction as the wave train. As a result, the velocity of the LCU actually reduces the degree to which the LCU is affected by the incident waves. Therefore, a conservative rough estimate of
the effects of wave impacts on the LCU would be to consider the stationary case version of the Morison equation.

Considering the simplified case of a cylinder, –which can be extended to the scale-model LCU by adjusting the geometry terms– Morison’s equation be rewritten in terms of the inertial and drag forces [35] as

\[ F(t) = F_I \sin \omega t + F_D \cos \omega t | \cos \omega t | \]  

(4.5)

The maxima of F is found by setting the derivative equal to zero and solving at some initial time, \( t_o \). Two solutions produce an \( F_{\text{max}} \). In the case where the ratio \( F_I/2F_D \) is greater than one, the drag force is zero and \( F_{\text{max}} \) is simply the inertial force. Assuming there is a drag force imparted to the LCU, the other case is the more valid of the two. In this second case, the maxima results from

\[ \sin \omega t_o = -\frac{F_I}{2F_D} \]

where

\[ \frac{F_I}{2F_D} \leq 1 \]

Integrating the maximum force over the length of the cylinder and substituting in equations (3) and (4) and writing the maximum force in terms of the \( F_I \) and \( F_D \) [35] results in

\[ F_{\text{max}} = F_D + \frac{F_I^2}{4F_D} \]  

(4.6)

where
\[ F_D = C_D h [\sinh 2kH + 2kH] \]
\[ F_I = \pi C_m d [4\sinh^2(kH)] \]

Substituting back into equation (6) and rearranging terms

\[ F_{max} = 32\pi C_D H \left( \frac{h}{\lambda} \right) + \frac{2\pi^3 C_D^2 d^2 H}{C_D h^2} \left( \frac{h}{\lambda} \right) \]  \hspace{1cm} (4.7)

where \( h \) is the height of the wave incident on the body. Remembering that \( h/\lambda \) is the steepness of the wave (Shore Protection Manual), equation (7) represents a relationship for the maximum force of a wave impacting a cylinder in terms of wave steepness.

The steepness variables result from the water velocity and acceleration terms, equations (3) and (4). Therefore, the argument that steepness is a significant factor in wave forcing on a cylinder can be extended to the scale LCU model. The form of Equation (7) would change somewhat due to body geometry but this would not affect the significance of the role that steepness plays in affecting the motion of the LCU.

4.4 Data extraction techniques

The data used in the analyses was extracted from the raw water surface elevation data collected from the wave gauges and vessel motion from the motion capture system (MoCapS). Two approaches to extract the data were explored. One approach involved dividing the LSTF basin into virtual polygons drawn around each wave gauge (Figure 4.2). The polygons were drawn by drawing lines midway between each set of consecutive gauges (1 and 2, 2 and 3, etc). Note the numbering of gauges starts at the beach with gauge 0 and ends offshore at gauge 15. The polygons were numbered in the opposite direction with the numbering beginning at 1 at the
seaward side of the basin and progressing to polygon16 at the beach. The other approach was limited to data extracted from the MoCapS and the initial conditions at the wave generators.

Once the final data extraction method was selected, two analysis methods were examined along parallel tracks with one track exploring spectral analysis techniques and the other track using regression techniques.

**Figure 4.2** LSTF basin data polygons

### 4.4.2 Polygon method

The first extraction technique developed is based on dividing the LSTF basin into polygons based on the angle of a generated wave as it traverses the basin. These angles for the polygons were calculated using a spreadsheet model developed for that purpose. The inputs for model are initial wave height, wave period, and wavelength. The data extraction code was a
modified version of a MatLab code written by personnel from the U.S. Army Engineer Research and Development Center (ERDC). The data were extracted based on the location of the LCU’s C_g in relation to each wave gauge’s polygon. The code generated plots for the C_g position with respect to the water surface elevation at each gauge (Figure 4.3) and the track of the C_g through each polygon (Figure 4.4) for each of the sea-to-shore transits. LCU model heading at the point the C_g entered each polygon and the heading when the C_g exited each polygon were saved. The water surface elevations for the respective wave gauge corresponding to the time the C_g was in the wave gauge’s polygon were also saved.

Figure 4.3 LCU C_g position with respect to water surface elevation
For each polygon, the LCU headings were differenced to calculate the yaw of the LCU through the polygon. Using the water surface elevation data for a given polygon, minimum and maximum water surface elevations were identified and saved for each polygon during the LCU’s transit through it and differenced. The calculated water surface elevation difference was then given a sign based on if the wave was rising as the $C_g$ passed, positive sign, or was falling, negative sign.

4.4.3 Motion capture only method

The other data extraction method involved using only the data from the MoCapS. The MoCapS collects data on the scale LCU model including x, y, and z position, roll, pitch, and yaw. The yaw data is actually a measurement of the heading of the model as it is a difference between the instantaneous heading of the model and the zero heading with regard to the MoCapS
coordinate system. These data provide the total yaw relative to the MoCapS coordinate system not the instantaneous yaw. Therefore, these data were treated as the heading of the model. The MoCapS data were collected at a rate of 60 Hz or 60 data points per second. The adjacent data points with regard to time were differenced to yield the instantaneous yaw data. Water surface data were obtained by using the z data from the MoCaps system. These data were ultimately used as surrogate wave data as they better represented the number of wave impacts per model transit. The uncertainty related to this approach is discussed in Chapter 5.

4.5 Water Surface Elevation Data analysis – Polygon data extraction

Using the water surface elevation data obtained by the polygon data extraction technique, two analyses were performed for the monochromatic wave signals for Wave ID 1 and Wave ID 2 (with added basin water levels) in the third round of experiments.

The first analysis was a comparison of the per polygon yaws as related to the rising or falling waves. Rising or falling waves were determined based on if the minimum water surface elevation –recorded by the wave gauge– occurred before the maximum (rising) or if the maximum occurred before the minimum (falling). The polygon was that polygon the LCU was transiting indicated by the location of the LCU’s Cg. Two example plots are presented in Figures 4.5 and 4.6 for wave id 1. The x-axis is the change in water level which is obtained by subtracting the first extrema recorded (minimum or maximum) from the second extrema recorded. The yaw is the heading of the LCU as the Cg enters the polygon from the heading as the Cg exits the polygon. Both plots show a general trend of increasing yaw with increasing water level variation or change; however, neither plot indicates a strong correlation –which would be quantified by a tightly spaced scatter plot with a measurable slope– with...
model’s position on the wave. Wave id 2 (with higher still water level) was similar in its strength of correlation.

Figure 4.5  Yaw vs Rising Water Level (wave trough to crest)
The next analysis was a polygon by polygon comparison of the yaw versus the change in water level due to wave passage. One of the plots for Wave ID 2 (with higher still water level) is presented as an example (Figure 4.7). Again, there is a general trend; however, no strong linear correlation was found in this data set either. The same poor correlation resulted when treating the water surface differences as wave heights and calculating a crude wave steepness that was compared back to yaw response. Therefore, the next step taken, using the data collected by polygon, was to determine if there was measurable lag between the wave forcing parameter and the LCU yaw response.
A cross covariance analysis was performed on the various datasets including water surface or elevation change, underkeel clearance, and initial polygon heading to determine the lag, if any, in LCU yaw response. No particularly strong positive or negative correlation were observed for time lags up to 60 Hz.

The lack of a strong correlation between yaw and wave impacts may be attributable in part to the concatenated wave dataset used for the data analysis. By assembling the data in this fashion, it was discovered the concatenated data sometimes indicated wave peaks where none existed. These false peaks are illustrated in Figure 4.2 in Chapter 5. These peaks were generated as a result of truncating the water surface elevation data with regard to individual polygons/gauges and the differencing the maximum and minimum values within each polygon. In order to reconstruct the waves experienced by the LCU model, a method needed to be developed which took the data from the individual wave gauges and combined it in such a
manner that when the reconstructed data is plotted a true representation of the waves impacting the LCU is shown. This would have been a very complex and time-consuming process which is beyond the scope of the present investigation. Therefore, the polygon data extraction method and the subsequent data analysis methods were abandoned in favor of analyzing data from the MoCapS data extraction method.

4.6 Data analysis – McCapS data extraction

Three different data analysis methods were explored using only the MoCaps data. These analyses were cross-spectral analysis, a one-to-one comparison of LCU model yaw versus heading with a 0.5 sec or 30 Hz (data collected at 60 Hz or 60 data points per second) lag of the instantaneous yaw response with respect to the instantaneous heading, and polynomial regression analysis of heading followed by a linear regression analysis of steepness. The 0.5 second lag corresponds to a range of approximately 0.5-0.2 wave periods as the periods of the initial monochromatic waves ranged from 1.1 s to 2.5 s.

4.6.1 Cross spectral analysis

The yaw response with regard to wave height—calculated by using MoCapS z-data, the LCU z-data (see explanation in Chapter 5)—was examined using cross-spectral analysis (CSA) which is a frequency-based technique and takes into account the lagging of the LCU model response to forcing. CSA addresses the time non-linearity that is inherent in surf zone processes due to the combination of spatial and time-dependent hydrodynamic variations. However, the issue with CSA as with any analysis that involves Fourier Transforms (FT) is a requirement for a sufficient amount of data. In the present investigation, the data in question is the number of waves impacting the LCU model during a transit and the overall number of points in the dataset.
There were approximately three to five wave impacts on the LCU model per experiment and an overall number of data points (wave gauge and MoCapS) per LCU experimental transit on the order of approximately 600. Due to the conditions under which the experiments were conducted—with a varying slope and an offshore berm—the CSA had to be run on an experiment-by-experiment basis and data from individual experiments run under similar conditions could not be concatenated to produce larger data sets. Concatenation was not possible due to two factors: the bed slope and timing within the wave field. The slope of the bed puts the LCU in less than 15 cm of water when the transit ends. By concatenating it to the next transit there would a discontinuity regarding depth as the depth at the berthing area is 67 cm. Also, wave parameters such as wavelength and period at the beach are significantly different than those at the berthing area which would produce another discontinuity. Therefore, the analysis was performed on individual transits not combined ones.

A CSA of one of the experimental transits is displayed in Figure 4.8. The CSA is a process which takes the wave parameters and corresponding out of the time domain and transforms them into the frequency domain through a series of fast fourier transforms coupled with covariance techniques applied to the two datasets—wave height and yaw response—being compared and quantifies the degree of correlation between the datasets [37]. The data are analyzed in the frequency domain then recombined using inverse fast fourier techniques into a reconstructed/predicted dataset. Therefore, the CSA shows if these domain transforms and subsequent analysis are suitable for the datasets being considered. Note the predicted yaw values are two orders of magnitude less than the observed values. However, it is important to note that the pattern of the estimated and predicted curves are somewhat similar. Several other transits were analyzed with CSA with similar results. As a test of methodology, a CSA analysis was
performed on idealized sinusoidal curve with 16,000 points. The purpose of the analysis was to determine if the curve could be reproduced/reconstructed after transforming it into the frequency domain using fast fourier transforms and covariance. Performing the analysis with 2048 lags, the CSA reproduced the curve exactly. Running with fewer points or fewer lags, the predicted curve had lower magnitudes than the generated curve. Coupling the idealized analysis results with actual results suggests that the CSA analysis for the LCU model transits is data starved due to the record length with regard to the nature of data [37]. In CSA estimates of the spectra of the response are developed. As the wave height and wavelength are changing throughout the LCU’s transit, this estimate of spectra requires more than three to five wave impacts to estimate the LCU response with any level of confidence. Increasing the record length with regard to the number of wave impacts by an order of magnitude or more –through spatially longer transits– would produce significantly closer agreement between the predicted and observed curves.
4.6.2 Linear regression analysis

While the concatenated datasets above did not produce significant correlation to the yaw response of the LCU model, a strong negative relationship was observed when the instantaneous heading recorded by the MoCapS and the instantaneous yaw were analyzed in this fashion.

The relationship of yaw to vessel/craft heading is an intuitive one. As the craft turns to port due to starboard wave impacts to the hull, less starboard side sail area is presented to the incident waves, approaching from the starboard side of the model, with each successive wave impact. Conversely, if the model were turned to starboard, an increased amount of starboard side sail area would be presented to the waves incident on the model.

Figure 4.8 Cross-Spectral Analysis of an LCU Model Transit
The correlation was discovered using a cross covariance analysis. For the Wave ID 2 data from testing phase 3, the lag was approximately 30 timesteps or 0.5 seconds (see Figure 4.9). The plot shows a negative correlation between heading of the LCU and yaw response meaning a more positive heading results in a lesser yaw response. In other words, it took the vessel 0.5 seconds to exhibit the effect of a decreased yaw rate due to a reduced sail area.

![Cross Covariance - Run 1788, Yaw vs. Heading](image)

**Figure 4.9** Example of Cross Covariance of Heading and Yaw

This negative correlation did not result in a linear relationship between yaw response and the craft heading. Applying the lag to the raw data, the resulting one to one plots resembled a periodic signal with a deformation. Figure 4.10 is an example of one of these lagged yaw vs. heading plots with a third order polynomial regression line plotted over the scatter data.
4.6.3 Polynomial regression analysis

An alternate approach to the linear regression analysis of heading versus yaw, polynomial regression, was tested and produced a better correlation. The analysis started with 0.5 sec lagged yaw response data similar to the linear approach. This approach involved rotating the coordinate system 10 degrees such that the x-axis of the lagged data coincided with the wave direction at the wave generator. The data for all transits of each wave condition were combined yielding a single dataset for each Wave ID (ID2, ID3, etc). All subsequent data analysis was performed on these combined datasets. The data were then sorted with respect to heading from the lowest value to the highest value for each dataset. The polynomial regression was then performed in two steps.
rather than one by dividing the scatter plots by negative and positive headings with x-axis being the zero heading of the LCU model and performing separate third order polynomial regressions on the two datasets. The datasets with their respective regressions were merged into a single plot for a given Wave ID. Figure 4.11 illustrates the results of this approach for Wave ID 5 with R² values of 0.04 and 0.106 for the negative and positive headings, respectively. The combined curve is similar to that of the tangent-shaped curve. This fact merits further analysis with regard to wave angle and craft heading in a future research effort.

![Graph showing third order regression on rotated yaw and heading data for Wave ID5](image)

Figure 4.11 Third order regression on rotated yaw and heading data for Wave ID5

The plots for the remaining Wave ID’s are given in Appendix A. The degree of variance as measured by the R² value varied between datasets with ranges of 0.014-0.076 (negative
heading) and 0.005-0.157 (positive heading). Wave ID 3 had better agreement than most of the other Wave ID’s with the exception of Wave ID 5. These variations are most likely attributable to the variation in starting position of the LCU model with regard to the incident wave (crest versus trough) and the variability of the initial heading.

The first parameters will determine the subsequent location of the LCU model with regard to the waves it encounters: crest, trough, or somewhere in between. The second parameter could affect how many data points are on the positive versus negative heading groupings. Variability in the wave maker could also result in varying LCU locations within the wave. The location on the LCU model (bow, stern, midship) of wave impacts could also affect this analysis.

The predicted values resulting from the regression equations were subtracted from the observed, rotated data to produced residual yaw datasets for each Wave ID. Each residual dataset was tested for normalcy using the t-test. All of the residual datasets were found to have a normal distribution. Figure 4.12 shows the distribution of residual yaw data for Wave ID 2.
The distribution plots for the other Wave IDs can be found in Appendix B.

The central limit theorem [36] from statistics states that a frequency histogram developed from repeatedly and random sampling of $n$ measurements will produce a normal distribution. In the present study, this histogram is a distribution of residual yaw response after the effects of LCU heading have been removed. This distribution can be used to predict the yaw response within a selected confidence interval with the bin at the peak of the curve representing the median response. As $n$, the number of yaw observations, increases this approximation of the normal distribution and the corresponding median value becomes more precise. The approach used in the present investigation is to compare the median values for each Wave ID’s distribution to a variable which could affect the yaw response of the LCU model.

Figure 4.12  Residual Yaw Distribution - Wave Id 2

![Residual Yaw Distribution - Wave Id 2](image)
In the present study, wave steepness was the variable examined using the median residual yaw datasets that resulted from the heading regression analysis. Specifically, the steepness of the initial wave proceeding from board of the wave generators were used in this analysis. These waves represent a waves in the transitional zone where the water depth to wavelength ratio, d/λ, is between ½ and 1/25. The hyperbolic tangent factor in the transitional zone steepness calculations yielded values from approximately 0.8 to 0.9 [12] depending upon the values of d/λ for a given Wave ID. However, deep water was assumed for the purpose of simplifying the calculations in the final model. The comparison of the median yaws to the initial wave steepness for a lag of 0.5 seconds is shown in Figure 4.13. While the correlation is somewhat poor, there is a noticeable trend in the relationship between wave steepness and LCU yaw response.

Also, since it is known that the data are periodic in nature, it could be argued that the comparison using a lag of 1 s in the data is equally valid. Figure 4.14 illustrates this choice of lag yields a significantly higher correlation between initial wave steepness and median residual yaw. An examination of the heading regression for a lag of 1 s produced results similar to those for a lag of 0.5 s. And while the case could be made for using the lag of 1 s, qualitative examination of the videos (viewing the wave impact/LCU response versus the video timestamps) of the experimental transits was not definitive in asserting the vessel response to a given forcing lagged the forcing by a full second, the lag of 1 s case. Therefore, it is still not known why the correlation at 1 s is significantly better than that of 0.5 s. Future experiments and analysis could be undertaken to more precisely determine the lag between the hydrodynamic forcing and vessel yaw response. However, the 0.5 s is more representative of the physics occurring, since it clearly shows the inverse relationship between heading and LCU yaw response.
Another factor to consider is the relationship between response lag and incident wave period. The incident wave period will determine the frequency of wave impacts on the LCU model as it transits the surf zone. Therefore, lag is potentially dependent on or a function of incident wave period which in the present investigation varied from 1.1-2.5 s. Although preliminary analysis did not indicate a strong correlation between incident wave period and yaw response, this relationship represents another potential area for future study.

Figure 4.13  Residual yaw vs initial wave steepness with a lag of 0.5 s
The predicted values from the steepness regression were subtracted from the residual yaw response data resulting from the heading regression analysis. This second set of residual data was then plotted against the depths that corresponded to the time at which the yaw data was collected. These plots are shown in Figure 4.15. This analysis was carried out based on model behavior during the experimental transits. The LCU model was observed to make a noticeably sharp turn back against the direction of wave propagation at the end of several transits when the model was in very shallow water (15 cm or less). This led to the hypothesis that UKC was playing a significant role in vessel motion, especially in very shallow water. Water depth at the LCU location was chosen for the analysis in the place of UKC as a simplification.
While the water depth is not strictly the same as underkeel clearance (UKC), it can serve as a surrogate as the UKC is simply the depth minus the draft of the vessel. Earlier rough analysis between response to depth versus response to UKC produced similar results to that found in the Figure 4.15. From the plots in Figure 4.15, it is noted that all Wave ID’s produced similarly flat clusters of points. Plots developed using the absolute value of the yaw responses also showed no discernable trend beyond that seen in Figure 4.15. As a result, depth/UKC was not considered for inclusion in the linear model described in the next chapter. A possible reason for the LCU motion back toward the direction of wave propagation is a strong wave impact to the stern of the LCU.

Figure 4.15  Second residual yaw data set vs. depth
Based on the analyses presented in this chapter, a model is developed in the next chapter which is comprised of the polynomial regressions of the negative and positive heading for each Wave ID and linear regression of the median residual yaw versus the steepness of the initial condition wave. Additional discussion regarding the cross-spectral analysis method and its use as a starting point for a nonlinear model are also presented.
5.1 Description of nonlinear mathematical model/analysis

This section describes the statistical nonlinear analysis developed to determine the nature of the LCU yaw response to the height of waves impacting the craft. The analysis consists of linear and nonlinear components with the nonlinear processes predominant. While this nonlinear analysis does not result in a model, it serves as a first step towards developing a useful stochastic model.

The linear part of the analysis consists of using a polynomial regression applied to the yaw observations plotted against heading data both of which were obtained from the camera system. The heading data was adjusted ten degrees which essentially transforms the coordinate system to have an x-axis in the direction of the incident waves coming from the wave generators. The data was then sorted by the heading value (x-value) from smallest to largest. A polynomial regression is applied twice: once to the yaw data associated with negative or starboard side headings and once to the yaw data associated with positive or port side headings. These regressions are performed separately for each dataset related to a given set of wave parameters. The linear regression equations are then used to produce predicted yaw responses for each data set. These responses are subtracted from the observed yaw responses leaving two residual yaw data sets (with heading effect removed) which are then concatenated.
The nonlinear and majority component of the analysis is a cross-spectral analysis method which uses the Fourier Transform (FT) as a basis for a method to predict LCU yaw response resulting from waves which are represented as variations in water surface elevation. Generally, a FT is used to take a complex wave and reduce it to a summation of simple sinusoidal component waves (Cool and Tukey, 1965). For deep water waves (depth-to-wavelength ratio greater than ½) this is a straightforward process of applying the FT method to the wave. However, in the nearshore, waves transform nonlinearly as they approach the beach, through processes of wave shoaling and breaking (see Chapter 2). As these are nonlinear processes, summation of a discrete number of sinusoidal waves will not produce an accurate representation of the transformed wave shape. Conversely, an infinite number of wave relationships would be required to reproduce the signal. As a result, the yaw response will be nonlinear, as well.

The FT is used to transform data between the time frequency and domains. This is especially useful when dealing with complex time domain signals. In the time domain, variables are observed and analyzed with regard to how the variable(s) change with time or space. In the frequency domain, the variables are observed and analyzed with respect to temporal or spatial frequencies of occurrence. The strength of key or important periodicities within a given data set can be identified without going through the arduous and time-prohibitive process of examining every component signal in the time domain to determine the dominant signals. Analysis in the frequency domain shows the strength of contribution of each component periodicity with respect to the composite signal. Once this process is completed, an inverse FT can be used to convert these component signals back to the time domain as part of a strategy to model or predict the complex signal in the time domain. In short, using a FT to move to the frequency domain
simplifies the analysis and exposes patterns in the data which may be difficult or nearly impossible to identify in the time domain.

Therefore, a cross-spectral analysis (CSA) method was used to analyze the yaw response of the LCU model to wave height. This CSA method uses a combination of a FT method and covariance methods to quantify amplitude and phase relationships and the degree of correlation between the observed wave field and by extension the yaw response of the craft [37]. Figure 5.1 is a graphical representation of the CSA performed on the water surface elevation and yaw datasets.

Auto-covariance shows periodicity in the data. Thus, the first step in the CSA process involved taking the auto-covariances of the instantaneous water surface elevations experienced by the LCU model and of the instantaneous LCU model yaw response to identify periodicities in the water surface elevation and yaw response. A FT of the auto-covariance of the water surface elevation dataset determines the amplitude of the periodicity of the water surface elevation data. It also identifies the change in cross-covariance per lag. Auto-covariance data were calculated by placing two copies of the water surface elevation dataset side-by-side and multiplying the individual data points by one another and summing the products. The next step was to move one dataset down by one increment or lag –the time increment of the data collection— and repeat the multiplication and summation steps. This process is repeated for up to 20 percent of the number of points in the data set. If the data contains periodicities, the series of auto-covariances will have large values at the lags equivalent to one or more periods apart. The process was repeated for the yaw response data.

The next step was to perform a cross-covariance analysis. The cross-covariance process is similar to the auto-covariance except the datasets are not copies of the same data set but two
different datasets. In the present model, the two datasets used area water surface elevation and the yaw response. Applying a FT to the cross-covariance analysis generates a cross-spectrum [37]. While auto-covariance shows the periodicity in a dataset, cross-covariance shows the strength of the relationship or correlation between the two data sets. This correlation can be negative, meaning one variable is inversely proportional to the other or positive that illustrates data sets which are proportional to one another.

In the present analysis, the covariance analyses—both auto and cross—were windowed. Windowing means applying a mathematical function that is zero-valued outside a given interval (e.g., start and end of the data set) and tapered symmetrically to a value of one in the central part of the data interval. The purpose of windowing is to minimize the effect of a finite record length on analysis of a periodic signal. This method is used to calculate a matrix of covariances. The matrix comes from moving the window through the data set and calculating the covariance. Therefore, the matrix represents the covariance of different windows of the data.

The results of the cross-covariance were run through a FT. Additionally a FT was performed on the observed data, water surface elevation and yaw. The FT process requires restricting the number of data points analyzed to a factor of two: 2, 4, … 64, 128, etc. For all the datasets, the number of points used in the FT was 64.

The FT of the cross-covariance generates a series of complex numbers, a cross-spectrum. The real parts of the complex numbers, the co-spectrum, will dominate when the variables are in phase. When the variables are out of phase, the quad-spectrum, the imaginary parts of the complex numbers, dominate.
The FT of the auto-covariances generate auto-spectrum for each variable. If the data contains periodicities, the auto-spectrum will have maxima where the lags are one or more periods apart e.g., one wave period.

The phase spectrum is a measure of the lag between the water surface elevation and yaw variables. It is calculated by taking the inverse tangent of the quotient of the quad-spectrum and co-spectrum [37]. It will be a constant value between $-\pi/2$ and $\pi/2$ if water surface elevation and yaw have periodicity in common [37].

The Response Function Amplitude (RFA) is the absolute value of the cross-spectral density divided by the auto-spectral density (X). If the relationship between water surface elevation and yaw is linear, then the yaw is obtained by multiplying the water surface elevation times the RFA [37].

The series of sine functions representing observed yaw data are then re-generated using the response function from the FT of the cross covariance, the amplitude from the FT of the WSL data, the instantaneous time, the delta time or lag (a single lag in the present analysis), and the phase angle which was obtained from the FT of the observed yaw response. The amplitudes of the regenerated sine series come from the response function amplitude which is the change in cross-covariance per lag. A flow chart illustrating the CSA is shown in Figure 5.1.

Recall the CSA performed as part of this investigation used the observed yaws and the observed MoCapS z-data and decomposed the yaw response. The final result of the CSA was a reconstructed yaw signal that was compared to the observed yaw signal (see Figure 5.1). In other words, what the CSA illustrates is that the yaw response to wave height is a nonlinear process and lends itself to a nonlinear CSA analysis.
Figure 5.1 Flow Chart of Cross-Spectral Analysis
5.2 Uncertainty in the cross-spectral analysis

Uncertainty and/or errors in the regeneration will increase as the number of cycles or periods in the data decrease (i.e., shorter input data series). These cycles refer to the number of wave impacts. Running the CSA on an idealized sinusoidal signal illustrated this assertion. By using a similar number of cycles and lags similar to that used in the analysis of the experimental data, approximately 600 data points and 64 lags, the regenerated curve—while still in phase—was approximately two orders of magnitude less than the idealized signal generated by a sine function. As noted in Chapter 4, when data points were increased to 16000 and the lags to 2048, the cross spectral analysis method produced a regenerated curve that matched the phase and matched the amplitude of the signal with a two percent or less difference. This phenomenon was observed in the analysis of the yaw data collected by the camera system using the camera’s z-data as the x(t). Regardless of the Wave ID analyzed, the regenerated curves were consistently lower than the collected data by approximately two orders of magnitude. This indicates that longer transits from the sea to the shore with a greater number of wave encounters and larger data sets—with an increase in the overall number of data points by an order of magnitude or more—would produce significantly better agreement between the observed data and the reconstructed data generated by the cross spectral analysis. Faster sampling rates would collect more data points. However, this will likely not increase the agreement between the observed and reconstructed signals as the number of waves would be the controlling factor. This is evidenced by the discussion of the reproduction of the idealized sinusoidal signal above.

Another source of uncertainty in the existing analysis arises from transitioning between depth regimes by the LCU model. The data collection starts when the LCU model is visible to the motion capture system (MoCapS). This starting point occurs consistently when the waves
are “climbing” the ramp. The depths over the ramp and subsequent berm represent shallow water (depth-to-wavelength ratio less than 1/25). As the LCU clears the berm it enters the transitional depth regime (depth-to-wavelength between 1/25 and ½).

The uncertainty in using the MoCapS z-data arises from how craft transit a wave environment. The LCU model—as with any boat—will plane or “ride” each wave as the model is overtaken by the wave. This phenomenon causes the crest in the z-data to be flatter than a true wave profile. However, this flatness was preferable as the other means of using the actual wave data resulted in far greater uncertainties due to discontinuities introduced by concatenation of wave gauge data.

Wave gauges were used to collect data (see Chapter 4). However, developing a method for tracking individual waves as they transited the LSTF basin is a complex process beyond the scope of the present research. The method examined involved extracting the data from each wave gauge when the LCU model was within the corresponding polygon (see Chapter 4) associated with that wave gauge and then concatenating the data from the individual wave gauges into a composite signal.

A comparison of the two methods for one LCU transit of Wave ID 2 conditions is shown in Figure 5.2. Note spikes in the wave data produced by concatenating data from individual gauge data. These spikes would indicate many more wave impacts to the model during an individual transit than existed. Examination of the video from each model transit coupled with the plots of the MoCapS z-data support the assertion that using concatenated wave gauge data significantly overestimates the number of wave impacts to the model. Use of the MoCapS data could be improved by identifying an approximate factor to multiply the z-data to make the peaks
more comparable to the wave gauge data. However, this would need to be done in a manner that balances the matching of the magnitude of the peaks with those of the trough magnitudes.

![Concatenated Wave Gauge Data versus MoCapS z-data (Wave ID2)](image)

Figure 5.2 Concatenated Wave Gauge Data versus MoCapS z-data (Wave ID2)

### 5.3 Linear model description

A linear model was developed to examine how individual parameters affect vessel yaw. A second and equally important purpose of the model is to serve as a predictor of LCU yaw response. A linear model was chosen as it allowed individual variables to be examined and their subsequent effects removed from the observed yaw response data. Also the resulting relationships from each variable could then be combined easily into one relationship or model. The model was developed in three steps. The first step in developing the model was to adjust the
vessel heading to be relative to the wave direction, in a manner similar to that detailed in the nonlinear model description section (see Figure 5.1). The second step was developing a regression for yaw with respect to incident or initial wave steepness. The third step, regression with respect to depth, was considered. However, after the heading and steepness effects were removed, the residual yaw plotted versus the depth in the basin at the location of the LCU produced a negligible correlation. These steps are described in the following discussion.

Several parameters were considered for regression analysis with the median residual yaw. Median residual yaw was developed from the residual yaw resulting from subtracting the effects of heading from the observed yaw data. The distribution of the residual yaw data for each Wave ID was determined to be normal and the median was selected for each Wave ID. A fuller discussion of the residual yaw calculations and median yaw is located in Chapter 4. A regression of initial wave height versus the median residual yaw was considered followed by a regression with respect to the initial wave period. Finally, the regression with wave steepness was selected. Also, while the incident/initial wave height regression produced a slightly higher $R^2$, the subsequent regression performed—with regard to wave period—on the residual (obtained by subtracting yaw predicted by the wave height regression) produced a negligible $R^2$. The steepness variable has the added benefit of being dimensionless number which simplified later refinements of the linear model and included both wave height and period in one parameter. Steepness was shown mathematically in Chapter 4—through the Morison Equation—to be important to vessel response.

The regression with respect to steepness was undertaken using the median residual yaw values for each Wave ID and test number plotted against the steepness of the incident wave of
each Wave ID. This was deemed sufficient as the residuals for each Wave Id resulting from the heading regression had a normal distribution (see Chapter 4).

The steepness was calculated using the wave height and period for each initial wave and relationships from linear wave theory [12] to define wavelength. Wave steepness is given by

\[
Steepness = \frac{H}{\lambda}
\]  

(5.1)

where \(H\) is the wave height and \(\lambda\) is the wave length. Note in the last chapter a lower case \(h\) (uppercase is the more traditional usage) was used for wave height due to equation being taken from a reference using that convention. The water depth at the wave generator represented transitional depth water as the depth divided by the initial wavelength for all conditions was less than \(\frac{1}{2}\) but greater than \(\frac{1}{25}\). The hyperbolic tangent factor in the transitional zone steepness calculations yielded values from approximately 0.8 to 0.9 [12] depending upon the values of \(d/\lambda\) for a given Wave ID which would have produced steeper waves based on reduced wavelength. However, deep water was assumed to simplify the calculations. Future improvements to the model should include the hyperbolic tangent term. The wave length using the deep water formulation [12] is

\[
\lambda = \frac{gT^2}{2\pi}
\]  

(5.2)

where \(g\) is the acceleration due to gravity and \(T\) is the wave period. Inserting the wavelength into the steepness equation yields
Steepness = \frac{2\pi H}{gT^2} \quad (5.3)

Using the initial values for height and period for each set of experiments, the regression plot between median residual yaw and wave steepness in Figure 5.3 was developed. Note the Wave ID was shortened to WID for the point names in the plot and the M at the end of each name denotes monochromatic for monochromatic waves. While the correlation is somewhat poor, there is a noticeable trend in the relationship between incident wave steepness and median residual yaw response. This differs from the depth comparisons (see Figure 4.15) which yielded a flat, horizontal pattern of data. As a result, depth was not included in the final regression model.

Figure 5.3  Linear regression of initial wave steepness to median yaw
5.4 Final Model

The final model is a combination of the polynomial regression equations for the heading of the LCU model created in Chapter 4 and the steepness regression using the initial wave steepness at the wave generator and the median residual yaw. As noted in Chapter 4, two regressions were performed for each of the eight monochromatic datasets considered for analysis: one for the positive headings and one for the negative. Sixteen regressions in all, eight positive and eight negative, were developed. In order to develop a unified model, the regressions were pared down to one each for the positive and negative headings, respectively.

All sixteen heading regressions are shown in Figures 5.4 and 5.5. The final negative and positive regression equations were obtained by performing a third order polynomial regression on each set of equations. Outliers were left out of the regression for each set of equations. The outliers for each equation set were identified qualitatively based on the shape of the equation’s curve. For example, Wave ID 22 is an obvious outlier for the negative equation set because its shape at either end of the curve is noticeably different from the other equations. The other outliers removed for the regression of negative equations were Wave IDs 1 and 3. For the positive equations, Wave ID’s 11, 17, and 22 are outliers and were removed from consideration for the regression. A quantitative approach was attempted comparing the initial conditions,
Figure 5.4  Negative heading regression equation comparison

Figure 5.5  Positive heading regression equation comparison
wave height and period, for each experiment. However, these comparisons did not identify the reason for the outliers. These outliers are most likely attributable to two factors: the position of the LCU model on the wave as it exits the berth and the timing of the end of experiments which was determined when the model was removed from the water at the beach. The third-order equations for the negative and positive heading degrees, respectively, are

\[
y_{neg \ hdg} = -3.15 \times 10^{-5}x^3 - 3.33 \times 10^{-5}x^2 - 0.00076x + 0.0078 \quad (5.4)
\]

\[
y_{pos \ hdg} = -0.00012x^3 + 0.001246x^2 - 0.00142x + 0.007454 \quad (5.5)
\]

where x represents the heading in degrees.

The above regression equations for the heading were then combined individually with the steepness regression to yield the final models for the positive and negative headings for predicting yaw, \(Yaw_{pred}\).

\[
Yaw_{pred(-)} = y_{neg \ hdg} - 0.0697s + 0.000411 \quad (5.6)
\]

\[
Yaw_{pred(+)} = y_{pos \ hdg} - 0.0697s + 0.000411 \quad (5.7)
\]

where s represents the steepness of the initial wave.

The model represented by equations 5.6 and 5.7 was then used to predict the yaw for each monochromatic data set collected (see Figures 5.8 and 5.9). The blue line represents the line of perfect agreement between the model and the data. The data model vs observed data is represented as contours of the density of scatter points. A qualitative examination of Figures 5.6
and 5.7 show the exact fit line going through the center of the red contour which represents the best agreement between the model and observed data. This indicates the model is producing good agreement with the mean of the observed data (plus random variations). The remaining Wave ID model plots are located in Appendix C.

Figure 5.6  Model of Wave ID 2 – Negative Headings
While Figures 5.6 and 5.7 show how the model was able to reproduce the yaw responses used in developing the model, Figures 5.8 and 5.9 illustrate predictions using the model. Figures 5.8 and 5.9 show yaw response predictions for Seed 1 (see Chapter 3), irregular wave signal for Wave ID 2. These plots show similar agreement to that found in Figures 5.6 and 5.7. The remainder of the predictive plots are in Appendix D. Note that not all predictive plots show the level of agreement found in Figures 5.6 and 5.7. A topic of future research will be to identify other parameters not in the present model to improve these predictions.
Figure 5.8  Model of Wave Id 2, Irregular Waves, Seed 1 – Negative Headings

Figure 5.9  Model of Wave Id 2, Irregular Waves, Seed 1 – Positive Headings
5.5 **Uses of the model**

The model developed in the present investigation has the capability to serve as a statistical representation of LCU yaw response to the craft heading and initial wave steepness variables identified by the analyses in Chapter 4. The conclusions drawn from the investigation and its limitations will be discussed in the next and final chapter. Areas of future research will also be suggested.
CHAPTER VI
CONCLUSIONS

LCU yaw in the highly complex and energetic near shore zone is a response to several different parameters including wave height, wave period, wave steepness, and wave angle with regard to the shoreline, and vessel heading with regard to the wave angle. The effects of the wave parameters are also affected by the duration with which these parameters impact the LCU.

6.1 Experimental results

Over 1400 experimental ship-to-shore transits were made with the Landing Craft Utility (LCU) scale model. The data are comprised of wave gauge measurements and 6DoF motion data collected from a motion capture system (MoCapS). These data sets were synced with regard to time. The data collected during these experiments represent a unique data set that did not exist before the present investigation was undertaken. The data will serve as the foundation for future improvements to our understanding of LCU operations in the surf zone.

Observations from the experiments and inspection of the data indicate that:

- Yaw response is a stochastic process as evidenced by the random, apparently Normal distributions of the yaw response time series across all Wave IDs
- The relationship between individual wave impacts and the associated yaw responses is nonlinear and calls for analysis in the frequency domain
- At the end of some transits near the beach the model sometimes made a sharp turn back to starboard into the waves possibly due to boundary layer effects
- Transits were somewhat short lasting between 10-15 s and the LCU model encountered only three to five wave impacts per transit
The berm installed in the basin to induce wave breaking limited the wave heights that could be tested as the corresponding wave troughs reduced underkeel clearance to the point where the model would impact the berm.

### 6.2 Statistical response model

Using the MoCapS z-data as a surrogate for wave data and the observed yaw response data, a cross-spectral analysis (CSA) was performed. The CSA-predicted yaw response was two orders of magnitude lower than the observed yaw response. This difference is attributed to the shortness of each experimental transit making the analysis data starved. However, this analysis did illustrate the existence of a relationship between the yaw response and wave impacts and was able to reproduce the overall shape of the response curve. While the cross spectral analysis presented in this study is not strictly a predictive model, using both the forcing and response to reproduce the curve, the stochastic nature and CSA results make a strong case for using some form of CSA in a future-developed model.

Using the monochromatic data collected, a statistical model was developed which describes the yaw response of the LCU model to two hydrodynamic variables experienced during transits through the idealized near shore represented by the LSTF wave basin, specifically the heading of the LCU model and the steepness of the initial wave. It was shown during the development of the model that yaw response to a wave signal was distributed normally (Gaussian) once the effects of the heading of the LCU relative to the wave direction were removed from the response. The model was able to adequately predict the median yaw response of the LCU model for each set of wave conditions used in the experiments. These model results coupled with the Morison equation discussion in Chapter 4 show a strong theoretical and empirical relationship (see equations 5.4-5.7 in Chapter 5) between yaw response and the model heading and initial wave steepness (see Figures 5.6 and 5.7 in Chapter 5). Since heading is the
culmination of the vessel’s yaw responses over time, an implicit relationship can be constructed to act as a reliable predictor of the yaw probability distribution function. From such a predictor, further research will produce a probabilistic “go/no go” algorithm for field application.

6.3 Limitations of model

There were several limitations to the research including the complexity of wave signal reconstruction with regard to the instantaneous spatial location of the LCU model during each transit, space limitations in LSTF, and wave generator angle.

Due to the complexity of reconstructing the actual wave signal experienced in real-time by the LCU model, the MoCapS data and initial wave conditions were used in the statistical model. This fact prevented examination of the yaw response on a wave-by-wave basis except when using the MoCapS z-data. The z-data showed a damped wave signal due to the fact that the LCU model surfed the waves as they overtook the craft. A potential solution to this problem was observed by the author during experiments performed in another vessel motion analysis study conducted after the construction of the LCU model. An onboard wave gauge was employed in these experiments which recorded the water surface experienced by the vessel model throughout the duration of each experimental transit.

The shortness of the experimental transits constrained by basin dimensions also impacted the analysis. The LSTF basin was sloped and data from individual experiments could not be concatenated, resulting in data sets with five wave impacts or less. These relatively small data sets impacted the CSA most as shown by the two order of magnitude difference between the observed and spectral-reconstructed yaw responses.

The starting position or berth of the craft model created uncertainty. The design was developed so that it did not significantly interfere with passing waves. However, this design also
allowed the model to move within the berth affecting the starting heading. Further improvements to the berthing area to restrict lateral movement of the vessel model before it leaves the berthing area would increase consistency of initial heading starting point of each experimental transit. This consistency would also result in more accurate determinations of the effects of hydrodynamic impacts on yaw response.

Finally, the heading analysis showed the heading angle to be important. The relatively low $R^2$ values of the heading regressions could be attributed to error in the initial heading of the craft which could not be fixed exactly from experiment to experiment and to natural scatter in the response. The wave generators in the LSTF basin were fixed at a ten degree angle with respect to the shore and could not be easily moved to generate waves at a different angle. This limitation is tied to the basin selection. An experimental basin needs to be chosen which has wave generators which can be moved to different angles. The most obvious choice is a directional spectral wave generator (DSWG) which possess wave paddles than can be adjusted to a variety of angles without moving the wave generator itself.

### 6.4 Future research

With regard to future research, the author first suggests using the lessons learned from the present investigation with respect to experimental conditions to conduct more data collection. Regardless of the amphibious craft model used (a longer basin in the cross-shore direction, at least twice that of the LSTF) needs to be used. This improvement would increase the amount of data per transit. It might be prudent to use CSA on an idealized data set which can be adjusted in size in order to determine the size of the data set required.

Another suggested improvement for future research would be the addition on an onboard wave gauge included in the design of the vessel model. This gauge should be in addition to
cross-shore gauges in the wave basin and should take the motion of the vessel into account. The cross-shore gauges could be used to verify the signal recorded by the onboard gauge. The onboard gauge data could be used as validation data for any method developed to reconstruct individual waves impacting the model from the cross-shore gauge data. This reconstruction process could be a research effort all its own.

Using the improved data collection method, both modeling approaches investigated in the present research could be studied further. With respect to the regression model, the steepness of individual waves impacting the amphibious model could be analyzed. Analyses of wave impact location could also be undertaken to determine the significance of waves impacting the stern, midship, and the bow. With regard to the CSA, the increased number of wave impacts per vessel model transit would significantly improve the predictions of any model employing CSA techniques as evidenced by the idealized analysis discussed in Chapter 4.

Also, a range of offshore wave angles should be investigated in future experiments as wave angle was shown, through the heading analysis, to play a significant role in yaw response. The DSWG mentioned in the above section could be employed for that purpose. The wave angle could be added to the statistical model as a variable to further improve prediction of yaw response.

Original discussions at the beginning of the research effort focused on effects of breaking waves impacting the LCU model. With the difficulties encountered in attempting to identify the characteristics of individual waves impacting the LCU model, the effects of breaking waves on LCU yaw response was not explored. This area will be a challenging problem even with the ability to measure individual wave characteristics in the laboratory environment.
While a model used for predicting go/no-go thresholds for shallow-hulled, amphibious craft is desirable, it is beyond the scope of the current investigation. The present model serves as a starting point for future work that could determine these thresholds. The model will need to be expanded through future research to combine craft heading and wave angle with the characteristics of multiple, individual wave impacts including the rapidity or period of those impacts. Also, any model developed for predicting yaw response would have to be coupled with a separate model which predicts near shore conditions such as a Boussinesq type model. Once these models are developed, the process for developing the yaw response in a given near shore zone would be an iterative one in which the surf zone model is run under a variety of conditions (wind sea, swell, etc) and then each set of outputs would be used as input into the yaw response model with a range of craft parameters (track/heading, speed, and starting location).

The statistical model developed represents a significant advancement in the understanding of LCU response in the near shore. It provides a statistical tool which describes LCU model response in an idealized surf zone. This model will serve as a starting point for the next phase of near shore vessel response modeling development.

In closing, this research subject is difficult to be sure. However, the people whom it serves (Figure 6.1) makes the effort worth it. It is hoped that the results of this research will be used to improve mission success and the safety of United States military personnel in the performance of their duties.
Figure 6.1  U.S. Marine Corps personnel exiting an LCU (picture courtesy of the U.S. Navy)
REFERENCES


APPENDIX A

HEADING REGRESSION PLOTS
Figure A.1  Third order regression on rotated yaw and heading data for Wave ID2

Figure A.2  Third order regression on rotated yaw and heading data for Wave ID3
Figure A.3  Third order regression on rotated yaw and heading data for Wave ID5

Figure A.4  Third order regression on rotated yaw and heading data for Wave ID11
Figure A.5  Third order regression on rotated yaw and heading data for Wave ID17

Figure A.6  Third order regression on rotated yaw and heading data for Wave ID18
Figure A.7  Third order regression on rotated yaw and heading data for Wave ID22
APPENDIX B

RESIDUAL YAW DISTRIBUTION PLOTS
Figure B.1  Residual Yaw Distribution - Wave Id 2

Figure B.2  Residual Yaw Distribution - Wave Id 3
Figure B.3  Residual Yaw Distribution - Wave Id 5

Figure B.4  Residual Yaw Distribution - Wave Id 11
Figure B.5  Residual Yaw Distribution - Wave Id 17

Figure B.6  Residual Yaw Distribution - Wave Id 18
Figure B.7  Residual Yaw Distribution - Wave Id 22
APPENDIX C

MODEL VALIDATION PLOTS
Figure C.1  Model of Wave id 2 – Negative Headings
Figure C.2  Model of Wave id 2 – Positive Headings
Figure C.3  Model of Wave id 3 – Negative Headings
Figure C.4 Model of Wave id 3 – Positive Headings
Figure C.5 Model of Wave id 5 – Negative Headings
Figure C.6  Model of Wave id 5 – Positive Headings
Figure C.7  Model of Wave id 11 – Negative Headings
Figure C.8  Model of Wave id 11 – Positive Headings
Figure C.9  Model of Wave id 17 – Negative Headings
Figure C.10  Model of Wave id 17 – Positive Headings
Figure C.11  Model of Wave id 18 – Negative Headings
Figure C.12 Model of Wave id 18 – Positive Headings
Figure C.13  Model of Wave id 22 – Negative Headings
Figure C.14  Model of Wave id 22 – Positive Headings
APPENDIX D

IRREGULAR WAVE MODEL COMPARISON PLOTS
Figure D.1  Model of Wave id 2, Seed 1 – Negative Headings
Figure D.2  Model of Wave id 2, Seed 1 – Positive Headings
Figure D.3  Model of Wave id 2, Seed 2 – Negative Headings
Figure D.4  Model of Wave id 2, Seed 2 – Positive Headings
Figure D.5  Model of Wave id 2, Seed 3 – Negative Headings
Figure D.6  Model of Wave id 2, Seed 3 – Positive Headings
Figure D.7  Model of Wave id 3, Seed 1 – Negative Headings
Figure D.8  Model of Wave id 3, Seed 1 – Positive Headings
Figure D.9  Model of Wave id 3, Seed 2 – Negative Headings
Figure D.10  Model of Wave id 3, Seed 2 – Positive Headings
Figure D.11  Model of Wave id 3, Seed 3 – Negative Headings
Figure D.12  Model of Wave id 3, Seed 3 – Positive Headings
Figure D.13  Model of Wave id 5, Seed 1 – Negative Headings
Figure D.14  Model of Wave id 5, Seed 1 – Positive Headings
Figure D.15  Model of Wave id 5, Seed 2 – Negative Headings
Figure D.16  Model of Wave id 5, Seed 2 – Positive Headings
Figure D.17  Model of Wave id 5, Seed 3 – Negative Headings
Figure D.18  Model of Wave id 5, Seed 3 – Positive Headings
Figure D.19  Model of Wave id 17, Seed 1 – Negative Headings
Figure D.20  Model of Wave id 17, Seed 1 – Positive Headings
Figure D.21  Model of Wave id 17, Seed 2 – Negative Headings
Figure D.22  Model of Wave id 17, Seed 2 – Positive Headings
Figure D.23 Model of Wave id 17, Seed 3 – Negative Headings
Figure D.24  Model of Wave id 17, Seed 3 – Positive Headings
Figure D.25  Model of Wave id 18, Seed 1 – Negative Headings
Figure D.26 Model of Wave id 18, Seed 1 – Positive Headings
Figure D.27  Model of Wave id 18, Seed 2 – Negative Headings
Figure D.28 Model of Wave id 18, Seed 2 – Positive Headings
Figure D.29  Model of Wave id 18, Seed 3 – Negative Headings
Figure D.30  Model of Wave id 18, Seed 3 – Positive Headings