REPORT DOCUMENTATION PAGE	*Form Approved* **OMB No. 0704-0188**

1. REPORT DATE *(DD-MM-YYYY)*
04/03/2019

2. REPORT TYPE
Masters Thesis

3. DATES COVERED *(From - To)*
Sept 2018 - Apri l 2019

4. TITLE AND SUBTITLE
A Launch and Recovery System for Integrating Unmanned Ocean Vehicles onto Surface Platforms

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Casey L strouse

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technology
77 Massachusetts Ave.
Cambridge, MA 02 139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Civilian Institutions Office (Code 522)
Naval Postgraduate School
1 University Circle, Herrmann Hall Rm HE046
Monterey, CA 93943-5033

10. SPONSOR/MONITOR'S ACRONYM(S)
NPS CIVINS

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This paper will analyze current manned launch and recovery systems across all naval surface platforms and present recommendations for improving these systems to be more adaptive to launching both manned and unmanned ocean vehicles. Specifically, this research will focus on minimizing the heave motions exhibited by the vehicle during launch and recovery. To achieve minimized heave motions and improve operational performance, an analysis was conducted to determine the feasibility, performance, and safety benefits of integrating an active heave compensating winch into the system.

15. SUBJECT TERMS
Unmanned Vehicles, Launch and Recovery

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Casey L Strouse
U	U	U	UU	64	**19b. TELEPONE NUMBER (*Include area code)*** 617-253-4339

A Launch and Recovery System for Integrating Unmanned Ocean Vehicles onto Surface Platforms

by

Casey L. Strouse

B.S. Naval Architecture
United States Naval Academy, 2012

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

NAVAL ENGINEER
AND
MASTER OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2019

Author..Casey Strouse..........
Department of Mechanical Engineering
April 3, 2019

Certified by..
Michael S Triantafyllou
Professor of Mechanical Engineering and Ocean Engineering
Thesis Supervisor

Accepted by..
Nicolas Hadjiconstantinou
Chairman, Department Committee on Graduate Studies
Department of Mechanical Engineering

A Launch and Recovery System for Integrating Unmanned Ocean Vehicles onto Surface Platforms

by

Casey L. Strouse

Submitted to the Department of Mechanical Engineering
on April 3, 2019, in Partial Fulfillment of the
Requirements for the Degrees of
Naval Engineer
and
Master of Science in Mechanical Engineering

Abstract

Unmanned vehicles (UxVs) are becoming more prevalent across all domains. As UxV technology improves and their operations become more essential to mission success, the challenge of integrating these vehicles onto current surface platforms becomes increasingly more important to solve. Surface ships are designed to be adaptive and meet the changing requirements of their operational environment over their 25-plus year life. However, the majority of the current surface fleet was not designed from the beginning for launch and recovery of unmanned ocean vehicles and must be retrofitted to support unmanned vehicle operations. While integration of UxVs will be limited by the size of the host platform, their integration should not be limited due to the inability to safely launch and recover them.

This paper will analyze current manned launch and recovery systems across all naval surface platforms and present recommendations for improving these systems to be more adaptive to launching both manned and unmanned ocean vehicles. Specifically, this research will focus on minimizing the heave motions exhibited by the vehicle during launch and recovery. To achieve minimized heave motions and improve operational performance, an analysis was conducted to determine the feasibility, performance, and safety benefits of integrating an active heave compensating winch into the system.

Thesis Supervisor: Michael S. Triantafyllou
Title: Professor of Mechanical and Ocean Engineering

Acknowledgments

The completion of this project could not have been completed without the constant support and encouragement from the following personnel:

- My family, for their support throughout my career as well as their encouragement and motivation throughout the entirety of my graduate studies.
- The 2N personnel for their guidance, both professionally and academically, towards completing this research and preparing me for continued success throughout my naval career.

THIS PAGE INTENTIONALLY LEFT BLANK

Table of Contents

List of Abbreviations

AHC	Active Heave Compensating
FBD	Free Body Diagram
FFG(x)	Future Frigate
FSC	Future Surface Combatant
IMU	Inertial Measurement Unit
KE	Kinetic Energy (KE=$\frac{1}{2}$mv^2)
L&R	Launch and Recovery
LCS	Littoral Combat Ship
LDUUV	Large Diameter Unmanned Underwater Vehicle
NAVSEA	Naval Sea Systems Command
PD	Proportional-Derivative
PE	Potential Energy (PE=mgh)
RHIB	Rigid Hull Inflatable Boat
SLAD	Slewing Arm Davit
USV	Unmanned Surface Vehicles
UUV	Unmanned Underwater vehicles
UxV	Unmanned Vehicles
XLUUV	Extra Large Unmanned Underwater Vehicle

List of Figures

Chapter 1: Introduction

1.1 Motivation

The motivation to conduct research related to launch and recovery (L&R) of unmanned ocean vehicles came both from the need to incorporate unmanned vehicles onto surface platforms as well as from the involvement in operating and integrating these systems. First, the necessity of developing safe and efficient methods of launch and recovery of unmanned vehicles can not be understated. The realm of unmanned technology and incorporation of these systems into naval missions is rapidly developing. However, the majority of the current surface fleet was not initially designed to integrate with unmanned vehicles. The importance of safely integrating unmanned vehicles is evident through design requirements for the most current surface ship, Littoral Combat Ship (LCS), as well the Future Surface Combatant (FSC) and the Future Frigate (FFG(x))[1]. These requirements called for the integration of unmanned vehicles as part of the initial design. This, however, means most of the surface fleet needs to be back fitted to incorporate unmanned vehicles.

Second, as a former shipboard operator who has multiple years of experience in launching and recovering a variety of manned surface craft, the ability to safely and efficiently launch or recover craft, whether manned or unmanned, is of utmost importance. From a shipboard operator perspective, a successful launch and recovery includes both personnel and craft safety, therefore the methods for launch and recovery must consider personnel safety, complexity of evolution, and environmental factors such as sea state.

Finally, with a future career associated with Naval acquisitions, the ability to develop a common L&R system that can be utilized across a variety of platforms and UxVs will have a great cost savings impact. Not only does commonality have cost savings in the material, budgetary and acquisition stage, but it will also have cost savings in the training and effectiveness stage because sailors will have higher proficiency with use of common operating systems throughout the fleet.

1.2 Relevant Research

The study of unmanned ocean vehicles encompasses many fields of expertise, but it is important to mention two specific research areas directly related to the study presented in this paper. For over a decade, researchers have been investigating motion control of offshore platforms. Specifically, as discussed in Woodacre et al. [2], various methods of active heave compensation and implementation of controls onboard offshore drilling platforms has shown great promise in reducing the overall effects of high seas on specific components.

To reiterate the importance of integrating unmanned vehicles into the surface fleet, Naval Sea Systems Command (NAVSEA) has developed a working group composed of six warfare centers with the common goal to "develop prototypes to demonstrate a common system for stowage, handling, launch, recovery, tendering, and transport capability for current and future UxVs for all naval maritime platforms and shore facilities."[3]

Naval Surface Warfare Center Philadelphia (NSWC PD)

Naval Undersea Warfare Center Newport (NUWC NPT)

Naval Undersea Warfare Center Keyport (NUWC KPT)

Naval Surface Warfare Center Port Hueneme (NSWC PHD)

Naval Surface Warfare Center Panama City (NSWC PCD)

Naval Surface Warfare Center Carderock Division (NSWC CD)

Figure 1-1. NAVSEA Warfare Centers, UxV Commonality

The work conducted by the warfare centers (Figure 1-1) towards achieving commonality in unmanned vehicle support and the work on active heave control has influenced the development of the problem statement. The overall goal of this project being that the results will continue to contribute to the advancements in fully integrating unmanned vehicles and improving the ability to launch and recovery these ocean vehicles.

1.3 Problem Statement

The focus of this study will be towards developing a common launch and recovery system for unmanned surface and unmanned underwater vehicles that can be integrated onto current surface platforms. The steps utilized in solving this problem are detailed below:

Step 1: Identify the current capabilities and requirements for launch and recovery of ocean vehicles. The technology gap between the capabilities and requirements are analyzed from both the shipboard and the UxV perspective as these must be aligned to best meet the integration goal across the fleet. (Chapter 2)

Step 2: Propose a possible solution for closing the technology gap for improving and integrating launch and recovery of ocean vehicles. (Chapter 3)

Step 3: Analyze the proposed design to include seakeeping and operational performance. (Chapter 4)

Step 4: Recommend future work for continuing to improve the process of launching and recovering Unmanned Surface Vehicles (USVs) and Unmanned Underwater Vehicles (UUVs) from surface platforms. (Chapter 5)

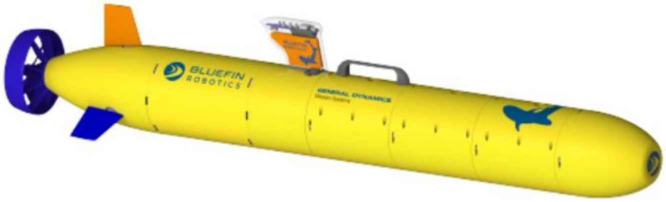
Before analyzing the capabilities and requirements, it is important to first develop a better understanding of the variety of unmanned vehicles currently available.

1.3.1 Unmanned Underwater Vehicles Explored

Unmanned Underwater Vehicles are categorized into classes ranging from small to extra large with diameters ranging between three inches to greater than 84 inches. For the purposes of this study, Extra Large Unmanned Underwater Vehicles (XLUUVs), which have a diameter greater than 84 inches, were not considered since they are typically pier launched as their size prevents them from being launched from surface ships. An overview of the different UUV classes, as well as their method and rate of launch and recovery are detailed in Figure 1-2[4].

The rate of launch and recovery is an important factor as it plays a role in selecting a system that can support operations as required and may influence system redundancy, robustness, and ease of operation.

Small



[5]

Size: 3-10-inch diameter

L & R: Surface Ships, LDUUV, XLUUV, Submarines; Man Portable

Rate of L & R: hourly

Medium

[6]

Size: 10-21-inch diameter

L & R: Surface Ships, XLUUV, Submarines

Rate of L & R: Daily

Large

[4]

Size: 21-84-inch diameter

L & R: Surface Ships, Submarines

Rate of L & R: Weekly

Figure 1-2. UUV Classes Explored

1.3.2 Unmanned Surface Vehicles Explored

Unmanned Surface Vehicles (USVs) range in size from very small (<7 m) to large (>90m) and are categorized into classes based on overall length. For the purposes of this study, the USV classes explored were limited to Class 1 (very small) and Class 2 (small) as these are the sizes of USVs that can be launched from any of the current surface platforms. Studying the larger classes of USVs will be important, however since their size limits them to specific platforms and thereby reducing commonality across the fleet they are considered outside the scope of this study. Figure 1-3 [4] summarizes the general characteristics of the USV classes that will be explored as part of this study.

Class 1: Very Small

[7]

Size: Length ≤ 7m (23 ft)

L & R: Man Portable, Surface Ship, Shore

Rate of L & R: Hourly

Class 2: Small

[8]

Size: Length 7m (23 ft) – 12m (39ft)

L & R: Surface Ship, Shore

Rate of L & R: Hourly - Daily

Figure 1-3. USV Classes Explored

1.4 Down Selection

The most common types of launch and recovery systems installed onboard surface vessels are a variation of either side launch or stern launch. Taking a closer look at the current US Navy Surface Fleet, an overwhelming majority of the vessels have some variation of side launch capability, which is most commonly used for launching their Rigid Hull Inflatable Boats (RHIBS). While some vessels do have stern launch, either stern crane or stern ramp, this is not as common across the fleet. Many of the vessels with stern launch capability also have side launch capability. Also, stern launching is a more inherent characteristic of the vessel determined before build, whereas many side launch methods can be made more adaptable and are not inherent to the hull of the surface platform. With that being said, this project will further be narrowed down to focus on side launching of UUVs and USVs ranging in length of 7-11 meters. The length of unmanned vessels chosen is most equivalent to manned craft already onboard the vessel and therefore will allow for more ease of integration.

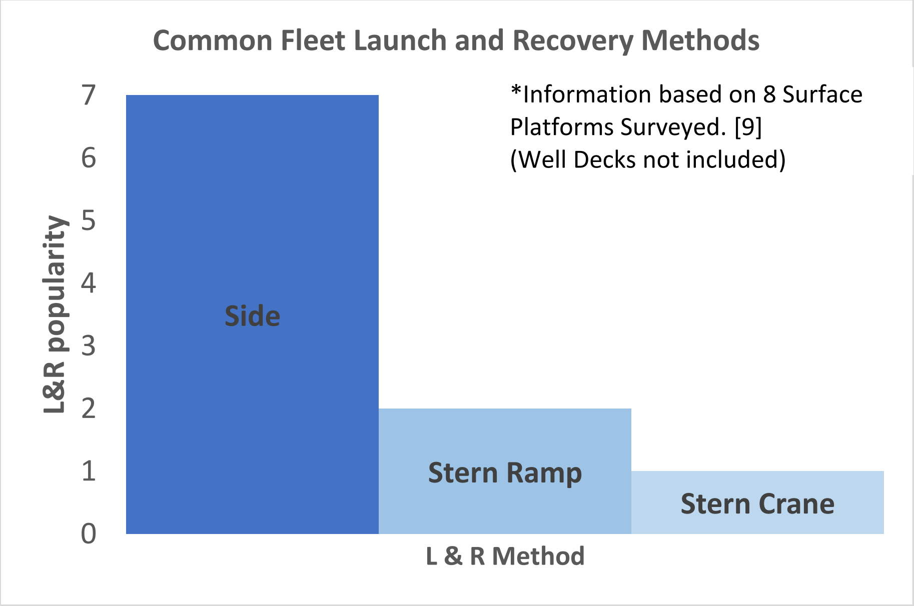


Figure 1-4. Common Fleet Launch and Recovery Methods

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 2: Analysis of Current State

2.1 Current Methods of Launch, Recovery, Handling, and Stowage for Surface Ships

To start the analysis, the current methods of launch and recovery of manned vehicles will first be reviewed to determine the best approach for adapting to launch and recovery of unmanned vehicles. During this analysis, it is important to remember the overall goal of this study, which is to develop commonality in launch and recovery of USVs and UUVs across the fleet. Since the current surface fleet varies greatly in size and capability, it is important to note the main restrictions on total commonality, most notably geometric size restrictions. Given these size restraints and the fact that the study will focus on launch and recovery of vessels 7-11 meters, the next step is to determine a specific platform that best represents the fleet and is most able to be adapted across the spectrum for launch and recovery of unmanned ocean vehicles.

As shown in Figure 1-4, the most common method across the fleet for launch and recovery is side launch. The following characteristics were derived from the advantages and disadvantages of each launch and recovery system and analyzed with a weighted sum analysis (Figure 2-1) based on their ability to currently launch and recovery unmanned vehicles.

The characteristic for comparing methods of launch and recovery are:

- **Adaptability**: This includes the ability of the L&R system to be modified in the future to incorporate unmanned vehicles without negatively impacting other mission areas and without requiring major hull modifications.

- **Unmanned Underwater Vehicles:** Ability of the current system to adapt to L&R of UUVs.
- **Unmanned Surface Vehicles**: Ability of the current system to adapt to L&R of USVs.
- **Familiarity**: Includes common methods across the fleet (Figure 1-4) and therefore better able to be retrofitted or adapted to incorporate unmanned craft across the fleet. References the sailor's level of knowledge with safely operating the system.
- **Relative motion & Hydrodynamic effects**: Side launched vehicles typically see lower relative motion when near the host platform due to proximity to the longitudinal center of flotation and the ability of the host platform to create a lee. Stern launched vehicles typically feel increased interference from the host platforms wake and therefore feel increased relative motions during launch and recovery.

CHARACTERISTIC	**SIDE**	**STERN RAMP**	**STERN CRANE**
ADAPTABILITY	5.00	1.00	2.00
UUV	3.00	0.00	3.00
USV	3.00	4.00	3.00
FAMILIARITY	4.38	1.25	0.63
RELATIVE MOTION / HYDRODYNAMIC EFFECTS	4.00	2.00	2.00
	3.88	1.65	2.13

Figure 2-1. Comparison of L&R Methods

Within the over the side method of launch and recovery, there are many variations of davits and cranes throughout the fleet. However, since the procedure is similar for each variation, this study will specifically focus on adapting the slewing arm davit (SLAD) system. The approach utilized can then easily be adapted to the other variations of side launch and recovery. A picture (Figure 2-3) as well as the advantages and disadvantages [9] of the slewing arm davit are summarized below (Figure 2-2).

ADVANTAGES	**DISADVANTAGES**
• Utilize shock absorbing and motion compensated systems to some degree • Due to location, reduced motions therefore able to L&R in higher sea states • Fleet Commonality • Higher Sailor experience / knowledge • Vehicle Stowage located at L&R site; reduced handling required • Host platform can create a Lee reducing relative motion felt by vessel • Stowage cradles can be more easily adapted to varying vessels	• Requires man in the loop for hooking/unhooking lines • Requires use of sea painter and steadying lines • Usually located on weather deck, so vessel components are exposed to varying weather conditions • Only utilizes passive devices for motion reduction

Figure 2-2. SLAD L&R Advantages and Disadvantages

Figure 2-3. Slewing Arm Davit

2.2 Analysis of Gap between Current Methods and Requirements

In further analyzing the slewing arm davit in ability to adapt to operations with unmanned ocean vehicles, we must first develop a basic understanding of the current features for launch and recovery that are inherent to unmanned ocean vehicles. These features include, but are not limited to:

- Object Recognition / Situational Awareness
- Hooks/Locations for rigging attachments
- Station keeping

Next, in order to improve or adapt the current SLAD system used for manned craft to incorporate unmanned vehicles, a gap analysis must be conducted. This gap analysis will assist in determining the needs of a common launch and recovery system for unmanned ocean vehicles as well as direct the focus of the approach in closing the technology gap. The gap analysis, summarized below in Figure 2-4, shows there are multiple areas in the launch and recovery process where a gap in technology prohibits the current SLAD system from safely launching and recovering unmanned ocean vehicles. The design approach for closing this technology gap will be discussed in further detail in Chapter 3.

L&R Requirement	Domain Analysis		Technology Gap
	Manned	**Unmanned**	
Mission Impact	Ship Speed of 3-5kts for 10-15 minutes Ample room to maneuver	Ship Speed of 3-5kts for 10-15 minutes Ample room to maneuver	No
Station keeping	Able to maintain station through sea state 3-4 Coxswain manually maintains station	Sea state for maintaining station is UxV specific Maintains station via onboard sensors	No
Line Handling / Manning	Manned during L&R and operations Required shipboard line handlers for steadying motion Requires manual connection/disconnection from L&R system and tending lines	Unmanned during L&R and operations Currently requires manual line handling and manual connect/disconnect which proves difficult since unmanned → requires more autonomy	Yes
Safety	Increased risk of personnel safety due to manning requirements	Minimum personnel safety Increased risk to equipment during transition from L&R to ocean environment	Yes
Ease of Integration	Design feature of most surface platforms	Not inherent to most surface platforms → requires upgrades to current system or installment of new system Limited space available onboard surface platforms Increased integration allows for both manned and unmanned systems	Yes
Launch	1. Vessel connect to the SLAD shipboard 2. Manned 3. Slowly lowered over the side 4. Crew manually releases all lines	1. Vessel connect to L&R system shipboard 2. Slowly lowered over the side 3. Lines must be released (currently manually)	Yes
Recovery	1. Coxswain positions vessel in L&R station 2. Lines lowered and manually connected 3. Vessel slowly raised 4. Unmanned 5. Vessel stowed	1. Vessel positions itself in L&R station via onboard sensors 2. Lines currently manually connected (ideally upgraded hook technology and utilization of object recognition) 3. Vessel slowly raised 4. Vessel stowed	Yes

Figure 2-4. L&R Gap Analysis for Commonality and Integration

2.3 Current SLAD Motion Compensating Configuration

The specific davits utilized for over the side launch and recovery varies slightly depending on the host platform and manufacturer. However, the slewing arm davits currently utilized each still have many commonalities, specifically regarding their motion compensating system. The motion compensating components currently utilized can be broken down into two categories: Shock Absorbers and Winches. The winch systems currently installed are either passive or non-passive, although the passive system is more commonly used.

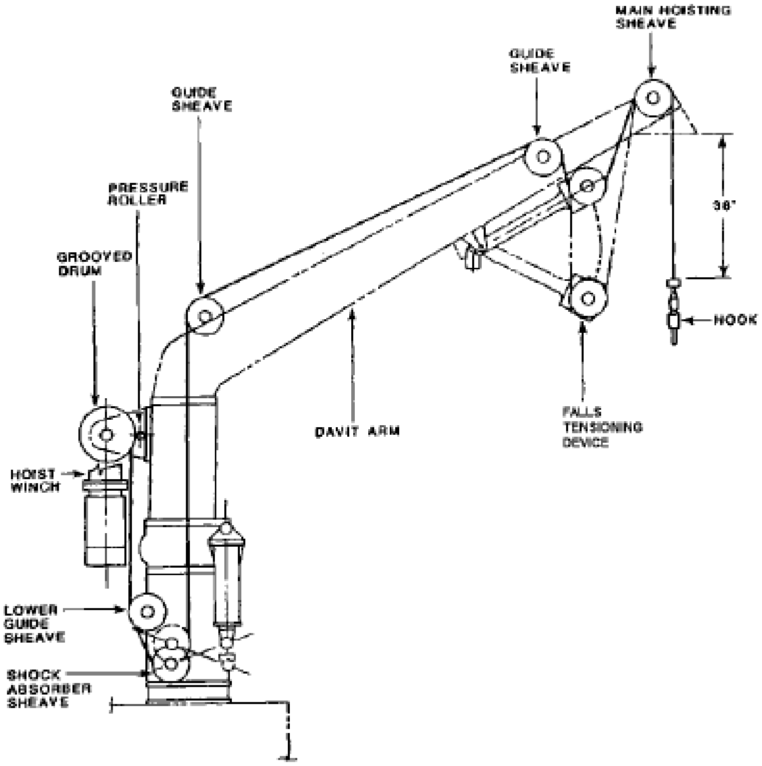


Figure 2-5. Standard Slewing Arm Davit with Shock Absorber and Falls Tensioning Winch

As shown in Figure 2-5 [10], the shock absorber for all SLADs is located the bottom of the pedestal where the davit is connected to the ships weather deck. The shock absorber's primary purpose is to help minimize the motions transmitted from the ship to the davit, mainly ship vibrations and to a small extent the pitch, heave, and roll motions. The shock absorbers themselves are a standard spring or hydraulic system [10] and can accommodate up to six inches of travel along their axis.

The passive compensating system installed, which is the most common across the fleet, is known as a Falls Tensioning Device. [10] This device is installed towards the end of the davit boom and is weighted to counterbalance the weight of the hook and wire rope. While it does help provide minimal motion compensation, specifically in the heave direction, it's mainly employed to quickly get the hook away from the small boat once disconnected. The falls tensioning device is a manually operated device, so since it does counter the weight of the hook, it could be employed to help steady the hook and wire rope in heavier sea states to minimize their pendulum motion felt due to the ships motion.

The non-passive motion compensating system utilized on slewing arm davits is a constant tension winch. This is not the preferred system by the operators, so is not as commonly installed. This system has a sensing device located near the tip of the davit arm while the winch is located at the base of the davit arm. The sensor does as the name suggests and senses the tension in the wire rope. It then relays the measurement to the winch which is pre-set to maintain a specific tension. As the name suggests, the winch will pay out or pull in the wire rope as necessary to maintain the pre-set constant tension indicated. This device is less desirable, because in rough seas when the hook and wire rope are constantly moving due to the motions felt by the seas and winds, the sensor and winch can become unreliable and cause the winch to continuously payout the wire rope which is not the desired outcome.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 3: Design

3.1 Design Approach Method

In determining the best approach for integrating unmanned ocean vehicles onto surface platforms, both developing an entirely new system for launch and recovery and developing implemental upgrades to the current system were considered. After analyzing the needs and requirements of a system for unmanned ocean vehicles as well as the technology gap, risk, cost, and operator interface, the incremental upgrade approach was determined to be the best method for this case. Implementing upgrades utilizing proven technology will reduce overall costs in manufacturing because a proven method of production has already been developed. Costs will be lowered during maintenance because spare parts already exist in the inventory. Also, the installation will not be as time consuming and therefore will be easier to accomplish during short availabilities. A final benefit of the incremental system upgrade approach is it will contribute to higher overall operator proficiency and safety since the operators will only be learning one new aspect of operation vice an entirely new system.

As shown through the technology gaps discussed earlier, there are many areas of focus for the first upgrade or improvement to the current system. This study will focus on improving the overall stability and reducing the motions of the vehicle during launch and recovery. Improving motion control will help to close the technology gaps in all areas, increase overall safety for both manned and unmanned ocean vehicles, and set the stage for implementing more specific technology to completely close the gaps. This first step in the process will also allow for improved integration and operator familiarity as it will allow the system to continue to be utilized for manned vehicles as well as allow for the integration of unmanned vehicles.

3.2 Design Considerations and Requirements

3.2.1 Ship Motion and Design Considerations

Before diving into the concept design, it is important to first review the six degrees of freedom axes depicting the motions a vessel in water will encounter. As depicted below in Figure 3-1[11], the three translational motions are surge, heave, and sway, while the three rotational motions are pitch, yaw, and roll. Like the host vessel, the vehicle will experience some degree of all six motions, however the typic motions most readily observed by the vehicle during side launch and recovery operations are:

- **Pitch**. While this is minimized since side launch occurs close to midship and therefore near the center of rotation for the pitch motion. However, the vehicle can still be affected by some forward and aft rocking motion. This motion will be most readily observed when the vehicle is in the water prior to recovery or at the end of launch due to wave interaction.
- **Heave**. This is the primary motion felt by the vehicle and this motion can be exaggerated when the vehicle is alongside the host platform due to the two bodies alternating motions. Heave is the up and down motion felt by a vessel in the water.

- **Yaw**. While the host vessel experiences roll, due to how the vehicle is connected to the launch and recovery system, this translates to a yaw motion in the vehicle. Currently this motion is minimized through the utilization of line handlers as shown in figure 2-3.

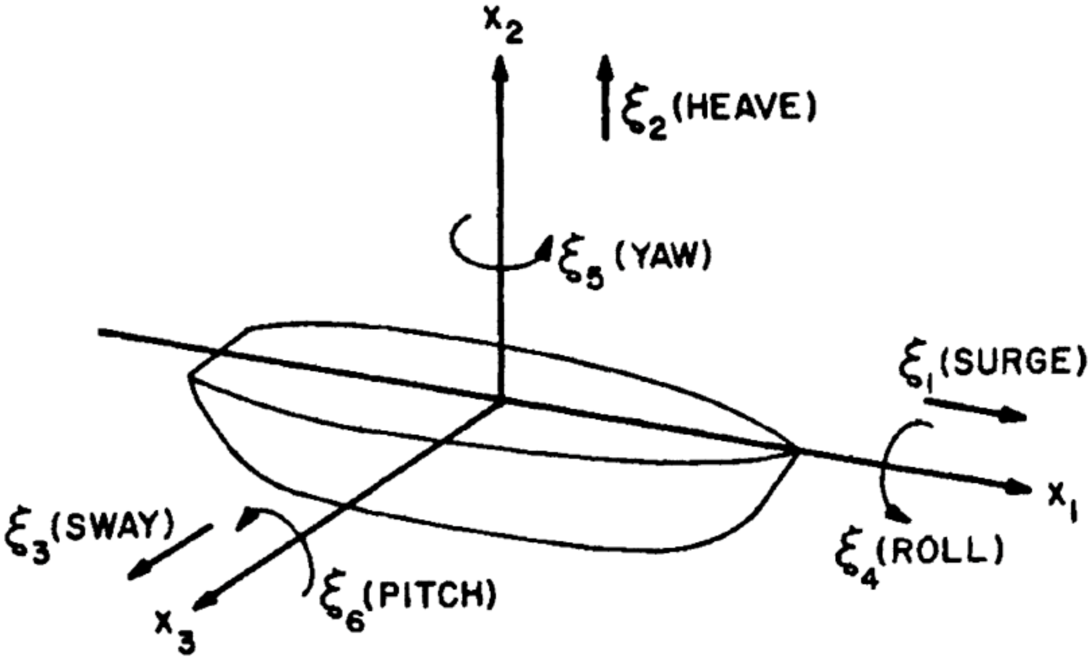


Figure 3-1. Vessel Six Degrees of Freedom

3.2.2 Design Requirements

The following concept design will strive to improve upon a system for side launch and recovery in order to integrate both manned and unmanned ocean vehicles. This will be achieved by adhering to the following goals and requirements:

- **Reduced Motions.** Reduction in motion will be achieved by implementing an active compensating system focused specifically on reducing the heave motions and affects transmitted to the vehicle during launch and recovery.

- **Reduced Footprint.** Maintain or reduce the footprint of the current system when implementing upgrades.
- **Operational Requirements.** The upgraded system needs to meet or improve upon the operational requirements of the fleet. The goal is by implementing improved motion control, the system will be able to safely operate in higher sea states than can currently be accomplished.

3.3 Concept Design

The concept design with recommended upgrades are discussed below and shown in Figure 3-2.

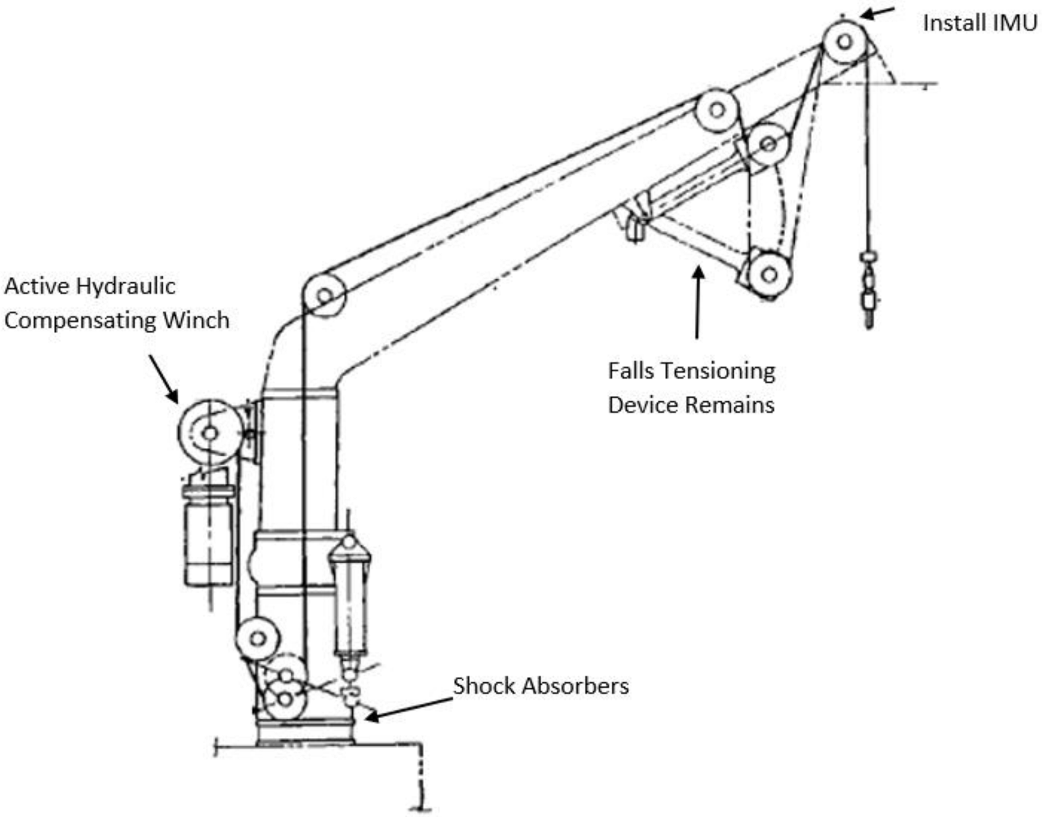


Figure 3-2. Recommended Upgrades

In the first iteration of upgrades to the L&R system, the following changes are recommended:

- **Shock Absorbers**. Maintain the shock absorbers that are currently installed as this will continue to assist in minimizing vibrations and some motions from the ships' hull to the L&R system.
- **Active Hydraulic Compensating Winch.** Replacing the current passive electro-mechanical winch system with an active hydraulic compensating winch system will greatly reduce the motions at the end of the davit arm and therefore minimize the motions experienced by the vehicles. This reduced motion will increase overall vehicle and operator safety. A hydraulic actuator system is recommended over an electric actuator system because it has a higher power to weight ratio, requires a smaller footprint, and is easier to maintain.[2] The performance and implementation of an AHC system is further analyzed in Chapter 4.
- **Inertial Measurement Unit (IMU).** The IMU will be installed at the end of the davit arm. This inertial measurement unit is equipped with gyroscopes and accelerometers that will measure the heave (up and down) motion experienced at the end of the davit arm in relation to the motion experienced at the surface platform. The IMU will then relay these motions back to the AHC winch which will then adjust the davit arm accordingly. This continuous feedback loop between the winch and the IMU will work towards minimizing the overall heave

motions experience by the davit arm thereby reducing the motions of the vehicle during launch and recovery.

- **Falls Tensioning Winch**. Keep the falls tensioning winch that is currently installed. This will help prevent snap loading of the line in the event of rogue waves. It also will assist in quickly clearing the line and hooks away from the vehicle once it is safely in the water. Clearing the lines and hooks is especially important with manned craft to prevent personnel injury.

Chapter 4: Analysis of Design

4.1 Design Motion Analysis

The first step in the motion analysis of the recommended system is to represent the system in a way that can be more easily analyzed. The following free body diagram (Figure 4-1) was developed to analyze the motions and seakeeping ability of the passive system. Once a representative model of the passive system was developed, then the controls for the recommended active system could be implemented and analyzed.

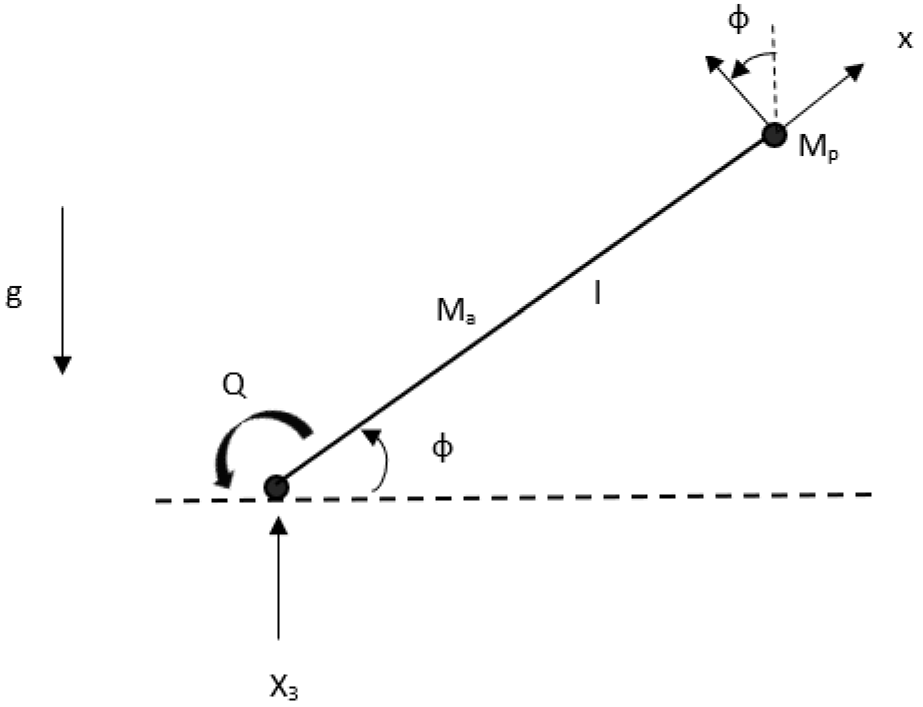


Figure 4-1. Free Body Diagram (FBD)

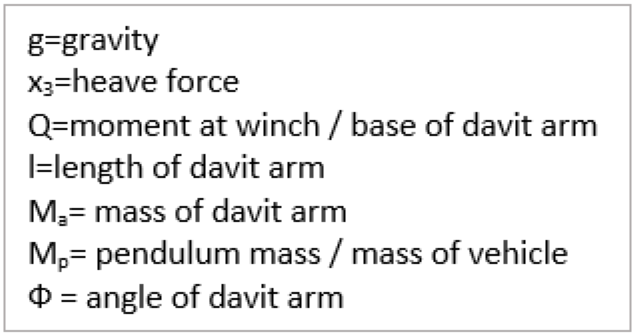

g=gravity
x_3=heave force
Q=moment at winch / base of davit arm
l=length of davit arm
M_a= mass of davit arm
M_p= pendulum mass / mass of vehicle
Φ = angle of davit arm

Figure 4-2. FBD Definitions

Next, utilizing the free body diagram, a system of equations was developed to solve for the motion of the system when subjected to heave force. The equations, non-linearized, and linearized solutions for the heave amplitude are as follows:

1. **Solve for Kinetic Energy:**

$$KE = \frac{1}{2} * M_p * \left(\dot{x}_p^2 + \dot{y}_p^2\right) + \frac{1}{2} * M_a \int_0^l (\dot{x}_a^2 + \dot{y}_a^2)$$

1a. Expand:

$$\boldsymbol{\dot{x}_p, \dot{y}_p, \dot{x}_a, \dot{y}_a}\textbf{:} = \tfrac{1}{2} * M_p * [(l * \dot{\varphi} * \cos(\varphi) + \dot{x}_3)^2 + (l * \dot{\varphi} * \sin(\varphi))^2] + \tfrac{1}{2} * M_a \textstyle\int_0^l [(x * \dot{\varphi} * \cos(\varphi) + \dot{x}_3)^2 + (x * \dot{\varphi} * \sin(\varphi))^2]$$

1b. Simplify:

$$= \frac{1}{2} * M_p * (l^2 * \dot{\varphi}^2 * cos^2\varphi + 2 * \dot{x}_3 * l * \dot{\varphi} * cos\varphi + \dot{x}_3^2 + l^2 * \dot{\varphi}^2 * sin^2\varphi) + \frac{1}{2} * M_a \int_0^l (x^2 * \dot{\varphi}^2 * cos^2\varphi + 2 * x * \dot{\varphi} * cos\varphi * \dot{x}_3 + \dot{x}_3^2 + x^2 * \dot{\varphi}^2 * sin^2\varphi) dx$$

$=\frac{1}{2} * M_p * (l^2 * {}^{\cdot}\varphi^2 + 2 * \dot{x}_3 * l * \dot{\varphi} * cos\varphi + \dot{x}_3^2) + \frac{1}{2} * M_a \int_0^l (x^2 * \dot{\varphi}^2 + 2 * x * \dot{\varphi} * cos\varphi *$

$\dot{x}_3 + \dot{x}_3^2)dx$

$$⇨\ KE = \frac{1}{2} * M_p * (l^2 * \dot{\varphi}^2 + 2 * \dot{x}_3 * l * \varphi * c\dot{o}s\varphi + \dot{x}_3^2) + \frac{1}{2} * M_a * \left(\frac{l^3}{3} * \dot{\varphi}^2 + \frac{l^2}{2} * \dot{\varphi} * cos\varphi * \dot{x}_3 + \dot{x}_3^2 * l\right)$$

2. **Solve for Potential Energy**:

$$PE = M_p * g * (l * sin\varphi + x_3) + M_a * g \int_0^l (x * sin\varphi + x_3)dx$$

2a. Simplify:

$$⇨\ \text{PE} = M_p * g * (l * sin\varphi + x_3) + M_a * g * (\frac{l^2}{2} * sin\varphi + l * x_3)$$

3. **Solve for the Lagrangian, L=KE-PE**

$$L = \frac{1}{2} * M_p * (l^2 * \dot{\varphi}^2 + 2 * \dot{x}_3 * l * \dot{\varphi} * cos\varphi + \dot{x}_3^2) + \frac{1}{2} * M_a$$
$$* \left(\frac{l^3}{3} * \dot{\varphi}^2 + \frac{l^2}{2} * \varphi^{\cdot} * \dot{x}_3 * cos\varphi + \dot{x}_3^2 * l\right) - M_p * g$$
$$* (l * sin\varphi + x_3) - M_a * g * (\frac{l^2}{2} * sin\varphi + x_3 * l)$$

3a. Solve for $\boldsymbol{\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\varphi}}\right) - \frac{\partial L}{\partial \varphi} = Q}$

i. **Solve for $\boldsymbol{\frac{\partial L}{\partial \varphi}}$:**

$$\frac{\partial L}{\partial \varphi} = \frac{1}{2} * M_p * (-2 * \dot{x}_3 * l * \dot{\varphi} * sin\varphi) + \frac{1}{2} * M_a \left(-\frac{l^2}{2} * \dot{\varphi} * \dot{x}_3 * sin\varphi\right) - M_p * g * (l * cos\varphi)$$
$$- M_a * g * \frac{l^2}{2} * cos\varphi$$

1. **Simplify:**

$$⇨ \frac{\partial L}{\partial \varphi} = -M_p * \dot{x}_3 * l * \dot{\varphi} * sin\varphi - \frac{M_a * l^2}{4} * \dot{\varphi} * \dot{x}_3 * sin\varphi - M_p * g * l * cos\varphi - M_a * g * \frac{l^2}{2} * cos\varphi$$

ii. **Solve for $\frac{\partial L}{\partial \dot{\varphi}}$:**

$$\frac{\partial L}{\partial \dot{\varphi}} = \frac{1}{2} * M_p * \left(2 * l^2 * \varphi \dot{+} 2 * \dot{x}_3 * l * cos\varphi\right) + \frac{1}{2} * M_a * \frac{2 * l^3}{3} * \varphi \dot{+} \frac{l^2}{2} * \dot{x}_3 * cos\varphi$$

1. **Simplify:**

$$⇨ \frac{\partial L}{\partial \dot{\varphi}} = M_p * (l^2 * \dot{\varphi} + \dot{x}_3 * l * cos\varphi) + M_a * \frac{l^3}{3} * \dot{\varphi} + \frac{l^2}{4} * \dot{x}_3 * cos\varphi$$

iii. **Solve for $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\varphi}}\right)$:**

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\varphi}}\right) = M_p * (l^2 * \ddot{\varphi} + l * (\dot{x}_3 * cos\varphi)' + M_a * \frac{l^3}{3} * \ddot{\varphi} + \frac{l^2}{4} * (\dot{x}_3 * cos\varphi)'$$

iv. **Apply the chain rule and simplify for $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\varphi}}\right) - \frac{\partial L}{\partial \varphi}$:**

$$⇨ \left(M_p + \frac{M_a * l}{3}\right) * l^2 * \ddot{\varphi} + \left(M_p + \frac{M_a * l}{4}\right) * l * \ddot{x}_3 * cos\varphi + \left(M_p + \frac{M_a * l}{2}\right) * g * l * cos\varphi = Q$$

4. **Linearize with respect to $\boldsymbol{\varphi_0 = \frac{\pi}{4}}$** ⇨ $\varphi = \frac{\pi}{4} + \psi, \psi \ll \frac{\pi}{4}$; Q=Q₀+q where Q₀ is the steady moment and q is the unsteady moment

$$\left(M_p + \frac{M_a * l}{3}\right) * l^2 * \ddot{\psi} - \left(M_p + \frac{M_a * l}{2}\right) * g * l * \frac{\sqrt{2}}{2} * \psi = q - \left(M_p + \frac{M_a * l}{4}\right) * l * \ddot{x}_3 * \frac{\sqrt{2}}{2}$$

5. Place in State Space form of:

$$\dot{x} = Ax + Bu, \text{ where } x=\psi \text{ and } u=x_3$$

$$y = Cx + Du, \text{ where } y=z(t)=x_3+l*\sin\boldsymbol{\varphi} \text{ and } C=\xi(t)=x_3(t)+l*\frac{\sqrt{2}}{2}*\psi$$

In the case of the passive system, the system feedback or unsteady moment q is set equal to zero since we are not actively controlling any aspect of the system. The heave inputs were measured utilizing the MaxSurf Seakeeping program running a five-minute simulation for a head seas irregular wave for a destroyer shaped hull. The output from the seakeeping analysis is shown in Appendix B. The measured results from the wave simulation were utilized as the heave, heave velocity, and heave acceleration inputs to solve for the system response. The results for the passive system in sea state five subjected to an irregular wave are shown in Figure 4-2.

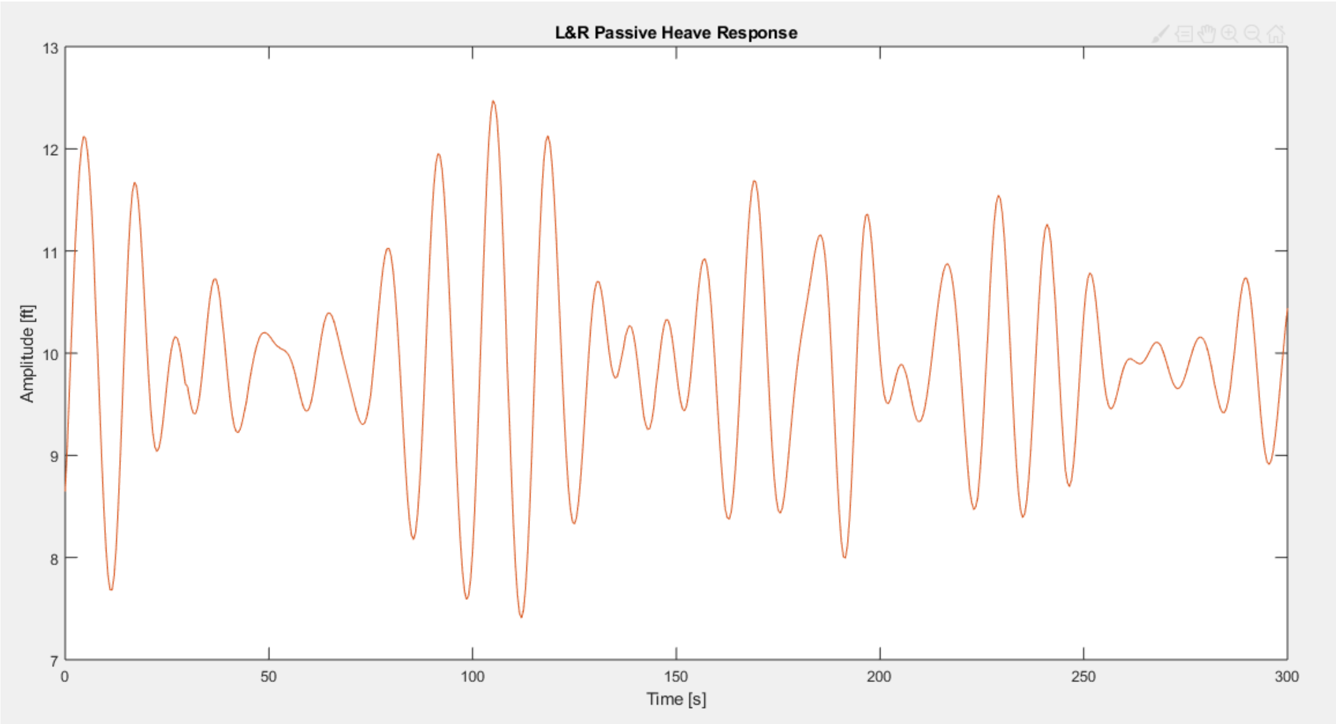


Figure 4-3. Passive System Response

In addition to the measured heave inputs, the following constants, derived from the current SLAD dimensions[10] and the weight of the C-Target 6 USV[12], were used to solve the heave response of the launch and recovery system:

l=14 ft
g=32.2 ft-lbm/lbf-s^2
M_a=1,085 lbs
M_p=2,645 lbs

Figure 4-4. System Constants

The weight of the C-Target was chosen to represent the vehicle being launched and recovered since it is an unmanned surface vehicle and is similar in size and weight to the manned vehicles that would also utilize this system.

4.2 Implementation of Controls

After analyzing the passive response of the system, the next step was to implement the active control feedback loop. Taking the goal for utilizing an active motion compensating system into consideration, the Proportional-Derivative (PD) Controller was determined the appropriate method of control for this scenario. A PD controller will increase the damping of the system and minimize system response overshoot.[13] A block diagram[14] depicting the feedback loop implementing the PD controller into the system is shown in Figure 4-5.

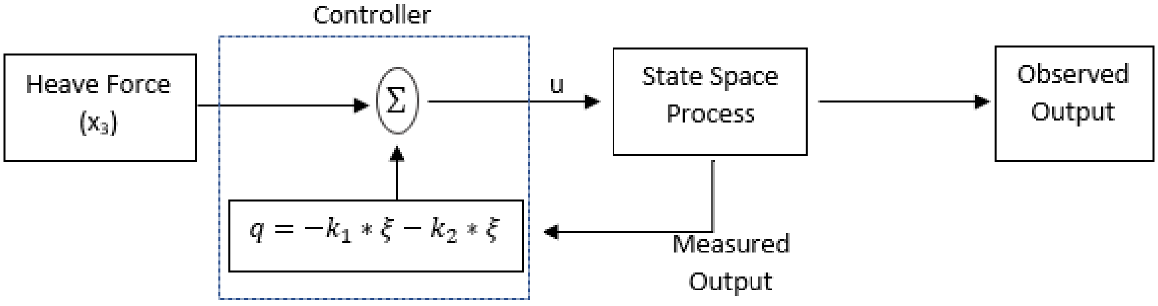


Figure 4-5. Proportional-Derivative Controller Block Diagram

In the passive system, we set q=0 since there was no feedback in the system. As shown in the above block diagram, this is the portion of the system that is now providing feedback to influence the system response. The feedback and the heave input are summed together at the control, or winch, portion of the system to provide an observed output as described by the state space process described above in section 4.1. This continuous feedback loop will remain in effect throughout the operation of the system working to minimize the heave motion felt by the vehicle at the end of the davit arm. After multiple iterations of adjusting k_1 and k_2 to get the desired value of q for feedback control, the results shown in Figure 4-6 were obtained. In future iterations of this problem, further simulations would be required to tune the system to account for sensor noise, motor response dynamics, and other similar various other dynamics not accounted for in this initial simplified analysis.

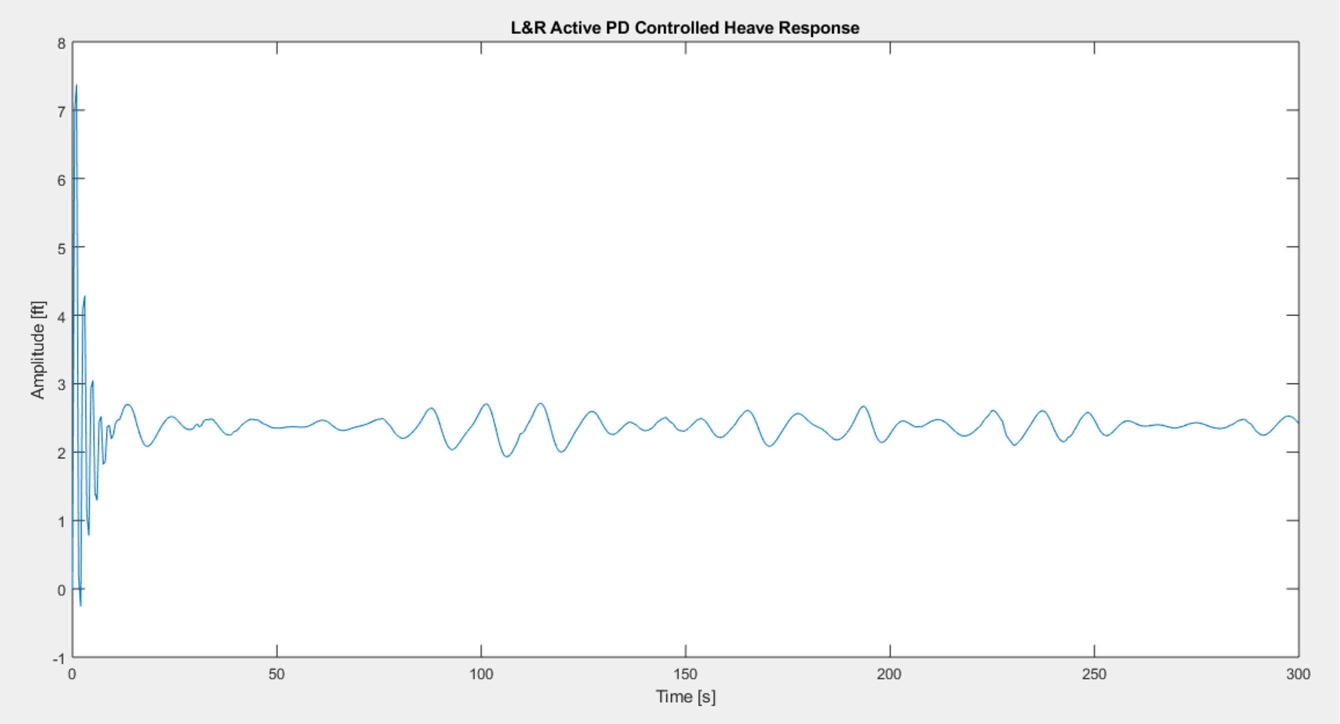


Figure 4-6. Active PD Controlled System Response

4.3 System Comparison

Comparing the results of the system after implementing the PD Controller feedback loop with the initial results of the passive system shows that upgrading the current side launch and recovery systems with an active heave control system will be very beneficial. The passive system response saw motions ranging up to four feet, which explains why sea state five is currently outside the safe operating range for this system. After implementing the active heave control, the new system motion response remained within six inches which is a much more reasonable for the safe operation of the system, personnel safety, and vehicle safety. While these results show great promise in implementing an active heave compensating system onto side launch and recovery systems, it is important to note that they represent a simplified version of the system and are only the first step in solving the problem of better motion control. As shown in the Free Body Diagram, only heave motions of the system were analyzed, thereby neglecting the other motions and their dynamic effects. By choosing to neglect the dynamic effects of the system, it was easier to analyze as a first approach. While the results are representative of what you would see, one would expect the results in full scale testing to be slightly different and further tuning of the active feedback controller would be required.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 5: Summary

5.1 Future Work

The recommendations presented in this paper are not the final solution to implementing a common launch and recovery system for ocean vehicles from surface platforms. In taking the incremental upgrade approach, this was just the first step toward achieving commonality. Below is an outline of recommended improvements to be made in following iterations of upgrading the launch and recovery system for utilization by both manned and unmanned ocean vehicles.

- **Control additional degrees of freedom within the motion axis.** As discussed in Chapter 3, heave is not the only motion the vessel is subjected to during launch and recovery. Utilizing a similar approach as outlined in this paper, other degrees of freedom such as Pitch and Yaw should be addressed to further minimize the motions of the vessel during launch and recovery.
- **Line handling.** As active feedback control reduces the motions of the vehicle, line handling will be utilized less frequently to control the vessel during launch and recovery. Ideally, the use of line handling can be eliminated. This will be very important in the case of unmanned ocean vehicles as connecting and disconnecting the lines is much more difficult without someone at the connection point.
- **Connection Points.** In the commercial sector, automatic smart hooks[15] that can remotely lock and unlock are already being implemented. With some additional study as to their performance in the marine environment, the use of smart hooks could be

one possible solution for improving the ease of connecting and disconnecting unmanned vehicles during the launch and recovery process.

- **Commonality.** The primary focus of this paper was the launch and recovery process for manned and unmanned vehicles. Another important aspect for implementing unmanned ocean vehicles onto surface platforms will be the ability to easily stow them in the limited space available. A recommendation for approaching this problem is the use of adjustable cradles. Adjustable cradles could improve the ability to stow various manned and unmanned cradles that all come in ranging shapes and sizes.

These recommendations are not meant to be all inclusive, but to serve as a starting point for the focus of the next incremental upgrade to the launch and recovery system with the final result being a common system that can safely operate manned and unmanned ocean vehicles.

5.2 Conclusion

In conclusion, the unmanned ocean vehicle realm is expanding rapidly. Unmanned ocean vehicles are becoming an increasingly integral part of the mission of many surface vehicles. With the ever-increasing role that unmanned ocean vehicles play and will continue to play for the foreseeable future, developing a safe method for stowing, handling, launching, and recovering these vessels becomes even more important. This is not just important for the future ships being built, but also for the surface platforms that are already in operation. This paper presented a solution for improving the launch and recovery process from a common side launch system by active controlling the heave motion and thereby significantly reducing the motions observed by the vehicle during operation. The solution to implementing ocean vehicles will never be a one stop solution, but instead a continuous improvement for generations to come. Like the approach presented in this paper, the solution will continue to advance and improve as technology and unmanned vehicles continue to advance and improve.

Appendix A: Definitions

Active Compensating System: This is a closed loop system that requires an energy input in order to achieve reduced motions. Basic components include a sensor that relays the motion to a controller that adjusts the output as necessary. [2]

Handling: This refers to anytime the vehicle is moved from its stowed position to another stowed position. Handling equipment is also used in connecting and disconnecting the vehicle during launch and recovery operations.

Launch: The evolution that includes moving the vehicle from its stowed position to the vehicle being in the water with all lines and equipment free. Upon completion of launch, the vehicle is free to maneuver and conduct its mission. On the shipboard side, launch is complete when the equipment has returned to its stowed / at sea condition.

Passive Compensating System: This is an open loop system that achieves reduced, partially decoupled output motion through vibration isolators and shock absorbers. No energy input is required to be put into the system to achieve reduced motions. [2]

Recovery: Recovery begins with the initial approach alongside the ship by the vehicle being recovery. The recovered vehicle is then connected and lifted from the water and moved to its stowed position. Recovery is complete when the recovered vehicle is secured for sea.

Stowage: This is the location or equipment used to keep the vehicle secure for sea during transiting onboard the ship when not in use. A cradle is an example of a typical type of stowage for surface and subsurface craft. The vehicle is secured within the cradle and the cradle itself is secure to the host ship or platform.

Appendix B: Seakeeping Results

In the MAXSURF seakeeping program after importing a ships hull, the user can run various seakeeping analysis by ranging the sea spectrum, both type and height of waves, as well as the ships speed and heading. For this analysis, the Brettschneider sea spectrum was used, with head seas and a ship speed of five knots. Since the launch and recovery location was the point of interest, this was added to the starboard side of the ship near the longitudinal center of flotation. Below in Figures B-1 and B-2 are the geometric characteristics of the ships hull utilized in the analysis as well as a snapshot of the hull with the L&R location used in the simulation.

Dimension	Value
Length at Waterline	482 ft
Displacement	6,921 LT
Draft	31 ft
Block Coefficient	0.2
L&R Location	203 ft aft FP, 30 ft to starboard

Figure B-1. Surface Platform Characteristics

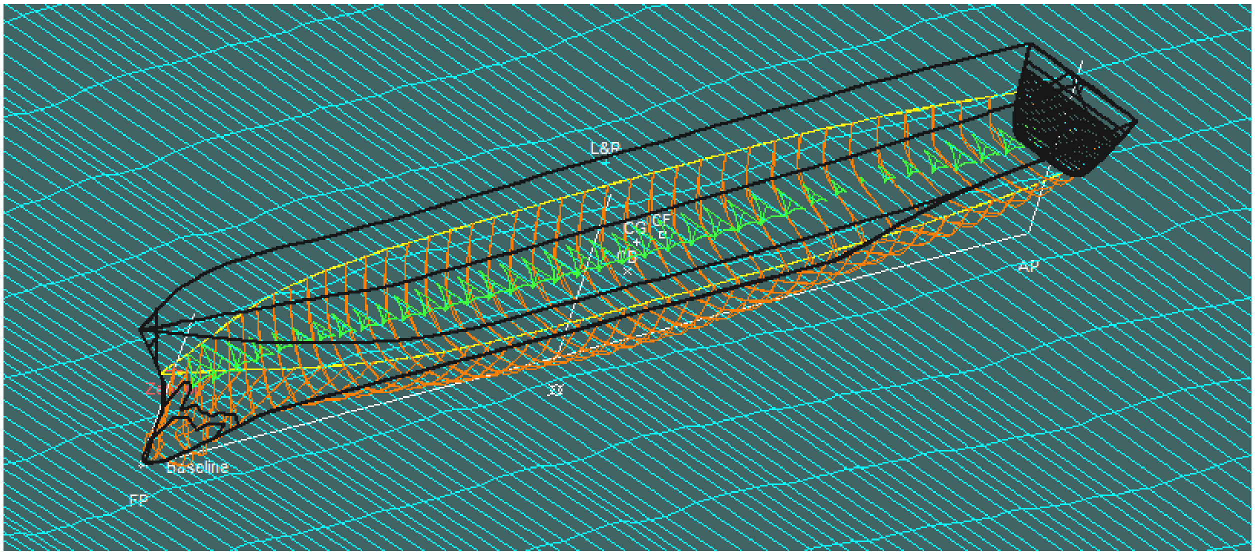


Figure B-2. Surface Platform with L&R location for analysis

After running the simulation for five minutes for an irregular wave with head seas, the output results provided the time, wave height, heave height. These results were then filtered to remove excess noise and the heave velocity and heave acceleration were determined. Below (Figure B-3) are the values for the wave height, heave height, heave velocity, and heave acceleration as an output from the simulation. The heave values were used as the input values in the motion analysis of the launch and recovery system. Figure B-4 and B-5 graphically show the wave height and heave responses, respectively.

Time (s)	**Wave Height (ft)**	x_3 **(ft)**	$\dot{x}_3$ **(ft/s)**	$\ddot{x}_3$ **(ft/s^2)**
0.0	-4.45	-1.68	0.86	0.00
0.5	-3.51	-1.25	0.86	0.32
1.0	-2.57	-0.82	1.02	0.06
1.5	-1.47	-0.30	1.05	-0.06
2.0	-0.48	0.23	1.02	-0.17
2.5	0.33	0.74	0.94	-0.26
3.0	0.96	1.20	0.81	-0.37
3.5	1.38	1.57	0.64	-0.40
4.0	1.72	1.90	0.44	-0.47
4.5	2.00	2.11	0.21	-0.45
5.0	2.32	2.22	-0.03	-0.48
5.5	2.66	2.21	-0.27	-0.42
6.0	3.07	2.06	-0.49	-0.40
6.5	3.44	1.83	-0.68	-0.33
7.0	3.76	1.49	-0.84	-0.47
7.5	3.92	1.07	-1.08	0.29
8.0	3.78	0.52	-0.92	-0.27
8.5	3.40	0.07	-1.06	0.08
9.0	2.63	-0.46	-1.02	0.20
9.5	1.53	-0.97	-0.91	0.32
10.0	0.18	-1.42	-0.75	0.43
10.5	-1.31	-1.80	-0.54	0.50
11.0	-2.81	-2.07	-0.29	0.56
11.5	-4.14	-2.21	-0.01	0.57
12.0	-5.21	-2.22	0.27	0.54
12.5	-5.90	-2.08	0.54	0.47
13.0	-6.13	-1.81	0.78	0.35
13.5	-5.90	-1.42	0.95	0.21
14.0	-5.22	-0.95	1.06	0.06
14.5	-4.18	-0.42	1.09	-0.11
15.0	-2.82	0.13	1.03	-0.26
15.5	-1.29	0.64	0.90	-0.40
16.0	0.32	1.09	0.71	-0.49
16.5	1.92	1.45	0.46	-0.54
17.0	3.37	1.68	0.19	-0.54
17.5	4.61	1.77	-0.08	-0.50
18.0	5.54	1.73	-0.33	-0.41
18.5	6.10	1.57	-0.53	-0.29
19.0	6.23	1.31	-0.68	-0.16
19.5	5.92	0.97	-0.76	-0.02
20.0	5.16	0.59	-0.77	0.11
20.5	4.00	0.21	-0.71	0.22
21.0	2.50	-0.15	-0.60	0.30
21.5	0.78	-0.45	-0.45	0.35
22.0	-1.01	-0.68	-0.28	0.36
22.5	-2.70	-0.81	-0.10	0.33
23.0	-4.15	-0.86	0.07	0.28
23.5	-5.19	-0.83	0.21	0.21
24.0	-5.76	-0.73	0.31	0.12
24.5	-5.78	-0.57	0.37	0.03
25.0	-5.29	-0.39	0.38	-0.06
25.5	-4.34	-0.19	0.35	-0.13

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
26.0	-3.08	-0.02	0.29	-0.19
26.5	-1.66	0.12	0.19	-0.22
27.0	-0.20	0.22	0.08	-0.23
27.5	1.11	0.26	-0.03	-0.21
28.0	2.17	0.25	-0.13	-0.16
28.5	2.94	0.18	-0.22	-0.10
29.0	3.39	0.07	-0.27	-0.03
29.5	3.55	-0.06	-0.28	0.01
30.0	3.48	-0.20	-0.28	0.26
30.0	3.46	-0.22	-0.26	0.13
30.5	3.25	-0.33	-0.20	0.18
31.0	2.90	-0.43	-0.11	0.22
31.5	2.48	-0.49	0.00	0.24
32.0	1.99	-0.49	0.12	0.23
32.5	1.41	-0.43	0.23	0.19
33.0	0.72	-0.32	0.33	0.13
33.5	-0.12	-0.15	0.39	0.05
34.0	-1.08	0.04	0.42	-0.03
34.5	-2.14	0.25	0.40	-0.11
35.0	-3.21	0.46	0.35	-0.19
35.5	-4.16	0.63	0.26	-0.24
36.0	-4.85	0.76	0.14	-0.27
36.5	-5.14	0.82	0.00	-0.27
37.0	-4.88	0.83	-0.13	-0.24
37.5	-4.02	0.76	-0.25	-0.20
38.0	-2.58	0.63	-0.35	-0.11
38.5	-0.38	0.43	-0.41	-0.05
39.0	1.53	0.25	-0.43	0.03
39.5	3.76	0.04	-0.42	0.09
40.0	5.73	-0.17	-0.37	0.15
40.5	7.17	-0.36	-0.30	0.18
41.0	7.83	-0.51	-0.21	0.20
41.5	7.60	-0.61	-0.11	0.19
42.0	6.47	-0.67	-0.01	0.17
42.5	4.52	-0.68	0.07	0.14
43.0	1.96	-0.64	0.14	0.10
43.5	-0.87	-0.57	0.20	-0.03
44.0	-3.65	-0.47	0.18	0.22
44.5	-5.74	-0.37	0.30	-0.14
45.0	-7.74	-0.23	0.24	-0.03

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
45.5	-8.60	-0.11	0.22	-0.05
46.0	-8.50	0.00	0.19	-0.07
46.5	-7.48	0.09	0.16	-0.08
47.0	-5.68	0.17	0.12	-0.08
47.5	-3.35	0.23	0.08	-0.07
48.0	-0.41	0.28	0.04	-0.07
48.5	1.77	0.30	0.01	-0.06
49.0	4.00	0.30	-0.02	-0.04
49.5	5.73	0.29	-0.04	-0.02
50.0	6.78	0.27	-0.05	-0.01
50.5	7.12	0.25	-0.05	0.01
51.0	6.68	0.22	-0.05	0.02
51.5	5.66	0.19	-0.04	0.02
52.0	4.22	0.17	-0.03	0.02
52.5	2.76	0.16	-0.02	0.01
53.0	0.70	0.14	-0.02	-0.01
53.5	-0.80	0.14	-0.02	-0.03
54.0	-2.56	0.12	-0.04	-0.05
54.5	-3.77	0.10	-0.06	-0.06
55.0	-4.59	0.07	-0.09	-0.06
55.5	-4.98	0.03	-0.12	-0.06
56.0	-4.93	-0.04	-0.15	-0.04
56.5	-4.47	-0.11	-0.17	-0.01
57.0	-3.65	-0.20	-0.18	0.03
57.5	-2.55	-0.29	-0.16	0.07
58.0	-1.28	-0.37	-0.12	0.11
58.5	0.03	-0.43	-0.07	0.14
59.0	1.27	-0.46	0.00	0.15
59.5	2.32	-0.46	0.07	0.15
60.0	3.06	-0.43	0.15	0.13
60.5	3.46	-0.36	0.21	0.09
61.0	3.48	-0.25	0.26	0.05
61.5	3.15	-0.12	0.28	-0.01
62.0	2.52	0.02	0.28	-0.06
62.5	1.70	0.16	0.25	-0.10
63.0	0.80	0.29	0.20	-0.13
63.5	-0.09	0.39	0.14	-0.14
64.0	-0.84	0.46	0.07	-0.14
64.5	-1.40	0.49	0.00	-0.12
65.0	-1.72	0.49	-0.06	-0.10

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
65.5	-1.80	0.46	-0.11	-0.07
66.0	-1.68	0.41	-0.14	-0.04
66.5	-1.42	0.33	-0.16	-0.01
67.0	-1.07	0.25	-0.17	0.00
67.5	-0.70	0.17	-0.17	0.01
68.0	-0.37	0.08	-0.17	0.01
68.5	-0.09	0.00	-0.16	0.00
69.0	0.12	-0.08	-0.16	0.00
69.5	0.28	-0.16	-0.16	0.00
70.0	0.41	-0.24	-0.16	0.00
70.5	0.52	-0.32	-0.16	0.02
71.0	0.63	-0.40	-0.15	0.04
71.5	0.74	-0.47	-0.13	0.07
72.0	0.83	-0.54	-0.09	0.11
72.5	0.87	-0.58	-0.04	0.14
73.0	0.84	-0.60	0.03	0.16
73.5	0.70	-0.58	0.11	0.17
74.0	0.45	-0.53	0.20	0.09
74.5	0.10	-0.43	0.24	0.31
75.0	-0.26	-0.31	0.40	0.04
75.5	-0.75	-0.11	0.41	0.06
76.0	-1.15	0.10	0.44	0.00
76.5	-1.43	0.32	0.45	-0.06
77.0	-1.56	0.55	0.41	-0.13
77.5	-1.51	0.75	0.35	-0.19
78.0	-1.26	0.93	0.26	-0.24
78.5	-0.86	1.06	0.14	-0.28
79.0	-0.34	1.13	0.00	-0.30
79.5	0.25	1.13	-0.15	-0.30
80.0	0.82	1.05	-0.30	-0.28
80.5	1.33	0.90	-0.44	-0.24
81.0	1.74	0.68	-0.57	-0.19
81.5	2.01	0.40	-0.66	-0.11
82.0	2.15	0.07	-0.72	-0.02
82.5	2.15	-0.29	-0.73	0.07
83.0	2.02	-0.65	-0.69	0.17
83.5	1.77	-1.00	-0.60	0.27
84.0	1.39	-1.30	-0.47	0.36
84.5	0.89	-1.53	-0.29	0.41
85.0	0.25	-1.68	-0.09	0.45

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
85.5	-0.52	-1.72	0.14	0.45
86.0	-1.41	-1.65	0.37	0.42
86.5	-2.35	-1.47	0.58	0.35
87.0	-3.27	-1.18	0.75	0.26
87.5	-4.08	-0.81	0.88	0.14
88.0	-4.65	-0.37	0.95	0.02
88.5	-4.85	0.11	0.96	-0.11
89.0	-4.60	0.59	0.91	-0.23
89.5	-3.82	1.04	0.79	-0.33
90.0	-2.54	1.44	0.62	-0.41
90.5	-0.86	1.75	0.42	-0.46
91.0	1.11	1.96	0.19	-0.47
91.5	3.16	2.05	-0.04	-0.46
92.0	5.03	2.03	-0.27	-0.42
92.5	6.49	1.90	-0.48	-0.35
93.0	7.37	1.66	-0.66	-0.29
93.5	7.52	1.34	-0.80	-0.20
94.0	6.93	0.93	-0.90	-0.11
94.5	5.65	0.49	-0.95	-0.02
95.0	3.84	0.01	-0.97	0.06
95.5	1.70	-0.48	-0.93	0.15
96.0	-0.48	-0.94	-0.86	0.24
96.5	-2.48	-1.37	-0.74	0.31
97.0	-4.15	-1.74	-0.58	0.39
97.5	-5.30	-2.03	-0.39	0.44
98.0	-5.90	-2.23	-0.17	0.48
98.5	-5.99	-2.31	0.07	0.50
99.0	-5.67	-2.27	0.32	0.49
99.5	-5.06	-2.12	0.56	0.44
100.0	-4.29	-1.84	0.78	0.37
100.5	-3.49	-1.44	0.97	0.27
101.0	-2.71	-0.96	1.10	0.14
101.5	-1.97	-0.41	1.18	0.00
102.0	-1.23	0.18	1.18	-0.14
102.5	-0.46	0.77	1.11	-0.28
103.0	0.44	1.32	0.97	-0.40
103.5	1.51	1.81	0.77	-0.49
104.0	2.72	2.19	0.52	-0.56
104.5	4.02	2.45	0.24	-0.63
105.0	5.28	2.57	-0.07	-0.46

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
105.5	6.45	2.54	-0.31	-0.58
106.0	6.99	2.39	-0.59	-0.45
106.5	7.13	2.09	-0.81	-0.35
107.0	6.62	1.69	-0.99	-0.24
107.5	5.46	1.19	-1.11	-0.36
108.0	3.72	0.64	-1.29	0.51
108.5	1.26	-0.02	-1.03	-0.14
109.0	-0.76	-0.52	-1.10	0.24
109.5	-3.02	-1.07	-0.98	0.34
110.0	-4.96	-1.56	-0.81	0.42
110.5	-6.35	-1.96	-0.60	0.48
111.0	-7.07	-2.26	-0.36	0.52
111.5	-7.09	-2.44	-0.10	0.54
112.0	-6.47	-2.49	0.17	0.52
112.5	-5.37	-2.41	0.43	0.48
113.0	-3.96	-2.19	0.67	0.41
113.5	-2.47	-1.86	0.87	0.31
114.0	-1.08	-1.42	1.03	0.19
114.5	0.07	-0.91	1.12	0.06
115.0	0.92	-0.36	1.15	-0.08
115.5	1.49	0.22	1.11	-0.22
116.0	1.83	0.77	1.00	-0.34
116.5	2.04	1.27	0.83	-0.43
117.0	2.24	1.69	0.61	-0.50
117.5	2.49	2.00	0.36	-0.53
118.0	2.83	2.18	0.10	-0.53
118.5	3.23	2.23	-0.16	-0.49
119.0	3.61	2.15	-0.40	-0.41
119.5	3.88	1.95	-0.61	-0.32
120.0	3.91	1.64	-0.77	-0.21
120.5	3.62	1.25	-0.88	-0.10
121.0	2.96	0.82	-0.93	0.02
121.5	1.95	0.35	-0.92	0.12
122.0	0.67	-0.11	-0.86	0.22
122.5	-0.72	-0.53	-0.75	0.29
123.0	-2.08	-0.91	-0.60	0.34
123.5	-3.25	-1.21	-0.43	0.38
124.0	-4.05	-1.42	-0.25	0.39
124.5	-4.43	-1.55	-0.05	0.37
125.0	-4.37	-1.57	0.13	0.34
125.5	-3.90	-1.51	0.30	0.29
126.0	-3.14	-1.35	0.45	0.21
126.5	-2.22	-1.13	0.56	0.13
127.0	-1.30	-0.86	0.62	0.04
127.5	-0.46	-0.54	0.64	-0.05
128.0	0.20	-0.22	0.62	-0.14
128.5	0.65	0.08	0.55	-0.22
129.0	0.94	0.36	0.44	-0.27
129.5	1.11	0.58	0.30	-0.30
130.0	1.24	0.73	0.15	-0.30
130.5	1.42	0.80	0.00	-0.27
131.0	1.66	0.80	-0.14	-0.22
131.5	1.97	0.73	-0.25	-0.14
132.0	2.30	0.61	-0.32	-0.05
132.5	2.56	0.45	-0.34	0.04
133.0	2.66	0.28	-0.33	0.12
133.5	2.49	0.12	-0.27	0.18
134.0	2.01	-0.02	-0.18	0.21
134.5	1.22	-0.11	-0.07	0.22
135.0	0.17	-0.14	0.03	0.20
135.5	-1.02	-0.13	0.13	0.12
136.0	-2.31	-0.05	0.20	0.05
136.5	-3.22	0.05	0.22	-0.03
137.0	-3.72	0.14	0.21	-0.09
137.5	-3.84	0.26	0.16	-0.18
138.0	-3.50	0.33	0.08	-0.22
138.5	-2.68	0.37	-0.03	-0.21
139.0	-1.35	0.35	-0.15	-0.20
139.5	0.00	0.28	-0.24	-0.14
140.0	1.32	0.16	-0.32	-0.07
140.5	2.42	0.00	-0.35	0.01
141.0	3.15	-0.17	-0.34	0.01
141.5	3.44	-0.35	-0.34	0.36
142.0	3.23	-0.51	-0.17	0.14
142.5	2.74	-0.60	-0.10	0.25
143.0	1.92	-0.65	0.03	0.25
143.5	0.97	-0.63	0.15	0.21
144.0	0.02	-0.56	0.26	0.27
144.5	-0.79	-0.43	0.40	-0.17
145.0	-1.47	-0.23	0.31	0.10

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
145.5	-1.78	-0.07	0.36	-0.10
146.0	-1.95	0.11	0.31	-0.17
146.5	-1.96	0.26	0.22	-0.23
147.0	-1.87	0.37	0.11	-0.25
147.5	-1.74	0.43	-0.01	-0.24
148.0	-1.59	0.42	-0.13	-0.20
148.5	-1.45	0.36	-0.23	-0.14
149.0	-1.28	0.24	-0.30	-0.06
149.5	-1.03	0.09	-0.33	0.03
150.0	-0.67	-0.08	-0.32	0.12
150.5	-0.16	-0.24	-0.26	0.19
151.0	0.49	-0.36	-0.16	0.25
151.5	1.24	-0.44	-0.04	0.27
152.0	2.02	-0.47	0.10	0.26
152.5	2.70	-0.42	0.23	0.23
153.0	3.18	-0.30	0.34	0.17
153.5	3.34	-0.13	0.43	0.09
154.0	3.11	0.08	0.47	-0.01
154.5	2.48	0.31	0.47	-0.10
155.0	1.51	0.55	0.41	-0.19
155.5	0.30	0.75	0.32	-0.26
156.0	-1.01	0.91	0.19	-0.31
156.5	-2.21	1.01	0.03	-0.33
157.0	-3.15	1.03	-0.13	-0.33
157.5	-3.68	0.96	-0.29	-0.29
158.0	-3.74	0.81	-0.44	-0.23
158.5	-3.29	0.59	-0.56	-0.16
159.0	-2.42	0.31	-0.64	-0.07
159.5	-1.23	-0.01	-0.67	0.02
160.0	0.11	-0.34	-0.66	0.12
160.5	1.39	-0.67	-0.60	0.20
161.0	2.49	-0.97	-0.50	0.19
161.5	3.26	-1.22	-0.41	0.48
162.0	3.60	-1.43	-0.17	0.28
162.5	3.47	-1.51	-0.03	0.37
163.0	2.92	-1.52	0.16	0.36
163.5	2.02	-1.45	0.34	0.33
164.0	0.86	-1.28	0.50	0.28
164.5	-0.43	-1.03	0.64	0.21
165.0	-1.71	-0.71	0.74	0.12

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
165.5	-2.88	-0.33	0.81	0.03
166.0	-3.82	0.07	0.82	-0.07
166.5	-4.45	0.48	0.78	-0.17
167.0	-4.69	0.87	0.70	-0.27
167.5	-4.50	1.21	0.56	-0.34
168.0	-3.87	1.50	0.39	-0.40
168.5	-2.80	1.69	0.19	-0.43
169.0	-1.36	1.79	-0.02	-0.43
169.5	0.37	1.78	-0.24	-0.40
170.0	2.26	1.66	-0.44	-0.34
170.5	4.15	1.44	-0.61	-0.26
171.0	5.80	1.13	-0.74	-0.16
171.5	7.04	0.77	-0.82	-0.04
172.0	7.67	0.36	-0.84	0.07
172.5	7.57	-0.06	-0.80	0.18
173.0	6.67	-0.46	-0.71	0.26
173.5	4.99	-0.82	-0.58	0.32
174.0	2.69	-1.11	-0.42	0.35
174.5	-0.04	-1.32	-0.24	0.37
175.0	-2.86	-1.44	-0.06	0.31
175.5	-5.79	-1.47	0.10	0.29
176.0	-7.54	-1.42	0.24	0.21
176.5	-8.84	-1.30	0.34	0.14
177.0	-9.18	-1.13	0.41	0.06
177.5	-8.54	-0.92	0.44	0.00
178.0	-7.02	-0.70	0.44	-0.05
178.5	-4.79	-0.48	0.41	-0.08
179.0	-2.23	-0.27	0.37	-0.09
179.5	0.39	-0.09	0.33	-0.08
180.0	2.76	0.08	0.28	-0.06
180.5	4.55	0.22	0.25	-0.03
181.0	5.62	0.35	0.24	0.00
181.5	5.94	0.47	0.24	0.02
182.0	5.56	0.58	0.25	0.02
182.5	4.64	0.71	0.26	0.01
183.0	3.44	0.84	0.26	-0.03
183.5	2.20	0.96	0.24	-0.08
184.0	1.11	1.09	0.20	-0.15
184.5	0.34	1.19	0.13	-0.22
185.0	-0.05	1.25	0.02	-0.28

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
185.5	-0.11	1.26	-0.12	-0.32
186.0	0.04	1.20	-0.28	-0.34
186.5	0.26	1.06	-0.45	-0.32
187.0	0.36	0.83	-0.61	-0.27
187.5	0.22	0.52	-0.75	-0.18
188.0	-0.23	0.15	-0.84	-0.06
188.5	-0.97	-0.27	-0.87	0.08
189.0	-1.90	-0.70	-0.83	0.22
189.5	-2.86	-1.12	-0.71	0.36
190.0	-3.64	-1.47	-0.53	0.46
190.5	-4.05	-1.74	-0.30	0.54
191.0	-3.96	-1.89	-0.03	0.56
191.5	-3.32	-1.91	0.25	0.53
192.0	-2.16	-1.78	0.51	0.45
192.5	-0.64	-1.53	0.73	0.32
193.0	1.00	-1.16	0.89	0.16
193.5	2.53	-0.71	0.97	-0.01
194.0	3.66	-0.23	0.97	-0.17
194.5	4.22	0.26	0.88	-0.32
195.0	4.10	0.70	0.72	-0.43
195.5	3.30	1.06	0.51	-0.49
196.0	1.95	1.32	0.27	-0.49
196.5	0.29	1.45	0.02	-0.46
197.0	-1.39	1.46	-0.21	-0.37
197.5	-2.83	1.36	-0.39	-0.26
198.0	-3.74	1.16	-0.52	-0.13
198.5	-3.96	0.90	-0.59	0.00
199.0	-3.42	0.60	-0.58	0.12
199.5	-2.22	0.31	-0.52	0.21
200.0	-0.53	0.05	-0.42	0.26
200.5	1.37	-0.16	-0.29	0.28
201.0	3.17	-0.30	-0.15	0.25
201.5	4.58	-0.38	-0.03	0.21
202.0	5.32	-0.39	0.08	0.14
202.5	5.29	-0.36	0.15	0.06
203.0	4.47	-0.28	0.18	-0.01
203.5	2.96	-0.20	0.17	-0.08
204.0	0.96	-0.11	0.13	-0.12
204.5	-1.21	-0.05	0.07	-0.14
205.0	-3.25	-0.01	0.00	-0.15
205.5	-4.89	-0.01	-0.08	-0.11
206.0	-5.93	-0.06	-0.14	-0.09
206.5	-6.06	-0.12	-0.18	-0.04
207.0	-5.48	-0.21	-0.20	0.01
207.5	-4.22	-0.31	-0.19	0.06
208.0	-2.45	-0.40	-0.17	0.11
208.5	-0.46	-0.49	-0.11	0.11
209.0	1.75	-0.55	-0.05	0.16
209.5	3.16	-0.57	0.02	0.15
210.0	4.32	-0.56	0.09	0.14
210.5	4.86	-0.52	0.17	0.13
211.0	4.75	-0.43	0.23	0.11
211.5	4.03	-0.32	0.28	0.08
212.0	2.83	-0.18	0.32	0.05
212.5	1.37	-0.02	0.34	0.01
213.0	-0.18	0.15	0.35	-0.02
213.5	-1.62	0.33	0.34	-0.06
214.0	-2.76	0.50	0.31	-0.09
214.5	-3.49	0.65	0.27	-0.12
215.0	-3.74	0.79	0.21	-0.15
215.5	-3.51	0.89	0.13	-0.17
216.0	-2.85	0.96	0.04	-0.19
216.5	-1.86	0.98	-0.05	-0.20
217.0	-0.67	0.95	-0.15	-0.20
217.5	0.60	0.88	-0.26	-0.20
218.0	1.79	0.75	-0.35	-0.18
218.5	2.79	0.57	-0.44	-0.14
219.0	3.50	0.35	-0.51	-0.09
219.5	3.86	0.10	-0.56	-0.03
220.0	3.84	-0.19	-0.58	0.03
220.5	3.44	-0.47	-0.56	0.11
221.0	2.69	-0.75	-0.51	0.20
221.5	1.66	-1.00	-0.41	0.22
222.0	0.26	-1.24	-0.28	0.33
222.5	-0.86	-1.36	-0.14	0.37
223.0	-2.13	-1.43	0.05	0.32
223.5	-3.40	-1.41	0.23	0.41
224.0	-4.12	-1.31	0.41	0.30
224.5	-4.68	-1.08	0.57	0.25
225.0	-4.73	-0.79	0.70	0.16

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
225.5	-4.36	-0.44	0.78	0.06
226.0	-3.57	-0.05	0.81	-0.06
226.5	-2.62	0.30	0.79	-0.16
227.0	-1.09	0.75	0.70	-0.28
227.5	0.35	1.09	0.56	-0.36
228.0	1.76	1.37	0.38	-0.42
228.5	3.00	1.56	0.17	-0.45
229.0	3.92	1.65	-0.06	-0.44
229.5	4.47	1.62	-0.28	-0.40
230.0	4.59	1.47	-0.48	-0.33
230.5	4.30	1.24	-0.65	-0.23
231.0	3.65	0.91	-0.76	-0.12
231.5	2.75	0.53	-0.82	-0.01
232.0	1.72	0.12	-0.83	0.11
232.5	0.68	-0.29	-0.77	0.21
233.0	-0.26	-0.67	-0.67	0.30
233.5	-1.01	-1.01	-0.52	0.36
234.0	-1.55	-1.27	-0.34	0.40
234.5	-1.86	-1.44	-0.14	0.41
235.0	-1.98	-1.51	0.06	0.39
235.5	-1.99	-1.48	0.26	0.35
236.0	-1.97	-1.35	0.44	0.29
236.5	-1.98	-1.13	0.58	0.21
237.0	-2.08	-0.84	0.69	0.12
237.5	-2.28	-0.50	0.74	0.02
238.0	-2.52	-0.12	0.75	-0.09
238.5	-2.74	0.25	0.71	-0.18
239.0	-2.82	0.61	0.62	-0.28
239.5	-2.66	0.91	0.48	-0.35
240.0	-2.16	1.15	0.31	-0.39
240.5	-1.26	1.31	0.11	-0.41
241.0	0.00	1.36	-0.10	-0.41
241.5	1.56	1.31	-0.30	-0.52
242.0	3.27	1.16	-0.56	0.04
242.5	5.11	0.89	-0.54	-0.34
243.0	6.24	0.62	-0.71	-0.07
243.5	7.06	0.26	-0.75	0.06
244.0	7.20	-0.11	-0.72	0.18
244.5	6.53	-0.47	-0.62	0.19
245.0	5.07	-0.78	-0.53	0.58

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
245.5	2.59	-1.05	-0.24	0.32
246.0	0.31	-1.17	-0.08	0.43
246.5	-2.49	-1.21	0.13	0.39
247.0	-5.18	-1.14	0.33	0.32
247.5	-7.39	-0.98	0.48	0.22
248.0	-8.85	-0.74	0.59	0.10
248.5	-9.38	-0.44	0.64	-0.03
249.0	-8.90	-0.12	0.63	-0.14
249.5	-7.46	0.19	0.56	-0.24
250.0	-5.21	0.47	0.44	-0.31
250.5	-2.45	0.69	0.28	-0.34
251.0	0.54	0.83	0.11	-0.33
251.5	3.36	0.89	-0.05	-0.30
252.0	5.72	0.86	-0.20	-0.23
252.5	7.43	0.76	-0.32	-0.15
253.0	8.29	0.60	-0.39	-0.06
253.5	8.28	0.41	-0.42	0.03
254.0	7.46	0.20	-0.40	0.10
254.5	5.99	0.00	-0.35	0.16
255.0	4.08	-0.18	-0.27	0.19
255.5	1.96	-0.32	-0.18	0.20
256.0	-0.11	-0.40	-0.08	0.18
256.5	-2.01	-0.44	0.01	0.15
257.0	-3.54	-0.44	0.09	0.10
257.5	-4.63	-0.39	0.14	0.06
258.0	-5.27	-0.33	0.17	0.01
258.5	-5.47	-0.24	0.17	-0.03
259.0	-5.29	-0.16	0.15	-0.06
259.5	-4.79	-0.08	0.12	-0.08
260.0	-4.06	-0.02	0.08	-0.08
260.5	-3.13	0.02	0.04	-0.07
261.0	-2.09	0.04	0.01	-0.05
261.5	-0.94	0.05	-0.02	-0.03
262.0	0.28	0.04	-0.03	0.00
262.5	1.49	0.02	-0.03	0.02
263.0	2.64	0.01	-0.02	0.04
263.5	3.66	0.00	0.00	0.05
264.0	4.45	0.00	0.02	0.05
264.5	4.95	0.01	0.05	0.04
265.0	5.08	0.03	0.07	0.02

Time (s)	Wave Height (ft)	x_3 (ft)	$\dot{x}_3$ (ft/s)	$\ddot{x}_3$ (ft/s^2)
265.5	4.78	0.07	0.08	0.00
266.0	4.03	0.11	0.08	-0.02
266.5	2.91	0.15	0.07	-0.05
267.0	1.49	0.18	0.04	-0.06
267.5	-0.37	0.20	0.01	-0.07
268.0	-2.00	0.21	-0.03	-0.08
268.5	-3.26	0.20	-0.06	-0.07
269.0	-4.43	0.17	-0.10	-0.05
269.5	-5.21	0.11	-0.12	-0.03
270.0	-5.36	0.05	-0.14	0.00
270.5	-4.96	-0.02	-0.14	0.02
271.0	-4.08	-0.09	-0.13	0.05
271.5	-2.80	-0.15	-0.10	0.07
272.0	-1.29	-0.20	-0.07	0.08
272.5	0.29	-0.23	-0.03	0.08
273.0	1.78	-0.25	0.01	0.08
273.5	3.04	-0.24	0.06	0.07
274.0	3.95	-0.21	0.09	0.05
274.5	4.44	-0.17	0.12	0.03
275.0	4.47	-0.11	0.13	0.01
275.5	4.08	-0.04	0.14	-0.01
276.0	3.35	0.03	0.14	-0.03
276.5	2.34	0.10	0.12	-0.05
277.0	1.17	0.16	0.10	-0.06
277.5	-0.03	0.21	0.07	-0.07
278.0	-1.16	0.24	0.03	-0.09
278.5	-2.14	0.26	-0.01	-0.07
279.0	-2.95	0.25	-0.05	-0.09
279.5	-3.33	0.23	-0.09	-0.08
280.0	-3.48	0.18	-0.13	-0.07
280.5	-3.33	0.12	-0.17	-0.05
281.0	-2.89	0.03	-0.20	-0.03
281.5	-2.21	-0.07	-0.21	0.01
282.0	-1.25	-0.18	-0.21	0.05
282.5	-0.44	-0.27	-0.18	0.08
283.0	0.50	-0.36	-0.14	0.12
283.5	1.37	-0.44	-0.08	0.15
284.0	2.07	-0.48	-0.01	0.17
284.5	2.56	-0.48	0.08	0.18
285.0	2.79	-0.44	0.17	0.17
285.5	2.74	-0.36	0.25	0.15
286.0	2.42	-0.23	0.33	0.08
286.5	1.79	-0.05	0.38	0.03
287.0	1.18	0.12	0.39	-0.03
287.5	0.39	0.31	0.37	-0.11
288.0	-0.40	0.50	0.32	-0.17
288.5	-1.10	0.66	0.23	-0.22
289.0	-1.65	0.77	0.12	-0.26
289.5	-2.00	0.84	-0.01	-0.27
290.0	-2.12	0.83	-0.14	-0.25
290.5	-2.01	0.76	-0.27	-0.22
291.0	-1.68	0.62	-0.38	-0.16
291.5	-1.19	0.44	-0.46	-0.09
292.0	-0.58	0.21	-0.50	-0.01
292.5	0.07	-0.04	-0.50	0.07
293.0	0.72	-0.30	-0.47	0.14
293.5	1.28	-0.53	-0.40	0.20
294.0	1.71	-0.73	-0.30	0.24
294.5	1.97	-0.87	-0.18	0.26
295.0	2.02	-0.96	-0.05	0.25
295.5	1.86	-0.99	0.08	0.23
296.0	1.49	-0.95	0.19	0.20
296.5	0.94	-0.86	0.29	0.15
297.0	0.23	-0.71	0.37	0.11
297.5	-0.55	-0.53	0.42	0.05
298.0	-1.36	-0.32	0.45	0.00
298.5	-2.10	-0.09	0.45	-0.05
299.0	-2.69	0.14	0.43	-0.09
299.5	-3.05	0.35	0.38	-0.13
300.0	-3.11	0.54	0.32	-0.16

Figure B-3. Wave Simulation Data

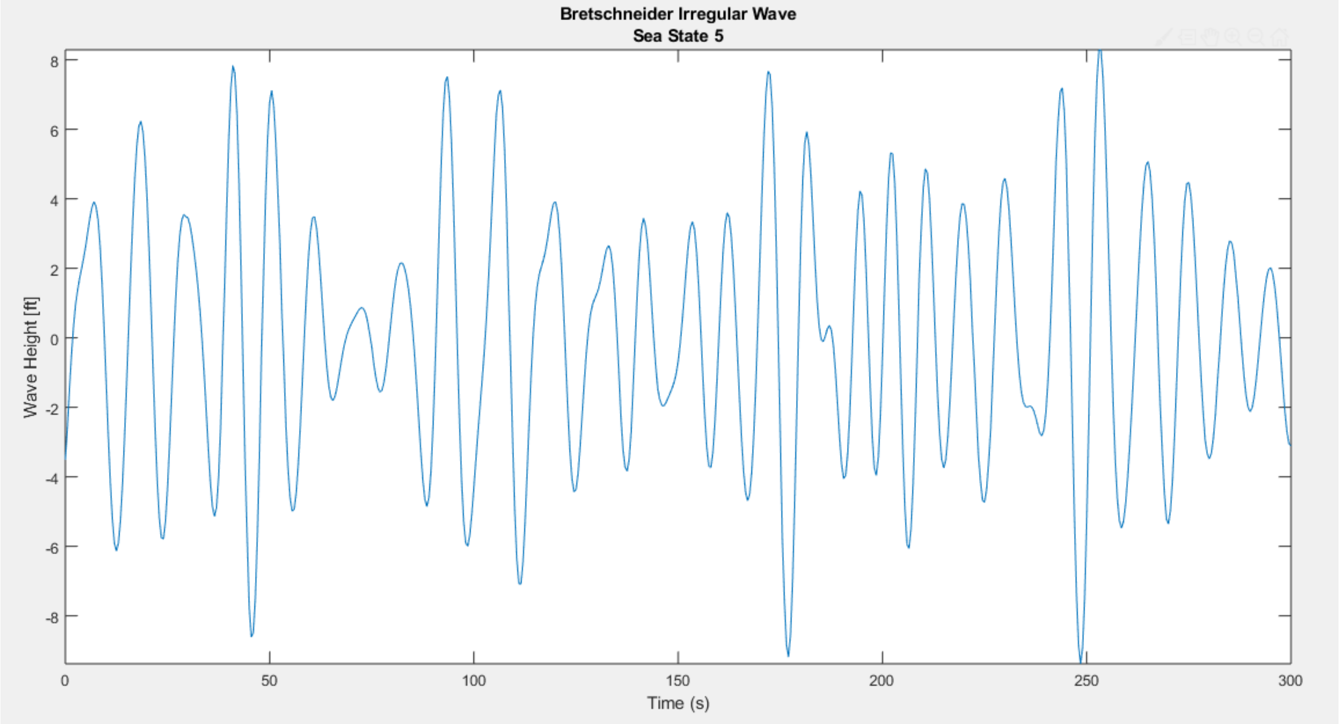


Figure B-4. Irregular Wave Simulation Results

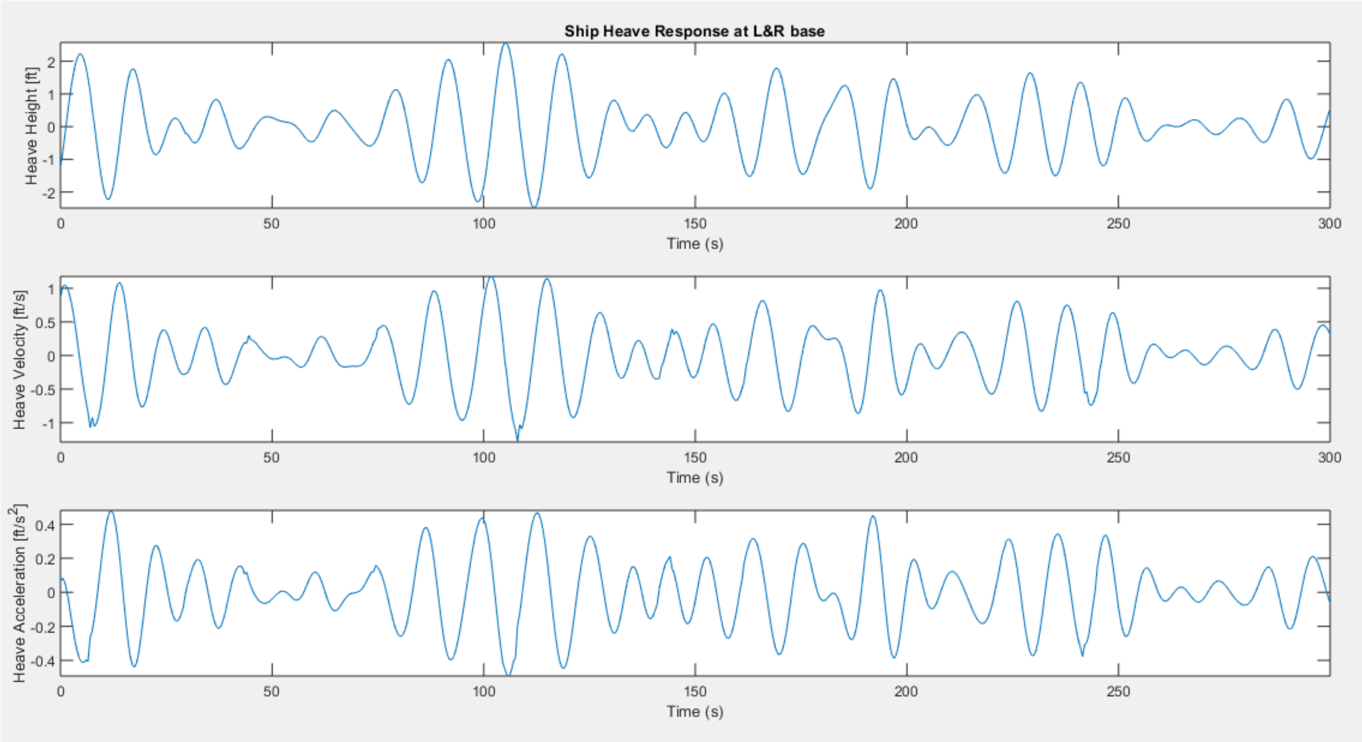
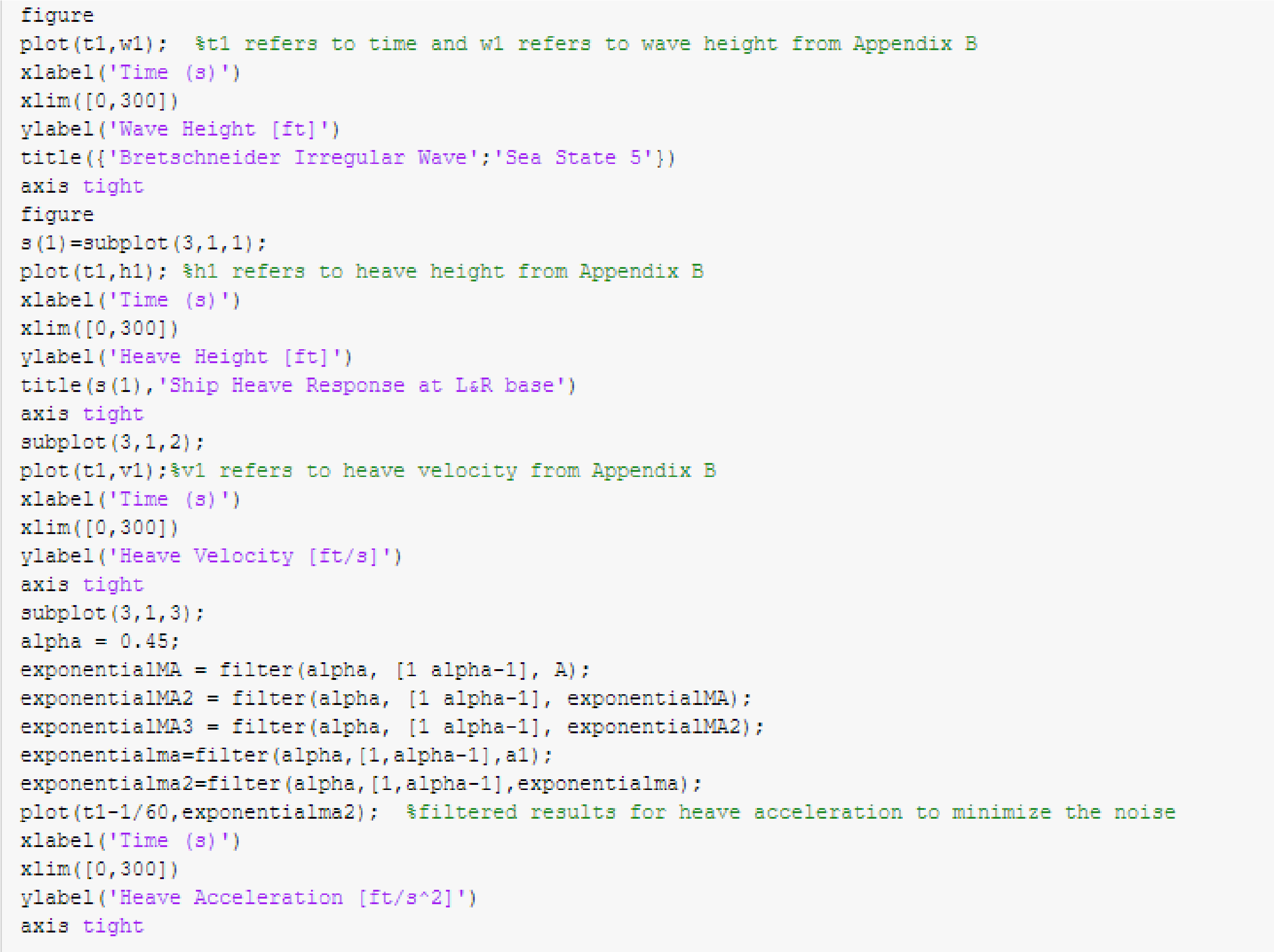


Figure B-5. Simulation Heave Response at Launch and Recovery side location

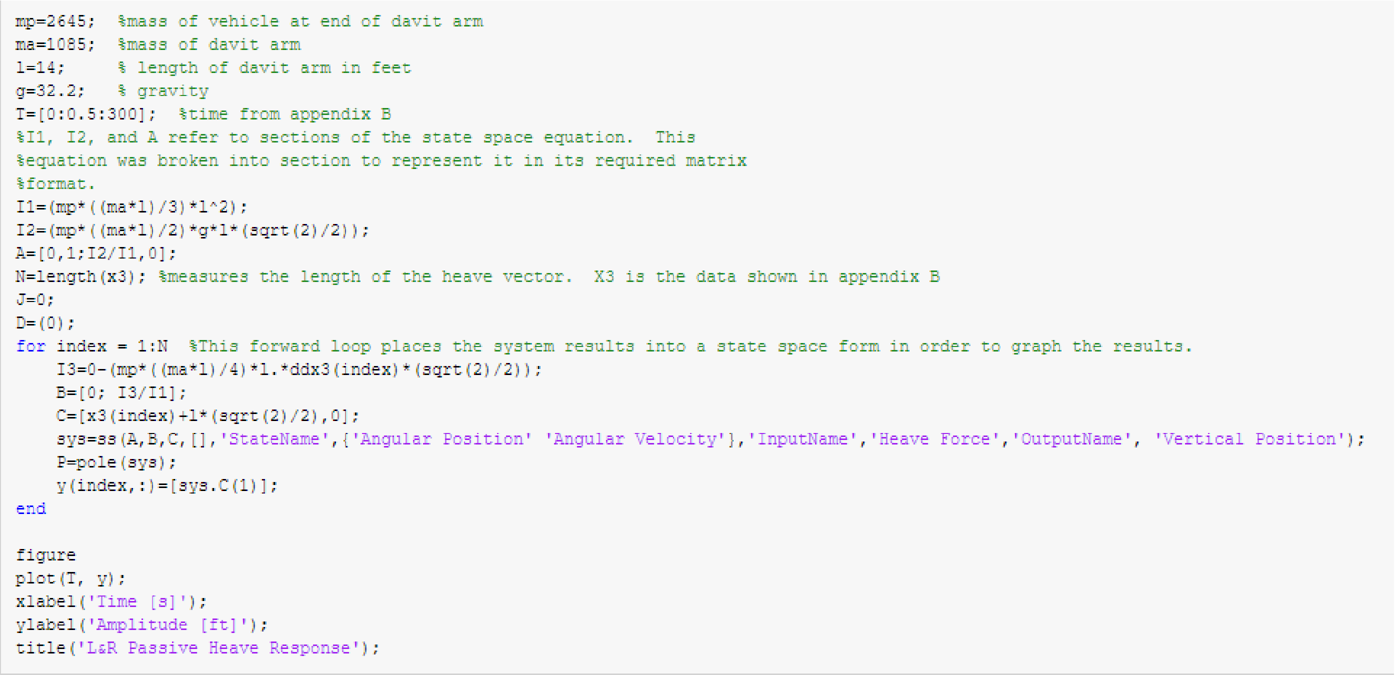
Appendix C: MATLAB Code

The following appendix shows the MATLAB code used for analyzing the data. For signal filtering and state space analysis, MathWorks documentation was used as a valuable reference.[16]



```
figure
plot(t1,w1);  %t1 refers to time and w1 refers to wave height from Appendix B
xlabel('Time (s)')
xlim([0,300])
ylabel('Wave Height [ft]')
title({'Bretschneider Irregular Wave';'Sea State 5'})
axis tight
figure
s(1)=subplot(3,1,1);
plot(t1,h1); %h1 refers to heave height from Appendix B
xlabel('Time (s)')
xlim([0,300])
ylabel('Heave Height [ft]')
title(s(1),'Ship Heave Response at L&R base')
axis tight
subplot(3,1,2);
plot(t1,v1);%v1 refers to heave velocity from Appendix B
xlabel('Time (s)')
xlim([0,300])
ylabel('Heave Velocity [ft/s]')
axis tight
subplot(3,1,3);
alpha = 0.45;
exponentialMA = filter(alpha, [1 alpha-1], A);
exponentialMA2 = filter(alpha, [1 alpha-1], exponentialMA);
exponentialMA3 = filter(alpha, [1 alpha-1], exponentialMA2);
exponentialma=filter(alpha,[1,alpha-1],a1);
exponentialma2=filter(alpha,[1,alpha-1],exponentialma);
plot(t1-1/60,exponentialma2);  %filtered results for heave acceleration to minimize the noise
xlabel('Time (s)')
xlim([0,300])
ylabel('Heave Acceleration [ft/s^2]')
axis tight
```

Figure C-1. Simulation Results MATLAB



```
mp=2645;  %mass of vehicle at end of davit arm
ma=1085;  %mass of davit arm
l=14;     % length of davit arm in feet
g=32.2;   % gravity
T=[0:0.5:300];  %time from appendix B
%I1, I2, and A refer to sections of the state space equation.  This
%equation was broken into section to represent it in its required matrix
%format.
I1=(mp*((ma*l)/3)*l^2);
I2=(mp*((ma*l)/2)*g*l*(sqrt(2)/2));
A=[0,1;I2/I1,0];
N=length(x3); %measures the length of the heave vector.  X3 is the data shown in appendix B
J=0;
D=(0);
for index = 1:N  %This forward loop places the system results into a state space form in order to graph the results.
    I3=0-(mp*((ma*l)/4)*l.*ddx3(index)*(sqrt(2)/2));
    B=[0; I3/I1];
    C=[x3(index)+l*(sqrt(2)/2),0];
    sys=ss(A,B,C,[],'StateName',{'Angular Position' 'Angular Velocity'},'InputName','Heave Force','OutputName', 'Vertical Position');
    P=pole(sys);
    y(index,:)=[sys.C(1)];
end

figure
plot(T, y);
xlabel('Time [s]');
ylabel('Amplitude [ft]');
title('L&R Passive Heave Response');
```

Figure C-2. Passive System Response

```
mp=2645;  %mass of vehicle at end of davit arm
ma=1085;  %mass of davit arm
l=14;   %length of davit arm in feet
g=32.2; %gravity
T=[0:0.5:300];  %time from appendix B
I1=(mp*((ma*l)/3)*l^2);
I2=(mp*((ma*l)/2)*g*l*(sqrt(2)/2));
A=[0,1;I2/I1,0];
N=length(x3);
J=0;
D=(0);
q=0;
x0 = (0);
x0h=(0);
t = 0;
dt = 0.5;
u=x3(1);
%this forward loop takes the state space form of the system and implements
%the feedback results into the system in a continuous loop.  Mathworks was
%used as a reference for determining the correct approach. [16]
for index = 1:N  %x3 refers to heave height and ddx2 refers to heave velocity from appendix B
    K=[-0.12,0.012];  %the k1 and k2 values in the feedback loop
    I3=-(mp*((ma*l)/4)*l.*ddx3(index)*(sqrt(2)/2));
    B=q-[0; I3/I1];
    C=[x3(index)+l*(sqrt(2)/2),0];

    ts(index) = t;

  y       = C*x0;
  yhat    = C*x0h;
  r       = y - yhat;


  x0     = expm(A*dt)+(B*dt);
  x0     = expm(A*dt)+(x0h+B*dt);
  t     = t + dt;
  q= K.*r;
  u=y;

  o(index,:)=[y(1)-y(2)];

end
p=asind(o/l);
angle_delta=std(p);
figure
 plot(T,o);
 xlabel('Time [s]');
ylabel('Amplitude [ft]');
title('L&R Active PD Controlled Heave Response');
```

Figure C-3. Actively controlled Heave response

References

[1] R. O'Rourke, "Navy Frigate (FFG[X]) Program: Background and Issues for Congress," Congressional Research Service, Report to Congress, Jul. 2018.

[2] J. K. Woodacre, R. J. Bauer, and R. A. Irani, "A review of vertical motion heave compensation systems," *Ocean Eng.*, vol. 104, pp. 140–154, Aug. 2015.

[3] NAVSEA Warfare Centers, "Holistic Approach to UxV Carriage from Warfare Centers Division," Newport, RI, Aug-2018.

[4] C. J. Rucker, "Unmanned Surface Vehicle (USV) & Unmanned Undersea Vehicle (UUV) Overview," 02-Apr-2018.

[5] "Bluefin SandShark Autonomous Underwater Vehicle (AUV) - General Dynamics Mission Systems." [Online]. Available: https://gdmissionsystems.com/products/underwater-vehicles/bluefin-sandshark-autonomous-underwater-vehicle. [Accessed: 07-Mar-2019].

[6] "Bluefin-21 Unmanned Underwater Vehicle (UUV) - General Dynamics Mission Systems." [Online]. Available: https://gdmissionsystems.com/products/underwater-vehicles/bluefin-21-autonomous-underwater-vehicle. [Accessed: 07-Mar-2019].

[7] M. M. Graham, "Unmanned Surface Vehicles : An Operational Commander's Tool for Maritime Security:," Defense Technical Information Center, Fort Belvoir, VA, Oct. 2008.

[8] "The Navy Unmanned Surface Vehicle (USV) Master Plan," Jul. 2007.

[9] Naval Sea Systems Command, "Launch, Recovery, and Handling of Surface and Subsurface Vehicles on Surface Ships," Naval Sea Systems Command, NAVSEA Design Practices and Criteria Manual T9070-BV-DPC-010/583–1, Jun. 2018.

[10] "NAVAL SHIPS' TECHNICAL MANUAL CHAPTER 583 VOLUME 2 - HANDLING AND STOWING BOATS AND SMALL CRAFT." 15-Jan-2013.

[11] J. N. Newman, “Definition sketch of body motions in six degrees of freedom.,” in *Marine Hydrodynamics*, Cambridge, Massachusetts: MIT Press, 1977, p. 286.

[12] “C-Target-6_Datasheet_2018.pdf.” [Online]. Available: https://www.asvglobal.com/wp-content/uploads/2018/06/C-Target-6_Datasheet_2018.pdf. [Accessed: 18-Mar-2019].

[13] “Introduction to PID Controller With Detailed P,PI,PD & PD Control,” *VivekBose.com*. [Online]. Available: https://vivekbose.com/introduction-to-pid-controller-with-detailed-ppipd-pd-control. [Accessed: 22-Jan-2019].

[14] K. J. Åström and R. M. Murray, *Feedback systems: an introduction for scientists and engineers*. Princeton: Princeton University Press, 2008.

[15] “Lifting Hook for Bell Furnaces | Smart Lifting Solutions,” *Elebia*. [Online]. Available: https://elebia.com/lifting-hook-for-bell-furnaces/. [Accessed: 19-Mar-2019].

[16] “Signal Smoothing - MATLAB & Simulink Example.” [Online]. Available: https://www.mathworks.com/help/releases/R2018b/signal/examples/signal-smoothing.html. [Accessed: 19-Mar-2019].